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Consequences of elevated carbon dioxide (CO$_2$) on soil organic carbon pools: A review

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Abstract

Carbon dioxide (CO$_2$) is an important heat-trapping/greenhouse gas that comes from the extraction and burning of fossil fuels (such as coal, oil and natural gas), wildfires and natural processes like volcanic eruptions. A higher concentration of atmospheric CO$_2$ above the ambient is called elevated CO$_2$. Open top chamber (OTC) and free air CO$_2$ enrichment (FACE) technology are used to elevate the atmospheric concentration of CO$_2$. A change in atmospheric CO$_2$ could affect soil carbon storage through changes in plant and microbial activities. Elevated atmospheric CO$_2$ consistently stimulates plant growth, thereby increasing inputs of carbon into soil, mainly through increased detrital production and root exudation. Most of the additional carbon released into the soil in response to elevated CO$_2$ is labile and decomposes quickly. Accelerated decomposition of soil organic matter by stimulated microbial activity as a result of the higher addition of easily degradable root exudates in response to elevated CO$_2$ conditions, is termed the priming effect. Elevated CO$_2$ increases the yield of C$_3$ plants and also increases the labile pool in the soil, but reduces the old organic carbon pools due to the priming effect. Moisture content at field capacity and moderate temperature (35 ˚C) along with elevated CO$_2$ (up to 650 ppm) increase soil organic carbon. The SRI method of rice cultivation followed by raised bed wheat cultivation increases total soil organic carbon. Soil carbon sequestration under elevated CO$_2$ can only be increased when additional nutrients are supplied.

Keywords: Climate change, elevated carbon dioxide, soil organic carbon pools, open top chamber, free air CO$_2$ enrichment

Introduction

The Earth's atmosphere is a layer of gases held close to its surface by gravity. It plays a crucial role in supporting plant and animal life, helps to maintain a global average surface temperature of about 14 °C, plays a major part in determining weather and climate, screens out harmful radiation from the Sun. By volume, the dry air in Earth's atmosphere is about 78.09 percent nitrogen, 20.95 percent oxygen and 0.93 percent argon. Trace gases account for the other 0.03 percent, including the greenhouse gases carbon dioxide, methane, nitrous oxide and ozone (NASA, 2022) [35]. Yet while these greenhouse gases make up just a tiny percentage of our atmosphere, they play major roles in trapping Earth's radiant heat and keeping it from escaping into space, thereby warming our planet and contributing to Earth's greenhouse effect. Climate change refers to the change in the environmental conditions of the Earth. Climate change is a global challenge. Climate change negatively affects all four pillars of food security: availability, access, utilisation and stability. Climate change puts the quantity, quality, stability and safety of the global food supply at risk. Changes such as rising temperatures, increasing atmospheric carbon dioxide, rising sea levels and changing weather patterns all affect the functionality and efficiency of food supply chains.

Human activity is adversely affecting the global carbon cycle, and contributing to climate change by producing more and more CO$_2$ and CH$_4$. Among the GHGs, CO$_2$ is the main one, the effect of which should be related to crop production. Carbon dioxide is the primary greenhouse gas, responsible for about three-quarters of emissions. Carbon serves as the primary substrate for photosynthesis and is the one to contribute to the yield formation in plants. With the extensive combustion of fossil fuel and other anthropogenic activities since the industrial revolution, the atmospheric CO$_2$ concentration has increased to 421 ppm in 2022 (NOAA, 2022) [36], and is predicted to reach 550 ppm in 2050 and 2,000 ppm by 2250 (IPCC, 2014) [18]. Plant tissue (including wood) is composed of about half carbon, all of which comes from CO$_2$ in the atmosphere. Generally, it is well known that the plant biomass production increases under elevated CO$_2$ for about 13 to 20% (De Graaff *et al*., 2006) [10], but up to 200% for some crops (Rogers *et al*., 1994) [42] compared with ambient. Trees grow faster under elevated CO_2 and acquire more nitrogen, ultimately producing more plant litter which alter the formation and cycling of SOM.

The global soil carbon (C) pool is about 2500 gigatons (Gt), which includes 1550 Gt of soil organic carbon (SOC) and 950 Gt of soil inorganic carbon (SIC). The SOC pool is 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times the size of the biotic pool (560 Gt). Moreover, soil inorganic carbon is greater than the carbon content in the atmosphere and the biotic pool (Lal, 2004) [27]. The global terrestrial soil organic carbon (SOC) pool is the largest terrestrial carbon (C) pool and constitutes a C stock that is more than twice the size of the atmospheric CO_2-C pool (IPCC, 2013) [17]. Therefore, even relatively moderate fluctuations in net C exchange between soil and atmosphere will impact the CO_2 concentration in the atmosphere profoundly. Faced by rising atmospheric CO_2 levels and the anticipated climatic changes that will result from this rise, we need to better understand how such changes will influence SOC decomposition. Accelerated decomposition of soil organic matter by stimulated microbial activity as a result of higher addition of easily degradable root exudates in response to elevated CO_2 condition, is termed as rhizospheric priming effect. Labile C released from roots stimulates microbial growth which decomposes the older soil organic matter and increases soil N availability (Olmedo *et al*., 2002) [38]. Some studies have suggested that elevated CO_2 increases lignin concentrations in plant litter that may reduce decomposition per gram litter and increase soil C sequestration (Ginkel *et al*., 1996) [13]. Under elevated CO_2 conditions, silt and clay content generally sequester more carbon than sandy soils and also enhance the C:N ratio of soil.

What is elevated carbon dioxide (CO_2)?

Higher concentration of atmospheric carbon dioxide (CO_2) above the ambient is called elevated CO_2. The concentration of carbon dioxide in Earth’s atmosphere is currently at nearly 421 parts per million (ppm) and rising. This represents a 50 percent increase since the beginning of the Industrial Age, when the concentration was near 280 ppm (in the early 1700s), and a 14 percent increase since 2000, when it was near 370 ppm. By adding more carbon dioxide to the atmosphere, people are supercharging the natural greenhouse effect, causing global temperature to rise. CO_2 levels are measured by hundreds of stations scattered across 66 countries which all report the same rising trend. India has atmospheric CO_2 monitoring stations at New Delhi, Ranichauri, Varanasi, Nagpur, Pune, Port Blair, Visakhapatnam, Guwahati, Kolkata, Jodhpur, Bhuj and Thiruvananthapuram.

How to measure carbon dioxide (CO_2)?

Carbon dioxide is a non-toxic and non-flammable gas. However, exposure to elevated concentrations can induce a risk to life. Whenever CO_2 gas or dry ice is used, produced, shipped or stored, CO_2 concentration can rise to dangerously high levels. Because CO_2 is odorless and colorless, leakages are impossible to detect, meaning proper sensors are needed to help ensure the safety of personnel. CO_2 is measured with a gas sensor specifically made to measure the concentration of CO_2 in the air. Examples of some widely used CO_2 sensors are Grove-CO_2 sensor (MH-Z16), SenseCAP SOLO CO_2 5000(A1)-NDIR CO_2 sensor, SenseCAP wireless CO_2 sensor, etc. There are three main types of CO_2 sensors:

a. Electrochemical sensors: Electrochemical sensors are generally less vulnerable to humidity and temperature changes.
b. Non-dispersive infrared (NDIR) sensors: NDIR sensors have a very long-life span. Other substances will also not interfere with readings. It works well at common CO_2 ranges. It is most widely-used.
c. Metal oxide semiconductor (MOS) sensors: MOS sensors are relatively easy to use due to their simple design.

Consequences of elevated carbon dioxide (CO_2)

The qualitative and quantitative improvement of above-ground and below-ground biomass following N enrichment in soil may enhance root respiration by alleviating C limitation for soil microorganisms. Diffusion of atmospheric CO_2 into soil becomes limited with increasing depth. Soil solubility triggers significant soil inorganic carbon loss, driven by dissolved inorganic carbon leaching and soil biogeochemical reactions. During precipitation events, the CO_2 enriched water percolates to deep soil layers and transports laterally to groundwater discharge locations, where it may also directly degas to the atmosphere. Low pH condition due to increased CO_2 typically allows more CO_2 dissolution in rainwater, which may lead to increased carbonate mineral leaching. Results of some studies on response of different plant species under elevated carbon dioxide are shortlisted in Table 1.

Table 1: Influence of elevated carbon dioxide (CO_2) among different plant species

Plant species	Treatments	Response	References
Zea mays	FACE	Positive response	Ma *et al.* (2022) [30]
Oryza sativa	Open-top chamber	Positive response	Kaleeswari *et al.* (2019) [21]
Helianthus annuus	Open-top chamber	Positive response	Lakshmi *et al.* (2014) [26]
Eucalyptus pauciflora	Open-top chamber	Positive response	Atwell *et al.* (2009) [4]
Alfalfa	Controlled environmental chamber	Positive response	Aranjuelo *et al.* (2009) [3]
Gossypium hirsutum	Controlled environmental chamber	Positive response	Yoon *et al.* (2009) [57]
Cucumis sativus	Controlled environmental chamber	Positive response	Kosobryukhov (2008) [25]
Oryza sativa	FACE	Positive response	Shimono *et al.* (2008) [45]
Pinus taeda	FACE	Positive response	Crous *et al.* (2008) [8]
Betula papyrifera	Controlled environmental chamber	No response	Zhang *et al.* (2008) [58]
Glycine max	Open-top chamber	Positive response	Srivastava *et al.* (2006) [48]
Temperate forest trees	FACE	No response	Korner (2005) [24]
Populus species	FACE	Positive response	Wittig (2005) [56]
Beta vulgaris	Controlled environmental chamber	Positive response	Ignatova *et al.* (2005) [16]
Trifolium alexandrium	Open-top chamber	Positive response	Madan *et al.* (2004) [31]

Lolium perenne	FACE	Positive response	Ainsworth *et al.* (2003) [1]
Citrus reticulata	Controlled environmental chamber	Negative response	Vu *et al.* (2001) [55]
Sorghum vulgare	FACE	No response	Ottman (2001) [39]
Solanum tuberosum	Open-top chamber	Acclimatory response	Lawson *et al.* (2001) [28]
Liquidambar styraciflua	FACE	Positive response	Norby *et al.* (2000) [37]
Solanum tuberosum	Open-top chamber	Acclimatory response	Schapendonk *et al.* (2000) [44]

Positive effects of elevated carbon dioxide (CO_2)

- Increases in dry weight or biomass production
- Increases carbon sequestration potential
- Reduces the incidence of cold shock
- Stimulate microbial population
- Stimulate nutrient use efficiency
- Increase in water use efficiency

Negative effects of elevated carbon dioxide (CO_2)

- Global warming
- Migration of eco-zones
- Changes in biodiversity
- Disturbance in hydrological cycle
- Decline in food quality
- Pest & diseases incidence
- Desertification
- Increase in the irrigation water requirement

Soil carbon

The total carbon density is the summation of SIC and SOC densities. The total carbon stock of India has been estimated at 35.55±1.87 Pg (Sreenivas *et al*., 2016) [46]. Understanding the distribution of organic & inorganic carbon storage in soil profile is crucial for assessing regional, continental and global soil C stores and predicting the consequences of global change. The stocks of organic matter in soils result from the balance between inputs and outputs of carbon within the belowground environment. Inputs are primarily from leaf and root detritus. Outputs are dominated by the efflux of carbon dioxide (CO_2) from the soil surface, although methane (CH_4) efflux and hydrologic leaching of dissolved and particulate carbon compounds can also be important. The production of CO_2 in soils is almost entirely from root respiration and microbial decomposition of organic matter. Like all chemical and biochemical reactions, these processes are temperature-dependent. Root respiration and microbial decomposition are also subject to water limitation.

Soil organic carbon (SOC): Organic carbon acts as a key factor of soil fertility and vegetation production. It is derived from the remains of plants and animals. SOC is more reactive, highly dynamic and a strong determinant of soil quality. The wide variability in SOC density and stock was reported by Sreenivas *et al*. (2016) [46] within various land use and land cover throughout India. The highest SOC density was observed in soils under plantation followed by forest and agricultural land although forest soils maintain the highest stock of organic carbon. The effect of land use on the SOC pool was specific to the Agro-Ecological Region. The soils of Western Ghats and Coastal Plains of India, with a hot humid to per humid climate observed to have higher SOC density. In contrast, lower values of SOC density were observed in arid to semi-arid regions of India. Total organic carbon pool size of India has been estimated at 22.72±0.93 Pg.

Soil inorganic carbon (SIC): The SIC pool consists of mineral forms of C and classified as lithogenic IC and pedogenic IC. LIC is inherited from the parent material of the soil. PIC is formed through the dissolution and precipitation of carbonated minerals. The high SIC density values are located in the Western India *i.e*., Western Rajasthan and Rann area of Gujarat, while North-East India is free from any accumulation of SIC. The North-Eastern region characterized by high rainfall resulted in very low SIC density in these soils. It was noted that the highest mean SIC density of 53.2 kg/m^2 was noticed in Rann area of Gujarat, where there is high amount of carbonate and bicarbonate deposition throughout the soil profile. Total inorganic carbon pool size of India has been estimated at 12.83±1.35 Pg (Sreenivas *et al*., 2016) [46].

Carbon cycle

The carbon cycle is the biogeochemical cycle by which carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere and atmosphere of the Earth. Carbon is the building block of life. Carbon is also present in the Earth's atmosphere, soils, oceans and crust. 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. Any movement of carbon between these reservoirs is called a flux.

Importance of carbon cycle

- Balancing various carbon pools
- CO_2 fixation and regeneration
- Warm blanket around the planet
- Stimulation of microbial growth
- Stimulation of photosynthesis rates

Carbon pools of the carbon cycle

- Atmosphere: The atmosphere contains approximately 750 PgC (Lal, 2004) [27], most of which is in the form of CO_2, with much smaller amounts of methane (CH_4) and various other compounds. Although this is considerably less carbon than that contained in the oceans or crust, carbon in the atmosphere is of vital importance because of its influence on the greenhouse effect and climate.
- Terrestrial ecosystems contain carbon in the form of plants, animals, soils and microorganisms (bacteria and fungi). Of these, plants and soils are the largest.
- Plants: Collectively, the Earth’s plants store approximately 560 PgC, with the wood in trees being the largest fraction.
- Soils: The total amount of carbon in the world’s soils is estimated to be 1500 PgC.
- Oceans: The Earth’s oceans contain 38,000 PgC, most of which is in the form of dissolved inorganic carbon stored at great depths where it resides for long periods of time.
- Fossil fuels: About 4,000 PgC is stored as fossil fuels in the lithosphere.
- Earth’s crust: The largest amount of carbon on Earth is stored in sedimentary rocks within the Earth’s crust.

These are rocks produced either by the hardening of mud (containing organic matter) into shale over geological time, or by the collection of calcium carbonate particles, from the shells and skeletons of marine organisms, into limestone and other carbon-containing sedimentary rocks. Together all sedimentary rocks on Earth store 100,000,000 PgC (Petagrams of carbon = 10^{15} grams).

Carbon fluxes of the carbon cycle

- Fluxes are usually expressed as a rate with units of an amount of some substance being transferred over a certain period of time (*e.g.* g cm^{-2} s^{-1} or kg km^{-2} yr^{-1}). A single carbon pool can often have several fluxes both adding and removing carbon simultaneously. For example, the atmosphere has inflows from decomposition (CO_2 released by the breakdown of organic matter), forest fires and fossil fuel combustion and outflows from plant growth and uptake by the oceans. The size of various fluxes can vary widely.
- Photosynthesis: During photosynthesis, plants use energy from sunlight to combine CO_2 from the atmosphere with water from the soil to create carbohydrates. In this way, CO_2 is removed from the atmosphere and stored in the structure of plants.
- Plant respiration: Plants also release CO_2 back to the atmosphere through the process of respiration.
- Litterfall: In addition to the death of whole plants, living plants also shed some portion of their leaves, roots and branches each year. Because all parts of the plant are made up of carbon, the loss of these parts to the ground is a transfer of carbon (a flux) from the plant to the soil.
- Decay of residues: When dead organic matter is broken down or decomposed by bacteria and fungi, CO_2 is released into the atmosphere.
- Sea-surface gas exchange: Inorganic carbon is absorbed and released at the interface of the oceans' surface and surrounding air, through the process of diffusion.
- Fossil fuel burning: Coal, oil and natural gas. These materials contain carbon that was captured by living organisms over periods of millions of years and has been stored in various places within the Earth's crust.
- Land use: Another human activity that has caused a flux of carbon to the atmosphere is land cover change, largely in the form of deforestation.
- Geological processes: Geological processes represent an important control on the Earth's carbon cycle over time scales of hundreds of millions of years. Processes include the formation of sedimentary rocks and their recycling *via* plate tectonics, weathering and volcanic eruptions.

Soil organic carbon (SOC) pools

Soil organic matter is the organic fraction of the soil and is made up of decomposed plant and animal materials as well as microbial organisms. Soil organic carbon refers to the carbon associated with soil organic matter. Conveniently, SOC has been divided into a number of pools according to its stability, namely labile, slow and recalcitrant pools, in increasing order of stability. Labile carbon mainly consists of soil microbial biomass carbon, dissolved organic matter, and easily oxidative organic matter, whereas the recalcitrant carbon usually refers to the component of SOM that is resistant to microbial decomposition or protected by mineral soil particles. Role of SOC pools are furnished in Table 2.

Table 2: Role of SOC pools

Soil fertility	Effects of SOC	C pools
Chemical fertility	Microbial decomposition of SOC releases nitrogen, phosphorus and a range of other nutrients for use by plant roots.	Labile & slow
Provides available nutrients to plants		
Physical fertility	In the process of decomposition, microbes produce resins and gums that help bind soil particles together into stable aggregates. The improved soil structure holds more water available to plants, allows water, air and plant roots to move easily through the soil, and makes it easier to cultivate.	
Improves soil structure and water holding capacity		
Biological fertility	Organic carbon is a food source for soil organisms and microorganisms. Its availability controls the number and types of soil inhabitants and their activities, which include recycling nutrients, improving soil structure and even suppressing crop diseases.	Labile
Provides food for soil organisms		
Buffers toxic elements and harmful substances	SOC can lessen the effect of harmful substances such as toxins and heavy metals by sorption, and assist degradation of harmful pesticides.	Slow and recalcitrant

Causes of depletion of SOC pools

- Deforestation
- *Jhum* (Shifting) cultivation
- Intensive agriculture
- Improper tillage and residue management
- Less organic nutrient sources
- Soil erosion

Impact of SOC depletion

- The loss of soil fertility
- Reduced microbial activity
- Negative nutrient/elemental balance
- Decreases the quality of biomass production
- Negative water balance
- Problem of soil crusting
- Deterioration of soil structure
- More soil erosion

How to enrich SOC pools?

- Application of manures
- Adoption of cover crops
- Residue management as mulching
- Providing continuous ground cover
- Enhancing biodiversity
- Conservation tillage

OTC and FACE technology

Open top chamber (OTC) and free air CO_2 enrichment (FACE) technology are used to elevate the atmospheric concentration of CO_2.

Open top chamber (OTC): Structure of OTC (Fig. 1) having a size of 3 m diameter x 2.4 m height (Chaturvedi *et al.* 2010) [7]. Covering of OTCs is UV stabilized transparent low-density polythene film 200 GSM with a special distribution system. Complete structure fixed at 2 feet below ground on a cement concrete platform up to 3 feet from Earth surface. CO_2 supply is controlled using a solenoid valve and pressure gauge with a timer. Chambers are equipped with a frustum at the top to deflect air and prevent dilution of the CO_2 concentration within the chamber. OTC having a cylindrical double walled plenum around the base for uniform CO_2 circulation. Blowers are used in maintaining inside air temperature closure to that of outside ambient atmosphere.

Free air CO_2 enrichment (FACE) technology: FACE technology (Fig. 2) is used to elevate the atmospheric concentration of CO_2 in the experimental plots (U.S. DOE, 2020) [53]. The FACE system is designed to maintain the level of CO_2 above the experimental planting at 550 parts per million (ppm), using sensors set up in and near the circles and a central control computer. The amount of pure CO_2 added is controlled by a valve inside the fan house. The CO_2 then is mixed with ambient air and this mixture is blown by a large fan into an underground pipe, called a plenum, which runs around the plot circle in the shape of an octagon. To conserve CO_2, the enriched air is only emitted on the upwind side of the circles.

Fig 1: Open top chamber

Fig 2: Free air CO_2 enrichment chamber

Effect of elevated carbon dioxide (CO_2)

Effect on plant growth

An increase in CO_2 concentration causes partial closure of stomata, thereby decreasing leaf conductance to CO_2 and H_2O vapour and reducing leaf transpiration while, increasing net carbon assimilation. The enrichment of atmospheric CO_2 could reduce potential transpiration rate, increase water and nutrient use efficiencies as well as growth and production of vegetation (Cardon *et al.*, 2001; Lin and Zhang, 2012) [6, 29]. Bhattacharyya *et al.* (2013) [5] recorded higher growth and grain yield of flooded rice under elevated CO_2 than ambient CO_2. Lakshmi *et al.* (2014) [26] observed that elevated CO_2 significantly increased the total biomass, grain yield and transpiration efficiency of sunflower (C_3) plant and transpiration efficiency of pearl millet (C_4) plant. Increased photosynthesis as well as reduced transpiration contributes to increased WUE in C_3 plants, whereas decreased transpiration contributes in C_4 plants under elevated CO_2 conditions. Talhelm *et al.* (2014) [49] found that elevated CO_2 significantly enhanced ecosystem carbon content by 11 per cent over the duration of 11 years. The treatment effects on ecosystem C content resulted from differences in tree biomass, particularly woody tissues (branches, stem, and coarse roots), and lower C content in the near-surface mineral soil.

Effect on total organic carbon

Three primary causes were hypothesized to be responsible for the observed changes under elevated CO_2: (i) increased litter input from above ground; (ii) increased rhizodeposition; and (iii) subsequent assimilation and formation of SOM by the soil microbial communities. The enrichment of atmospheric CO_2 could reduce potential transpiration rate, increase water and nutrient use efficiencies as well as net primary productivity (NPP). With the increase of net primary productivity, more organic carbon was inputted to the soil carbon pools, resulting in SOC increase. Treseder *et al.* (2003) [52] found that the pools of total C in bulk soil and in water-stable aggregates significantly increased 1.5 times and three times, respectively, between the 250 to 650 ppm CO_2 concentration. In addition, C concentrations in WSA had a significantly stronger response to elevated CO_2 than did those in bulk soil. It might be due to the inputs of excess C may have been distributed evenly among soil fractions, but the physical structure of the WSA could have protected WSA C from decomposers. Jastrow *et al.* (2005) [19] reported that soil organic carbon and total nitrogen in the prairie soil increased significantly throughout the surface 30 cm with CO_2 enrichment. An increase in photosynthate production might be a source of extra C. Lower CO_2 levels elicited a net loss of C from plants and soil over the same time period (Graaff *et al.*, 2006; Lin and Zhang, 2012; Bhattacharyya *et al.*, 2013) [14, 29, 5]. Srinivasarao *et al.* (2016) [47] recorded that profile SOC status was higher in the soils exposed to 550 $\mu mol\ mol^{-1}$ CO_2 level compared to the ambient and 700 $\mu mol\ mol^{-1}$ CO_2 levels. Increase in SOC stock and sequestration rates were seen in the study under 550 $\mu mol\ mol^{-1}$ CO_2. On the other hand, reduction in these parameters under 700 $\mu mol\ mol^{-1}$ could be due to the likelihood of positive priming of SOC decomposition, in addition to altered microbial efficiency. Reduced SOC accumulation under higher CO_2 is likely driven by microbial priming effect. Tfaily *et al.* (2018) [51] observed that bulk SOC and total N concentrations were significantly greater under elevated CO_2 than ambient CO_2. Moreover, this enhancement was more evident with soils closer to the surface (0.1 m) compared to the deeper soils (0.9 m). Higher root biomass produced at elevated CO_2 level contributed higher C input into the soil which would lead to a higher sequestration (Kaleeswari *et al.*, 2019) [21]. Samal *et al.* (2020) [43] recorded that elevated atmospheric CO_2 significantly decreased the total organic carbon (TOC) content in soil. This might be due to higher decomposition of TOC *via* rhizospheric priming effect, which is defined as accelerated decomposition of soil organic matter (SOM) by stimulated microbial activity as a result of higher addition of easily degradable root exudates in response to elevated CO_2 conditions.

Effect on microbial biomass carbon

Microbial biomass carbon (MBC) is a measure of the carbon contained within the living component of soil organic matter (*i.e.* bacteria and fungi). For the formation of the organic pool, soil microbial biomass carbon acts as a key indicator of soil organic carbon by decomposing organic matter and controlling nutrient dynamics which affect the primary productivity of the terrestrial ecosystem (Kara and Bolat, 2008) [22]. Bhattacharyya *et al.* (2013) [5] recorded maximum MBC under elevated CO_2 (550 µmol mol^{-1}) over the ambient CO_2 (394 µmol mol^{-1}). Srinivasarao *et al.* (2016) [47] recorded that the MBC was significantly higher under the soil exposed to higher CO_2 (700 µmol mol^{-1}), followed by 550 µmol mol^{-1}, while lower MBC under ambient conditions was observed. Kaleeswari *et al*. (2019) [21] revealed that with increase in CO_2 concentration, an increase in MBC content was observed. Ma *et al.* (2022) [30] observed that MBC concentration showed a significant increase at most major stages, particularly at the tasseling stage during the maize growth period under elevated CO_2. It might be due to higher activities of C-related soil extracellular enzymes under elevated CO_2, particularly at the tasseling stage, which coincided with concurrent increased MBC under elevated CO_2.

Effect on water soluble organic carbon

Water soluble organic carbon (WSOC) is considered the most mobile and reactive soil carbon source. Water soluble organic carbon is a ubiquitous and significant fraction of fine particulate matter. The potential of soil and sediment for providing dissolved organic carbon (DOC) to natural waters depends on the content and the sorption coefficient of the WSOC (Tao and Lin, 2000) [50]. Bhattacharyya *et al*. (2013) [5] recorded the highest water soluble carbohydrate carbon under elevated CO_2 (550 µmol mol^{-1}) over the ambient CO_2 (394 µmol mol^{-1}). Kaleeswari *et al.* (2019) [21] reported that with increase in CO_2 concentration, water soluble organic carbon did not change significantly.

Effect on dissolved organic carbon

Dissolved and particulate organic carbon are important components in the carbon cycle and serve as a primary food source for aquatic food webs. Dissolved organic carbon (DOC) is defined as the organic matter that is able to pass through a filter which removes material between 0.7 and 0.22 µm. Marsh *et al.* (2005) [32] observed that in a series of 12 monthly samples, the elevated CO_2 significantly increased mean annual dissolve inorganic carbon (DIC) concentrations in porewater in the case of C_3 community at the depth of 30 cm. Mean DOC was higher in the elevated CO_2 treatment than the ambient CO_2 treatment, but the differences were not significant. Much of the CO_2 emitted from roots in these saturated soils would be expected to dissolve and accumulate in the DIC pool. Elevated CO_2 stimulated soil respiration, which in turn increased the DIC pool. The effects of elevated CO_2 on the DOC pool can be expected to be less dramatic than for the DIC pool because microorganisms efficiently consume labile DOC. Ma *et al.* (2022) [30] observed that DOC concentration showed a significant increase under elevated CO_2.

Effect on particulate organic carbon

Particulate organic carbon (POC) refers to the mass of non-carbonate carbon in the particulate organic matter (POM), while POM refers to the total mass of the particulate organic matter. In addition to carbon, POM includes the mass of the other elements in the organic matter, such as nitrogen, oxygen and hydrogen. Cardon *et al.* (2001) [6] revealed that C_4 plant significantly reduced the particulate organic matter in soil whereas C_3 plant significantly increased the particulate organic matter in the 0-15 cm depth after the duration of 2 years. Elevated CO_2 caused an increase in C_3 POM and a decrease in C_3 mineral-bound SOC, suggesting that the movement of C_3 carbon from roots to long-lived, mineral-bound pools was retarded. Greater rhizodeposition, associated with the much larger root mass in elevated CO_2, might have caused this depression of C_4-SOM breakdown. Hofmockel *et al*. (2011) [15] reported that soils exposed to elevated CO_2 tended to contain more ^{15}N in coarse particle organic matter (cPOM >250 µm) and fine particle organic matter (fPOM <53 µm) than did the same soil fractions under ambient CO_2. Procter *et al.* (2015) [41] indicated that particulate organic matter C increased under elevated CO_2. Srinivasarao *et al.* (2016) [47] recorded that POC was higher in the soil under 700 µmol mol^{-1}, followed by 550 µmol mol^{-1} exposure. Samal *et al*. (2020) [43] indicated that elevated atmospheric CO_2 significantly decreased the POC content in soil. Decrease of labile carbon under elevated CO_2 might be due to higher decomposition of SOC *via* rhizospheric priming effect.

Effect on mineral-associated organic carbon

Mineral-associated organic matter (MAOM) is the largest and most persistent pool of carbon in soil. Mineral associations include chemical bonds between SOM and mineral surfaces and occlusion within micropores or small aggregates (< 50-63 µm), which all render SOM less accessible to decomposers and their enzymes. Because of this fundamental difference in their levels of protection from decomposition, MAOM tends to persist for much longer than POM (Kögel-Knabner *et al*., 2008) [23]. Hofmockel *et al.* (2011) [15] reported that soils exposed to elevated CO_2 tended to contain less ^{15}N in mineral-associated organic matter (MAOM) than did the same soil fractions under ambient CO_2. Samal *et al.* (2020) [43] recorded that elevated atmospheric CO_2 significantly increased the mineral-associated organic carbon content under elevated CO_2 than ambient. Elevated CO_2 reduces the decomposition of old SOC in recalcitrant pools contributing to an increase of recalcitrant carbon pools.

Effect on potassium permanganate oxidizable carbon

Potassium permanganate oxidizable carbon (POXC) is a sub-pool of labile soil organic carbon (SOC) and is defined as the carbon (C) that can be oxidized by potassium permanganate ($KMnO_4$). The readily mineralizable C and potassium permanganate oxidizable C which are indicators of readily available C for microbial metabolism (Das *et al*., 2011) [9], were increased significantly under elevated CO_2 (Bhattacharyya *et al*., 2013) [5]. Srinivasarao *et al.* (2016) [47] recorded that the permanganate oxidizable carbon/active carbon remained same in 0-0.2 m under all the three CO_2 levels (380, 550 and 700 µmol mol^{-1}). The active carbon showed a variation in the depth-wise soils. Higher root biomass produced at elevated CO_2 levels contributed higher C input into the soil.

Effect of fertilization on SOC under elevated CO_2

Generally, soil organic carbon can be increased by increasing organic carbon inputs and/or reducing losses. Application of optimal chemical fertilizer along with organic manure have positive impacts on soil health through changes in soil organic carbon content and microbial activities (Muchhadiya *et al*., 2021b) [34]. Dijkstra *et al*. (2005) [12] found that the elevated CO_2 treatments significantly increased the size of the labile carbon pool in all plots by 32 per cent on average but in contrast N fertilization significantly decreased the labile carbon pool by 22 per cent. Elevated CO_2 increased labile C pools in soils, likely because of increased above- and below ground plant productivity, but perhaps also because of increased root exudation with elevated CO_2. N fertilization might increase the decay rate constant of the labile C (k) can explain the reduced labile C pool. Graaff *et al.* (2006) [14] revealed that total soil carbon increased significantly under elevated CO_2, but the elevated CO_2 response depends on soil N availability. Under low N availability soil carbon contents were significantly lower than under high N availability and also found the soil C:N ratio of the woody species increased significantly under elevated CO_2. It is because soil C sequestration is a function of C input through plant growth and C output through mineralization. The stimulation of above- and below plant growth by elevated CO_2 is larger under high compared with low nutrient availability. Nitrogen fixers can supply additional N needed to sustain plant growth and support C sequestration under elevated CO_2, but only do so when other nutrients are added. In 74 per cent of the studies (79 per cent of the N fertilized and 63 per cent of the non-N fertilized studies) a positive effect of elevated CO_2 on soil carbon was found. On an average soil carbon increased by 0.205 g kg^{-1} yr^{-1} in the N fertilized studies and by 0.008 g kg^{-1} yr^{-1} in non-N fertilized studies (Dijkstra and Morgan, 2012) [11]. Because elevated CO_2 may induce a decrease in soil N availability, which will result in a decrease in plant growth and soil C sequestration. Results showing the relatively fast depletion of available N pools under elevated CO_2 caused predominantly by young trees. Overall, this implies that C sequestration in both plants and soils under elevated CO_2 can only be sustained when additional nutrients are supplied. Kaleeswari (2015) [20] reported that with increase in CO_2 concentration, organic C content increased and they also found that application of organics recorded higher organic carbon content followed by integrated plant nutrient system. Application of inorganics alone and untreated control recorded lowest organic carbon content. This might be due to higher plant photosynthesis, biomass production, enzymatic activity and increased microbial biomass under elevated CO_2. The application of organic substances or manure at high rates in the fields caused the deposition of soil and organic substances which resulted in increased soil organic carbon.

Changes in SOC of different soils under elevated CO_2

Although the overall impact of climate change on SOC stocks is very variable according to the region and soil type, rising temperatures and increased frequency of extreme events are likely to lead to increased SOC losses. Whereas, an increase in photosynthate production under elevated CO_2 may be a source of extra C. Lower CO_2 levels elicited a net loss of C from plants and soil over the same time period. Procter *et al.* (2015) [41] reported that active (easily-decomposable) soil organic C increased linearly across the CO_2 gradient in the black clay. This result explains that elevated CO_2 increased the soil C sequestration & it might be a positive function of soil clay content, with greatest C sequestration in the black clay and the least in the sandy loam. They also reported that in the two clay-rich soils, coarse particulate organic matter (POM)-C increased four-fold across the CO_2 gradient in the black clay but increased by about 50% in the sandy loam. Coarse POM-C increased exponentially with CO_2 concentration in the black clay and linearly with CO_2 in the silty clay and sandy loam soils. Interestingly, mineral C declined 22% across the CO_2 gradient in the silty clay, but did not respond linearly to CO_2 in the other two soils. Soil texture had significant effects on soil organic carbon accumulation and its response to CO_2. CO_2-induced plant growth was peak on the intermediate (silty clay) or highest-clay (black clay) soil. These soil types can provide plants with more water and nutrients, allowing higher growth at elevated CO_2. In contrast, CO_2 stimulation of decomposition would decrease in finer textured soils. Clay content influenced SOC accumulation by protecting soil organic matter from decomposition. In sandy soil least labile C accumulation, likely because new C was unprotected from decomposition. Dissolved organic C and microbial biomass C were increased under elevated CO_2 in both rhizospheric and bulk soils (Ma *et al.*, 2022) [30].

Effect of agronomic management practice on SOC under elevated CO_2

Soil organic matter quality varies depending on plant inputs as well as agronomic management practices. Practices that influence SOM include crop rotation, tillage, residue management, cover crops and use of manure or compost. It was reported that black-silver plastic mulch significantly increased the soil air CO_2 content. Mulches can affect the CO_2 and O_2 concentrations in the soil in several ways: (i) the mulch layer physically restricts the flux of the gases between the soil and atmosphere, (ii) mulch increases soil moisture by restricting evaporation, which in turn affects microbial activity, and (iii) mulch modifies the soil temperature. Plastic mulch can increase the soil temperature by a few degrees celsius. Increased soil temperature can induce functional and structural changes in microbial communities, which can lead to enhanced breakdown of organic matter and increased release of CO_2 (Anon., 2014) [2]. Pal *et al.* (2014) [40] found that significantly higher total organic carbon recorded in soils collected from furrow irrigated raised bed which remained at par with happy seeder and SRI practices. The FIRB helps in regulated water supply and might be the reason for increasing the labile fractions of organic C. On the other hand, happy seeder helps in retention/incorporation of crop residue, the lignocellulolytic material, further helps in improving the less active pool of SOC. As SRI involves regulated water and nutrient supply and also organic amendments for stimulating higher root growth and root metabolites, the plant-derived C input under SRI enhances C input. They also reported that significantly higher total organic carbon was obtained at 60 percent water holding capacity and 35 °C during the 60 days incubation period under elevated CO_2. This might be due to the effect of temperature dependence on soil respiration and other biological processes in regulating soil C dynamics at higher temperature. Wider spacing under crop intensification method decrease competition between plants for light, water, space and nutrient due to higher light interception, root distribution and nutrient availability that play important role in plant growth which might be turned in better vegetative growth and produced more dry matter accumulation per plant, root volume per plant and root dry weight per plant, which resulted in more C input in soil (Muchhadiya *et al.*, 2021a) [33].

Effect on carbon sequestration

Soil organic carbon sequestration is the process by which carbon is fixed from the atmosphere *via* plants or organic residues and stored in the soil. When dealing with CO_2 , SOC sequestration involves three stages: (i) the removal of CO_2 from the atmosphere *via* plant photosynthesis, (ii) the transfer of carbon from CO_2 to plant biomass, and (iii) the transfer of carbon from plant biomass to the soil where it is stored in the form of SOC in the most labile pool. Carbon sequestration in both plants and soils under elevated CO_2 can only be sustained when additional nutrients are supplied (Graaff *et al.*, 2006; Dijkstra and Morgan, 2012) [14, 11]. Viswanath *et al.* (2010) [54] recorded significantly lower decomposition rate and higher C:N ratio of rice and wheat residues in soil grown under elevated CO_2 than ambient CO_2 condition. The amount of residues left over after 150 days of decomposition was comparatively higher in the elevated CO_2 grown residues indicating their slow rate of decomposition. Ambient atmospheric CO_2 grown residues exhibiting narrow C:N ratios decomposed to a faster rate than the elevated CO_2 grown residues. Due to lower decomposability of elevated CO_2 grown residues might cause more C sequestration in soil. Srinivasarao *et al.* (2016) [47] noted an increase in SOC stock and sequestration rates under 550 µmol mol^{-1} CO_2. On the other hand, reduction in these parameters under 700 µmol mol^{-1} could be due to the likelihood of positive priming of SOC decomposition, in addition to altered microbial efficiency.

Conclusion

Elevated CO_2 increases the yield of C_3 plants and also increases the labile pool in the soil, but reduces the old organic carbon pools due to the priming effect. Moisture content at field capacity and moderate temperature (35 $^{\circ}$C) along with elevated CO_2 (up to 650 ppm) increases soil organic carbon. Under elevated CO_2 conditions, high nutrient availability raises SOC. Therefore, soil carbon sequestration under elevated CO_2 can only be increased when additional nutrients are supplied. The SRI method of rice cultivation followed by raised bed wheat cultivation increases total soil organic carbon. Labile C inputs accelerate the turnover of older SOC pools and alter the C dynamics of the system under elevated CO_2. In the long-term, the net C balance under elevated CO_2 depends on the extent to which the buildup of new organic C compensates for the increased loss of older organic C pools.

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