Science Societies

# Role of soil moisture management and carbon sequestration in agriculture on mitigating greenhouse gas emissions

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Soil moisture management and carbon sequestration

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Climate change, defined as long-term alterations in weather and temperature patterns, poses a significant threat to life on Earth. These variations may result from natural processes or human activities (Hardy, 2003). A major driver of climate change today is the greenhouse effect, caused by greenhouse gases emitted primarily from fossil fuel combustion, deforestation, and the depletion of soil carbon (C) storage. Among these gases, carbon dioxide ($CO_2$), methane ($CH_4$), nitrogen oxides ($NO_x$), and fluorinated gases, including hydrofluorocarbons (HCFs), perfluorocarbons (PFCs), and chlorofluorocarbons (CFCs), contribute significantly to global warming with $CO_2$ being the most abundant (Lehmann et al., 2006). In 2022, agriculture accounted for 11% of total U.S. greenhouse gas emissions with half of those emissions linked to soil and crop management practices (USEPA, 2025).

## Role of carbon sequestration on greenhouse gas emissions

Soil is the largest terrestrial C reservoir, storing approximately 2,500 PgC in the top meter of soil while vegetation holds an additional 620 PgC. Together, these two carbon pools store nearly three times the 880 PgC present in the atmosphere (Lal et al., 2021). As a result, soil plays a crucial role in mitigating greenhouse gas emissions by reducing atmospheric $CO_2$ levels (Lal et al., 2007).

Carbon sequestration, the process of capturing and storing atmospheric $CO_2$ in the soil, helps minimize net $CO_2$ emissions from agriculture. It retains carbon either in solid form as organic matter or in dissolved form in soil solution, thereby reducing its gaseous presence in the atmosphere and mitigating the greenhouse effect (Cheddadi et al., 2001; Lal et al., 2021). In addition to lowering atmospheric $CO_2$, carbon sequestration enhances soil moisture retention, improves soil fertility, and boosts overall soil health and agricultural productivity (Hao et al., 2025).

Carbon sequestration

*Carbon sequestration, the process of capturing and storing atmospheric CO? in the soil, helps minimize net CO? emissions from agriculture. Image courtesy from USGS.*

Soil management practices significantly influence carbon sequestration potential. While some practices enhance soil C storage, others degrade it. Sustainable approaches such as cover cropping, no-till or minimum tillage, and organic farming increase carbon sequestration, whereas conventional tillage, deforestation, and overgrazing diminish it (Smith & Conen, 2006; Zerssa et al., 2021). Additionally, environmental factors such as temperature and soil moisture play key roles in regulating soil carbon dynamics. Since soil organic matter decomposition depends on microbial activity, cooler temperatures slow decomposition and increase soil C storage, whereas warmer temperatures accelerate decomposition and decrease C retention (Lal et al., 2015).

Sustainable approaches such as cover cropping, no-till or minimum tillage, and organic farming

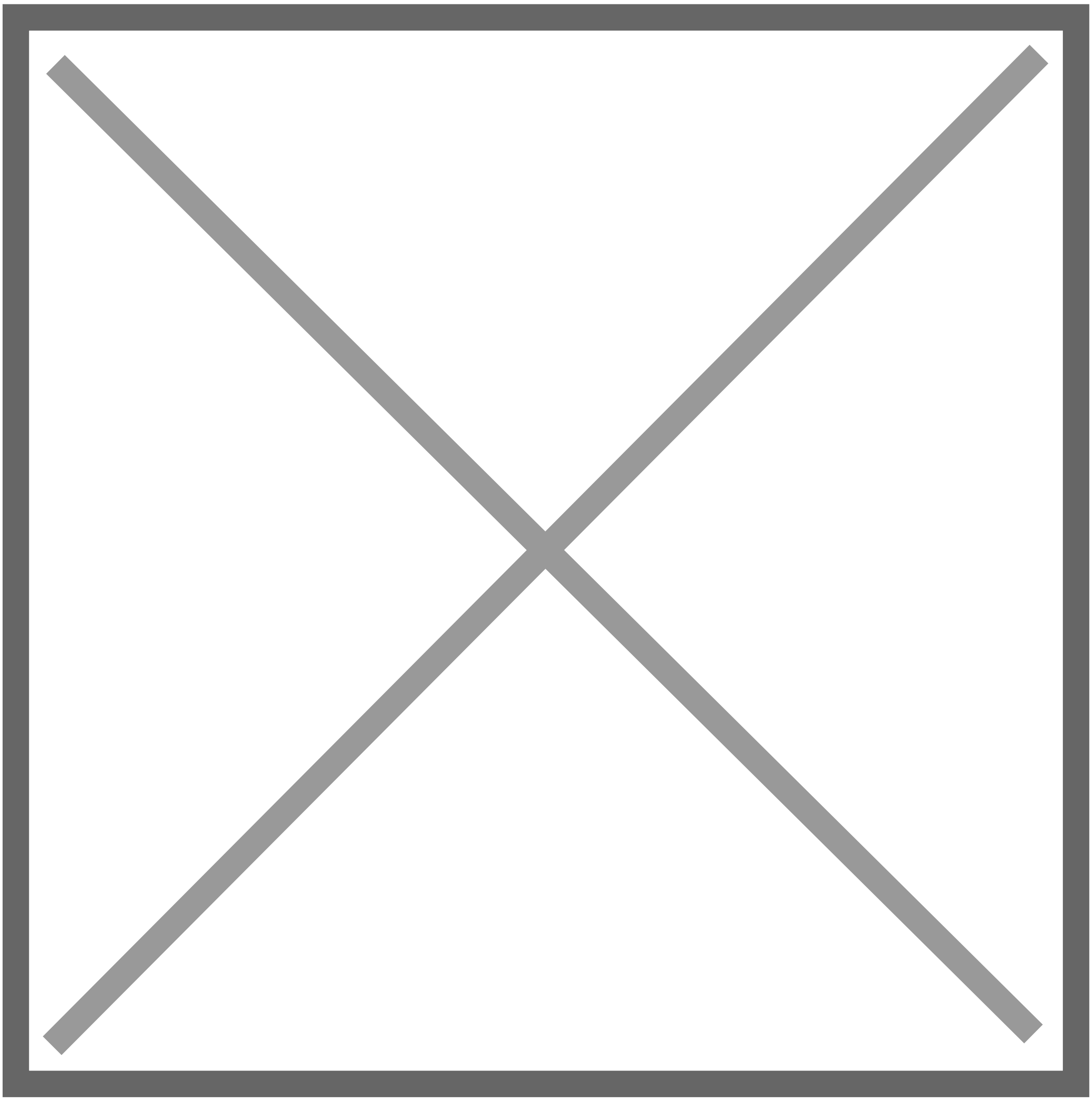
*Sustainable approaches such as cover cropping, no-till or minimum tillage, and organic farming increase carbon sequestration. Photos courtesy of (l to r) Kelsey Greub, Nall Moonilall, and Doug Collins.*

## Role of soil moisture in greenhouse gas emissions

Soil moisture indirectly affects greenhouse gas emissions by influencing plant growth, microbial activity, and organic matter decomposition. These processes directly impact atmospheric C fixation, soil carbon sequestration, and greenhouse gas fluxes (Hao et al., 2025). Limited soil moisture impairs photosynthesis, reducing $CO_2$ fixation and decreasing organic matter inputs to the soil. Consequently, soil microbial communities are affected, slowing organic matter decomposition. Approximately 90% of the variability in global soil C uptake is attributed to soil moisture fluctuations (Humphrey et al., 2021).

Soil respiration, the release of $CO_2$ from the soil, consists of two components: autotrophic respiration (from plant roots) and heterotrophic respiration (from microbial decomposition). Soil moisture affects both processes at different levels (Hu et al., 2018). Drought conditions, for example, have been shown to reduce autotrophic respiration by 50% in subtropical forests and by 47% in grasslands (Huang et al., 2018; Balogh et al., 2016).

However, extreme moisture conditions—both excessive dryness and excessive wetness—reduce heterotrophic respiration. This process follows a "peak and decline" pattern where heterotrophic respiration increases with soil moisture up to an optimal threshold (~80% water-filled porosity, WFP) but declines beyond this point due to anaerobic conditions (Widanagamage et al., 2025). Under excessive moisture (>80% WFP), oxygen depletion promotes anaerobic microbial respiration, leading to methane production (methanogenesis). Agricultural practices such as flood irrigation, furrow irrigation, and ponding water can increase anaerobic conditions, thereby enhancing methane emissions. Thus, sustainable soil moisture management is critical for minimizing greenhouse gas emissions and maximizing soil C sequestration. Soil texture and structure also influence C sequestration by regulating soil moisture and protecting organic matter within soil aggregates (Blanco-Canqui & Lal, 2004). Tillage and soil compaction caused by agricultural machinery can disrupt soil aggregates, exposing previously stabilized organic carbon and increasing greenhouse gas emissions.



*Extreme moisture conditions—both excessive dryness and excessive wetness—reduce heterotrophic respiration. Images courtesy of Adobe Stock (Kitinut and ChiccoDodiFC).*

## Soil management practices to minimize greenhouse gas emissions

Sustainable soil management practices, including minimum tillage, conservation agriculture, mulching, and cover cropping, play a vital role in promoting carbon sequestration and reducing greenhouse gas emissions (Follet, 2001). Minimum tillage minimizes soil disturbance while no-till farming preserves soil structure and enhances aggregate formation, thereby improving carbon storage capacity and soil hydrological properties (Lal & Kimble, 1997). Conservation agriculture and mulching increase organic matter content, protect soil aggregates, reduce erosion, and enhance soil moisture retention. Similarly, cover cropping ensures continuous vegetation cover, preventing soil erosion, enriching organic matter, stabilizing soil aggregates, and improving overall soil health and carbon storage (Kaye & Quemada, 2017).

Sustainable irrigation practices are essential for lowering agriculture-related greenhouse gas emissions

Sustainable irrigation practices are also essential for lowering agriculture-related greenhouse gas emissions. For example, in rice production, prolonged water saturation creates anaerobic conditions that promote methane production, which has 28 times the global warming potential of $CO_2$(Hao et al., 2025). Additionally, some irrigation practices increase nitrous oxide ($N_2O$) emissions due to excessive soil moisture.

Excessive nitrogen fertilizer application further exacerbates $N_2O$ emissions, a greenhouse gas with 298 times the global warming potential of $CO_2$ Moreover, land-use practices such as tillage and deforestation, accelerate $CO_2$emissions while soil and crop management techniques that enhance nitrogen availability inadvertently increase $N_2O$ emissions.

Sustainable irrigation practices are essentia

*Sustainable irrigation practices are essential for lowering agriculture-related greenhouse gas emissions. Photo courtesy of Adobe Stock/Floki.*

## Conclusion

Climate change, driven by both natural processes and human activities, is primarily fueled by greenhouse gas emissions such as $CO_2$, $CH_4$, and $N_2O$. Agriculture plays a significant role in these emissions, particularly through soil and crop management practices. While destructive practices like excessive nitrogen use, tillage, and deforestation contribute to greenhouse gas emissions, the soil being the largest terrestrial carbon sink, has the potential to mitigate climate change through carbon sequestration. Implementing sustainable management strategies such as cover cropping, no-till farming, and organic agriculture enhances carbon storage, whereas poor land management practices reduce sequestration capacity. Additionally, factors like soil moisture, temperature, and structure influence carbon dynamics, making sustainable land management essential for mitigating greenhouse gas emissions and combating climate change effectively.

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