

A review of the role of carbon sequestration in regulating greenhouse gas emissions and carbon footprints

M.M. Getso¹, Y. I. Kallah², F.A. Akande³, K.A. Maradun⁴, A.M. Barde⁵, A. Iliyasu⁶, S.K. Muhammad⁷, Y. Salisu⁸, I.B Buji⁹, M.B. Sharu¹⁰, F.D. Haruna¹¹ and N.G. Hayatu^{4*}

¹Department of Animal Health and Production Technology, Federal University of Science and Technology, Kabo, Kano, Nigeria.

²Department of Soil Science, Bayero University Kano, Nigeria.

³Department of Crop Science, Usmanu Danfodiyo University, Sokoto, PMB 2346, Nigeria.

⁴Department of Soil Science and Land Resources Management, UDUS, PMB 2346, Nigeria.

⁵Department of Animal Science, Federal University Dutse, Jigawa State, Nigeria.

⁶Department of Biological Science, Kaduna State University, Nigeria.

⁷Department of Animal Health and Production Technology, Audu Bako College of Agriculture, Dambatta, Nigeria.

⁸Department of Soil and Land Management, Faculty of Agriculture and Natural Resources Management, Sule Lamido University, Kafin Hausa, PMB 048, Jigawa State, Nigeria.

⁹Department of Soil Science, University of Maiduguri, Maiduguri, Borno State, Nigeria.

¹⁰Department of Agricultural Science, Shehu Shagari College of Education, Sokoto, Sokoto State, Nigeria.

¹¹Department of Soil Science, Federal University Dutsinma, Katsina, Nigeria.

*Corresponding author. Email: nafiu.hayatu@udusok.edu.ng; +23480616548454.

Copyright © 2026 Getso et al. This article remains permanently open access under the terms of the [Creative Commons Attribution License 4.0](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Received Date: 17 July 2026 | Accepted Date: 29 August 2026 | Published Date: 30 October 2026

ABSTRACT: As atmospheric carbon dioxide (CO₂ levels exceed 420 parts per million (ppm), the urgency to mitigate humanity's carbon (C) footprint- defined as the total greenhouse gas (GHG) emissions from human activities, expressed as CO₂-equivalent, has intensified. With global GHG emissions reaching 36.8 billion tonnes annually, reducing emissions alone is insufficient to meet the Paris target of reducing the temperature by 1.5°C and GHG emissions by 55% as compared to 1990. Carbon sequestration offers a critical strategy to actively remove CO₂ from the atmosphere. This review synthesises the mechanisms, potential, and challenges of C sequestration, highlighting its role in offsetting GHG emissions and C footprints. Natural methods, including reforestation and soil management, could sequester 5-10 gigatons of CO₂ yearly, while technological approaches like C capture and storage and bioenergy with C capture may contribute an additional 5-15 gigatons by 2050. The benefits extend beyond GHG emissions reduction to enhancing soil productivity, ecosystem health, and economic opportunities via C markets. However, scalability, cost barriers, and policy gaps posed significant threats. By integrating natural and technological strategies, C sequestration emerges as a vital tool in achieving net-zero GHG emissions, bridging the gap between current trajectories and sustainable climate goals.

Keywords: Carbon dioxide, carbon footprint, greenhouse gas emission, methane, nitrous oxide.

INTRODUCTION

In gatherings centred on global climate change, carbon footprint has become a widely used term. As atmospheric CO₂ concentrations soar beyond 420 ppm, the escalating

impacts of climate change underscore the urgent need to address humanity's carbon footprint. Carbon footprint is the amount of CO₂ emitted due to daily activities, ranging

from washing clothes to driving, essentially measuring the impact of human activities on the environment in terms of GHGs (Wiedmann and Minx, 2008). According to Wiedmann and Minx (2008), the carbon footprint is the total amount of GHG emissions caused by an individual, event, organisation, or product, expressed as CO₂e.

Carbon footprint encompasses both direct emissions from activities and indirect emissions accumulated across product life cycles (Pandey *et al.*, 2011) and quantifies our contribution to global warming in tonnes of CO₂e over time (IPCC, 2014). Carbon footprint has emerged as a critical lens for assessing environmental pressure from consumption-driven emissions embedded in global trade to the broader climate impacts of human activities (Galli *et al.*, 2012). Conversely, reducing GHG emissions alone by 55% may not suffice to meet the Paris Agreement goal of reducing the temperature by 1.5°C by the year 2030. Carbon sequestration, however, spans natural sinks such as forests and soils, geological storage, and engineered solutions that offer a vital strategy to actively remove CO₂ from the atmosphere by mitigating the footprint of our industrialised world. This review therefore explores mechanisms, potential, and challenges of C sequestration, as well as revealing its vital role in achieving net-zero emissions.

THE GROWING CONCERN OVER GHG EMISSIONS AND CLIMATE CHANGE

One of the most significant environmental factors in a region, a nation, or the world is its climate. Climate change is the result of long-term changes in an area's natural conditions over around 30-35 years, comprising the average amount of light, temperature, humidity, wind, gases, air, water, and soil. Since plants are producers on the Earth's surface, these changes could have an impact on agriculture, industry, animals, the hydrological cycle, wind patterns, rainfall distribution, plant growth and development, and even the food chain (Ahmad *et al.* 2022). Due to human activity, carbon emissions have been on the increase ever since the 20th century set in. The escalating surge of GHG emissions has put climate change at the forefront of global consciousness, igniting widespread concern among scientists, policymakers, and communities as well.

In 2022, global CO₂ emissions from fossil fuels and industrial activities reached a staggering 36.8 billion tonnes, indicating a 1.1% increase as compared to 2021. This shift is driven by growing energy demands and persistent deforestation (Friedlingstein *et al.*, 2022). This surge has driven atmospheric CO₂ concentrations above 420 ppm, intensifying global warming by 1.1°C above pre-industrial levels (IPCC, 2021). The consequences of these rising temperatures are glaring and multidimensional, ranging from rising sea levels, prolonged heat waves, and

intensified storms, with damages projected to cost the global economy about 23 trillion US dollars by the year 2050 if the current rate of emissions remains unchecked (Burke *et al.*, 2018). Ecosystems are also crumbling; thawing permafrost releases methane (CH₄), which speeds up a dangerous feedback loop, while coral reefs cause catastrophic bleaching due to increasing ocean heat and acidification (Hoegh-Guldberg *et al.*, 2017; Schuur *et al.*, 2015).

This dire crisis has not been overlooked. For example, the IPCC (2021) report has shown that public anxiety has surged, as reflected in climate change marches and youth crusading, while scientific warnings have skyrocketed owing to the IPCC cautioning that exceeding 1.5°C of global warming could lead to irreversible tipping points such as the collapse of the Greenland ice sheet. Hitherto, despite international commitments such as the Paris Agreement, current emissions trajectories fall short of the reductions needed by 2030 (IPCC, 2021; Rogelj *et al.*, 2016). This tragedy is not coincidental and would continue to rise if proper actions are not taken. For instance, economic sectors (from transportation to manufacturing) remain heavily reliant on fossil fuels, and land-use changes such as deforestation could compound the problem by diminishing natural C sinks (Lovejoy and Nobre, 2018). This misalignment has amplified the sense of urgency, pushing the discourse beyond mere GHG emissions to active C removal. As the window to forestall upsurge GHG emissions narrows, carbon sequestration emerges as a critical ally. Therefore, the rising concern over GHG emissions and climate change for a sustainable future stresses a twofold imperative, that is, to rapidly decarbonise and to harness C sequestration.

CARBON SEQUESTRATION AS A STRATEGY TO REDUCE GHG EMISSIONS

A key concern of the 21st century is slowing the rate at which the concentration of CO₂ rises due to annual emissions from energy, process industry, land-use conversion, and agriculture. As the misalignment between current emissions trajectories and the Paris Agreement's 1.5°C target widens, the limitations of emissions reduction alone have become hideously evident (Rogelj *et al.*, 2016). With annual CO₂ releases (around 36.8 billion tonnes), natural sinks are weakening owing to deforestation pressure (Friedlingstein *et al.*, 2022; Lovejoy and Nobre, 2018). Carbon sequestration emerges as a cornerstone strategy to mitigate emissions by harnessing both natural and engineered processes to capture and store CO₂.

Carbon sequestration spans a range of methods, each with distinctive mechanisms and potentials. For example, terrestrial C sequestration could leverage forests, soils, and wetlands as natural sinks, with reforestation alone adept at sequestering up to 205 gigatons of C annually

(Bastin *et al.*, 2019). Similarly, geological C sequestration, as demonstrated by Norway's Sleipner project, is typified by C capture and storage (CCS), and locks CO₂ in subsurface reservoirs (Bickle, 2009). Oceanic C sequestration, though less developed and faced with a lot of ecological uncertainties, explores enhancing the ocean's natural uptake through techniques like iron (Fe) fertilisation (Boyd *et al.*, 2007). Meanwhile, engineered solutions such as direct air capture (DAC) and bioenergy with C capture and storage (BECCS) push technological limits, with DAC extracting CO₂ directly from the air and BECCS reducing emissions by pairing biomass energy with storage (Keith *et al.*, 2018; Fuss *et al.*, 2018). These strategies could sequester about 5–15 gigatons of CO₂ annually (IPCC, 2021; Schuur *et al.*, 2015). Overall, C sequestration not only mitigates C footprints, but it also buys time for deeper systemic change, positioning it as an essential tool in reclaiming planetary stability.

Understanding carbon sequestration: What is carbon sequestration?

To appreciate its role in mitigating climate change, a deeper understanding of C sequestration as a pivotal strategy to counter ever-increasing emissions is needed. Carbon sequestration is the process of capturing CO₂ from the atmosphere or emission sources and storing it in stable reservoirs, thereby reducing the emissions burden that drives global warming (IPCC, 2005). Globally, forests alone sequester about 2.4 billion tonnes of CO₂ annually. Unlike emissions reduction, which decreases novel CO₂ inputs, sequestration removes or sequesters prevailing C, thereby presenting a complementary pathway to reduce the anthropogenic C footprint (Lal, 2008; Rogelj *et al.*, 2016).

Sequestration manifests through diverse mechanisms. For instance, in natural ecosystems, photosynthesis drives terrestrial C sequestration via plants absorbing CO₂ and storing C in the plant biomass and soils (Pan *et al.*, 2011). In contrast, geological C sequestration encompasses adding captured CO₂ into underground formations like saline aquifers (Bickle, 2009). Oceanic sequestration leverages the ocean's vast capability to absorb CO₂ either naturally or through experimental methods like iron (Fe) fertilisation (Boyd *et al.*, 2007). Engineered approaches such as DAC employ chemical reactions to extract CO₂ from ambient air, storing it in geological or mineral forms (Keith *et al.*, 2018). Each sequestration method centres on two key stages: capture- which isolates CO₂ from the atmosphere or point sources- and storage- which ensures its stability whether in roots, rocks, or reactors. Overall, sequestration bridges the gap between today's emissions reality and tomorrow's climate goals, making it essential for sustainable planetary stewardship (Schuur *et al.*, 2015).

Natural and technological methods of carbon sequestration

Natural C sequestration taps into biological and geochemical processes that improve over time. For example, terrestrial ecosystems such as forests, grasslands, and wetlands drive this through photosynthesis, where plants convert CO₂ into biomass, storing C in the tree trunks, roots, and in the soils. Specifically, forests alone have the potential to sequester up to 2.4 billion tonnes of CO₂ yearly, whereas determined reforestation could sequester 205 gigatons over a decade (Pan *et al.*, 2011; Bastin *et al.*, 2019). Soil C sequestration could be improved via agricultural practices such as zero-tillage, cover cropping, and biochar application. More so, biochar application alone could sequester between 0.4 and 1.2 gigatons of CO₂ per annum (Lal, 2008; Woolf *et al.*, 2010). Wetlands, on the other hand, though covers around 6% of land, could store up to 30% of soil C. This potential could be ascribed to their waterlogged conditions leading to high soil organic matter (SOM) residence time and slow rate of decomposition of SOM (Nahlik and Fennessy, 2016). Oceanic C sequestration, however, depends on the ocean's natural ability to absorb about 25% of anthropogenic CO₂ (Boyd *et al.*, 2007). Overall, the natural methods of C sequestration are acclaimed for their affordability and co-benefits, such as habitat restoration and flood control (Anderegg *et al.*, 2015; Griscom *et al.*, 2017; Lovejoy and Nobre, 2018).

In contrast, technological C sequestration methods exert precision and stability through human skills. Technique such as CCS usually capture CO₂ from power plants or factories, injecting it into geological formations such as saline aquifers or depleted oil fields. A good example of a CCS technique is Norway's Sleipner project, which has stored more than 20 million tonnes CO₂ since 1996, with less than 1% leakage risk over the period (Bickle, 2009). The DAC uses chemical sorbents to extract CO₂ from ambient air. The ClimeWorks plant is a popular DAC technique that could remove thousands of tonnes CO₂ yearly (Keith *et al.*, 2018). Another technological C sequestration technique is BECCS, which burns plant biomass for energy, thereby capturing and storing the resultant CO₂. BECCS has the potential to offset emissions by 3–5 gigatons yearly, noting that it demands vast land for the cultivation of biomass (Fuss *et al.*, 2018; Smith *et al.*, 2016). Overall, these methods excel in scalability and durability; however, their high energy intensity and costs pose barriers to their usage (IPCC, 2005; Global CCS Institute, 2023; Rubin *et al.*, 2015).

ROLE OF SOIL, PLANTS, AND ECOSYSTEMS IN CARBON SEQUESTRATION

While natural and technological C sequestration methods

bid divergent ways to mitigate CO₂ emissions, the role of soil, plants, and ecosystems as nature-based C sequestration sinks cannot be overemphasised. These natural biological systems could sequester huge amounts of C via interconnected processes, thereby providing a scalable, low-cost solution to cut atmospheric GHG emissions. However, the efficacy of these natural biological systems is threatened by deforestation and land degradation; therefore, understanding and enhancing their ability to sequester CO₂ or offset GHG emissions is paramount to avert climate crises such as global warming and rising sea levels.

Plants are the major sinks of C sequestration in terrestrial ecosystems, leveraging photosynthesis to absorb CO₂ and transform it into soil organic C (SOC). Approximately 2.4 billion tonnes of CO₂ per year were sequestered collectively by forests, grasslands, and arable soils, with tropical forests alone sequestering between 200 and 300 tonnes of C per hectare (Pan *et al.*, 2011; Lewis *et al.*, 2009). Reforestation and afforestation could further strengthen this potential by refurbishing around 350 million hectares of degraded land, thereby sequestering up to 205 gigatons of C (Bastin *et al.*, 2019). Notwithstanding, perennial grasses and agroforestry systems are important C sinks. These systems increase C uptake by extending root systems, which vertically transfer C into deeper subsoils, sustaining long-term storage (Lorenz and Lal, 2014). Overall, the capacity and durability of these systems centre on their resilience. Natural phenomena such as flooding, droughts and wildfires could trigger and transform these C sinks into sources, thereby releasing stored C back into the atmosphere (Anderegg *et al.*, 2015).

Soil is an immense C pool, housing three times as much C as the atmosphere (that is, about 2,500 gigatons) in the topsoil only (Lal, 2008). Plants deposit C into soils via release of plant root exudate and microbial activity that stabilises in the soil as SOM. This process could be boosted (sequestering around 0.4–1.2 gigatons of CO₂-e annually) by agricultural practices such as zero-tillage cultivation, cover cropping, mulching and manure incorporation (Poeplau and Don, 2015). Furthermore, biochar application enhances soil C storage in the amended fields by resisting SOC decomposition, potentially locking C away and increasing C sequestration rates by 10–20% (Woelf *et al.*, 2010). Another C sink is wetlands (though covers just 6% of land mass). Wetlands could potentially store up to 30% of terrestrial ecosystems' C due to anaerobic conditions that slow down SOM decomposition (Nahlik and Fennessy, 2016). Hitherto, the long-term potential of soil to store C is fragile owing to erosion, overgrazing, and tillage that can release centuries-old C stocks in mere years (Sanderman *et al.*, 2017).

Ecosystems strengthen this synergy by integrating plants and soils into dynamic C sinks. For instance, mangroves sequester C per hectare at rates five times higher than tropical forests, storing it in both plant biomass

and soil sediments, whereas peatlands (covering just 3% of land mass) lock away approximately 500–600 gigatons of C globally (Donato *et al.*, 2011; Yu *et al.*, 2010). In spite of the co-benefits these ecosystems offer in biodiversity conservation, water retention, and climate resilience, they face threats from land-use change. For example, the loss of around 35% of peatlands' C since 1985 was ascribed to drainage and agriculture (Leifeld and Menichetti, 2018). Therefore, protecting and restoring these ecosystems, in conjunction with enhancing plant-soil interactions, could offset 20–30% of annual GHG emissions, making them essential cronies in C sequestration (Griscom *et al.*, 2017).

THE LINK BETWEEN CARBON FOOTPRINTS AND CARBON SEQUESTRATION

The C footprint measuring GHG emissions from human activities serves as both a measure of our climate impact and a call to action, with C sequestration emerging as a vital offset. As daily routines and industrial practices drive GHG emissions upward, the interaction between these C footprints and C sequestration's capacity to offset them reveals a pathway to environmental sustainability.

Contribution of daily activities to GHG emissions

Everyday life is a tapestry of C emitting choices, often indiscernible; hitherto cumulatively intense. For example, transportation, a basis of modern movement, accounts for 29% of global CO₂ emissions, with the average car emitting 4.6 tonnes CO₂ yearly, which is the same as burning 2,000 litres of gasoline (IEA, 2022). Also, household energy usage, ranging from heating to appliance operation (largely from fossil fuel-derived electricity), adds another layer, contributing 5.5 tonnes of CO₂ per household annually in developed nations (EIA, 2021). Similarly, food consumption could further amplify the C footprint. According to Poore and Nemecek (2018), producing one kilogram of beef emits 60 kg CO₂-e, dwarfing the two kilograms from vegetables, driven by CH₄ from livestock and land clearing. Another important sector that significantly contributes to GHG emissions is waste disposal. Waste disposal plays a key role in the release of CH₄, which is 25 times more persuasive (totalling 1.5 billion tonnes CO₂-e yearly) than CO₂ (Bogner *et al.*, 2008). Together, in technologically advanced countries, an individual's yearly C footprint contribution is around 11 tonnes CO₂-e (IPCC, 2021). These daily activities pile up a web of GHG emissions that C sequestration must offset.

The role of C sequestration in offsetting GHG emissions

Carbon sequestration stands as a powerful remedy to the

surge in GHG emissions that is capable of offsetting significant amounts of anthropogenic C footprint via various methods, mainly known as natural and technological methods. In natural methods, activities such as reforestation and soil improvement by the use of organic amendments such as biochar, organic manure, etc, could sequester 5–10 gigatons of CO₂ per annum, thereby neutralising around 15–30% of the global GHG emissions (Griscom *et al.*, 2017). For instance, a hectare of restored mangrove can sequester 3–5 tonnes of CO₂ per annum, matching a household's C footprint (Keith *et al.*, 2018; Donato *et al.*, 2011). Another natural method of C sequestration is geological storage. Geological storage has a capacity to sequester between 2,000 and 13,500 gigatons of CO₂, and offers a near-permanent sink for captured CO₂, thereby dwarfing global annual GHG emissions by 36.8 billion tonnes (IPCC, 2005; Friedlingstein *et al.*, 2022). Technological methods, on the other hand, could strengthen this potential via DAC and BECCS. Together, DAC and BECCS could remove approximately 5–15 gigatons of CO₂ annually, with BECCS alone offsetting up to 40% of industrial GHG emissions (Fuss *et al.*, 2018; Realmonte *et al.*, 2019). In practice, a single functional DAC plant (e.g. Climeworks' Orca) can sequester 4,000 tonnes of CO₂ yearly, an amount equivalent to 800 cars' GHG emissions (Keith *et al.*, 2018; Donato *et al.*, 2011). Overall, by bridging the gap between GHG emissions and net-zero goals, C sequestration could transform C footprints from a liability into an opportunity.

Industries and practices that can benefit from carbon sequestration

In principle, all industries and practices with high C footprints potential stand to benefit from the C sequestration's possibilities. With projects like Petra Nova, the energy sectors (responsible for 42% of global GHG emissions) can capture up to 1.6 million tonnes of CO₂ yearly (Global CCS Institute, 2023). Agriculture emits 10–12 gigatons of CO₂-e annually, mainly from livestock production and soil disturbances (such as tillage). Agricultural practices such as cover cropping and agroforestry can improve C sequestration and offset 20–30% of the GHG emissions, while increasing crop yields (Poeplau and Don, 2015; Zomer *et al.*, 2016). Another extremely C intensive industry is cement production, which releases 2.2 billion tonnes of CO₂ yearly (Leung *et al.*, 2014). With proper management, adopting biochar application to urban waste management (which is known to generate CH₄ from landfills), can stabilise C and reduce GHG emissions by 10–15% per site (Woolf *et al.*, 2010). Another versatile industry that could benefit from C sequestration is the aviation sector. It was reported that the aviation industry could emit up to 1 billion tonnes of

CO₂ yearly; however, it still has the potential to offset GHG emissions via afforestation and/or incorporating DAC technology (ICAO, 2022). Overall, these examples have clearly demonstrated the versatility of C sequestration in converting C heavy sectors into C sinks as well as agents of climate change mitigation.

Nature-based carbon sequestration strategies

Nature-based C sequestration approaches often harness Earth's biological systems to sequester and store CO₂, thereby proposing scalable, cost-effective methods to offset C footprints from daily household life and industrial activities. These methods, rooted in forests, soils, and ecosystems, could provide immediate, nature-based solutions to offset the 36.8 billion tonnes of CO₂ released yearly through building on the synergy amongst GHG emissions and C sequestration (Friedlingstein *et al.*, 2022). Generally, by improving and conserving these C sinks, climate change mitigation is certain alongside other ecological co-benefits.

Forest and agroforestry

Forests and agroforestry are giant nature-based C sequestration methods that leverage photosynthesis to lock C in plant biomass and in the soils. Mature forests sequester 2.4 billion tonnes of CO₂ yearly, with tropical systems storing 200–300 tonnes per hectare, yet deforestation has slashed this capacity by 11% since 2000 (Pan *et al.*, 2011; Lewis *et al.*, 2009). Tree planting reverses this loss by restoring 350 million hectares of degraded land and could sequester 205 gigatons of carbon by 2100, thereby offsetting two decades of global emissions (Bastin *et al.*, 2019). Initiatives like the Bonn Challenge, targeting 350 million hectares by 2030, exemplify this potential, with countries like Ethiopia planting 5 billion trees since 2019 (Griscom *et al.*, 2017). Forest conservation could complement this by protecting existing sinks. For example, halting Amazon deforestation alone could preserve 37 billion tonnes of carbon (Lovejoy and Nobre, 2018). Integrating trees into farmland via agroforestry could boost this further, sequestering 1–18 tonnes of CO₂ per hectare annually while enhancing food security (Zomer *et al.*, 2016; Anderegg *et al.*, 2015).

Soil health and regenerative agriculture: No-till, cover cropping, and composting

Soil, holding 2,500 gigatons of carbon globally, is a sequestration powerhouse revitalised by regenerative agriculture (Lal, 2008). No-till farming minimises soil disturbance, thereby retaining 0.1–1 tonne of CO₂ per

hectare yearly by preserving organic matter (Derpsch *et al.*, 2010). Cover crops, planted between harvests, add 0.3–0.6 tonnes per hectare by boosting root carbon inputs. A meta-analysis showed up to a 15% increase in soil carbon stocks over a decade owing to cover cropping (Poeplau and Don, 2015). Composting was reported to sequester 0.2–0.5 tonnes C per hectare while reducing methane from landfills (Brown *et al.*, 2011; Woolf *et al.*, 2010; Lal, 2018).

Preserving natural carbon sinks: Wetlands and grasslands

Wetlands and grasslands, though less heralded, are prodigious C sinks warranting preservation. Wetlands, covering 6% of land, store 30% of soil C, with coastal mangroves sequestering 3–5 tonnes per hectare annually, five times more than tropical forests, owing to waterlogged soil conditions that halt or lower decomposition (Nahlik and Fennessy, 2016; Donato *et al.*, 2011). Peatlands hold 500–600 gigatons of C globally and can lock C for millennia, yet 35% has been lost to drainage since 1850 (Yu *et al.*, 2010; Leifeld and Menichetti, 2018). Grasslands, spanning 40% of Earth's land, store 300 gigatons in deep roots and soils, with restoration adding 0.5–1 gigaton yearly (Conant *et al.*, 2017). Preserving these sinks, e.g., through wetland restoration or grazing management, could offset 10–15% of GHG emissions, while safeguarding biodiversity and flood control (Griscom *et al.*, 2017). Threats like conversion to cropland or urban sprawl, however, demand urgent attention, as drainage or ploughing can release centuries of C (Sanderman *et al.*, 2017).

Technological approaches to carbon sequestration

While natural strategies like forests and wetlands anchor C sequestration efforts, technological approaches could offer precision, scalability, and permanence to tackle the 36.8 billion tonnes of CO₂ emitted annually (Friedlingstein *et al.*, 2022). These engineered solutions, spanning soil enhancement to atmospheric extraction, address the limitations of natural sinks, such as saturation and vulnerability, by integrating human innovation into the C cycle. From biochar's soil synergy to industrial-scale capture, these methods expand sequestration's reach, aligning with net-zero ambitions.

Biochar application: Biochar is a C-rich material produced by pyrolysing biomass. Biochar bridges natural and technological sequestration by enhancing soil C storage. Unlike organic matter that decomposes within years, biochar's stable structure resists microbial breakdown, locking C in soils for decades or even longer (Lehmann, 2007). When applied to fields, biochar increases soil C stocks by 10–20%, with global adoption

potentially sequestering 1–2 gigatons of CO₂ annually, equivalent to 3–5% of current CO₂ emissions (Woolf *et al.*, 2010). In practice, a tonne of biochar can sequester 2.5–3 tonnes of CO₂-equivalent, depending on feedstock and soil type, while improving fertility and water retention (Gaunt and Lehmann, 2008; Sohi *et al.*, 2010; Woolf *et al.*, 2010).

Carbon capture and storage: Carbon capture and storage (CCS) targets CO₂ at its source, capturing emissions from power plants and industries before they reach the atmosphere, and then storing them in geological reservoirs. Pioneered by concepts like those outlined by Lackner (2009), CCS involves three steps: (i) capturing CO₂ via chemical absorption (e.g., amine scrubbing), (ii) transporting it via pipelines, and (iii) injecting it into formations like saline aquifers or depleted oil fields, where it remains trapped by impermeable caprock (Lackner, 2009). The Sleipner project in Norway, operational since 1996, has stored over 20 million tonnes, proving technical feasibility with leakage risks below 1% over millennia (Bickle, 2009). Globally, CCS could potentially sequester 2–5 gigatons annually by 2050, with a theoretical capacity of 2,000–13,500 gigatons far exceeding current emissions (IPCC, 2005; Rubin *et al.*, 2015; Global CCS Institute, 2023; Lackner, 2006). CCS excels in permanence and industrial applicability but requires rapid deployment to match climate urgency.

Innovations in atmospheric carbon removal: Direct air capture: Direct air capture (DAC) represents the frontier of C sequestration, extracting CO₂ directly from the atmosphere using chemical sorbents. Innovations like Climeworks' solid sorbent systems and Carbon Engineering's liquid hydroxide process have slashed costs from \$600 to \$100–200 per tonne, with plants like Orca removing 4,000 tonnes annually, offsetting emissions from 800 cars (Keith *et al.*, 2018; IEA, 2022). DAC's strength lies in its flexibility: it targets diffuse emissions unaddressed by CCS, with a potential to remove 5–10 gigatons yearly (Realmonte *et al.*, 2019). Storage options include geological injection or mineralisation into stable carbonates, ensuring permanence (Lackner, 2009). However, energy demands of 1.5–2.5 GJ per tonne pose challenges, requiring 10–15% of global renewable capacity for large-scale deployment (Breyer *et al.*, 2020). Pilot projects, like Iceland's CarbFix, which mineralises 12,000 tonnes yearly, showcase viability, but costs and scaling remain hurdles (Matter *et al.*, 2016). DAC's promise lies in its universality, offering a backstop for GHG emissions reduction shortfalls.

BENEFITS OF CARBON SEQUESTRATION IN REDUCING FOOTPRINTS

Carbon sequestration, whether through natural or technological means, transcends mere GHG emissions

management, delivering a suite of benefits that directly shrink C footprints while fostering environmental and economic resilience. As global CO₂ emissions hover at 36.8 billion tonnes annually, C sequestration's capacity to mitigate GHG emissions, enhance ecosystem function and unlock financial incentives (Friedlingstein *et al.*, 2022). These advantages amplify its role beyond offsetting GHG emissions, interlacing sustainability into the fabric of human systems.

Reducing GHG emissions

The primary benefit of C sequestration lies in its ability to lower GHG concentrations. Natural sinks like forests and soils could sequester 5–10 gigatons of CO₂ yearly, reducing atmospheric levels by 2–5 ppm annually if scaled globally, critical when concentrations exceed 420 ppm (Griscom *et al.*, 2017; IPCC, 2021). Technological methods could amplify this via direct air DAC and CCS, which could potentially remove approximately 5–15 gigatons by 2050, possibly slashing 10–20% of industrial GHG emissions (Realmonte *et al.*, 2019; Rubin *et al.*, 2015). Real-world impacts are tangible: Climeworks' Orca plant removes around 4,000 tonnes yearly, while Sleipner's CCS has locked away 20 million tonnes since 1996 (Keith *et al.*, 2018; Bickle, 2009). This drawdown mitigates warming, with models suggesting that removing 10 gigatons annually could limit temperature rise by 0.1–0.2 °C by the end of the century, thereby buying time to forestall tipping points like permafrost thaw (Fuss *et al.*, 2018; Schuur *et al.*, 2015). By shrinking the C footprint's atmospheric legacy, carbon sequestration offers a direct counter to the greenhouse effect.

Enhancing soil productivity and ecosystem health

Beyond GHG emission reduction, C sequestration revives soils and ecosystems and enhances their productivity and resilience. For example, biochar application and regenerative agricultural practices such as cover cropping boost SOC by 10–20%, improve water retention by up to 15% and crop yields by 10–30% (Woolf *et al.*, 2010; Poeplau and Don, 2015). Similarly, forests and wetlands were reported to sequester 2.4 billion and 3–5 tonnes of C per hectare yearly, respectively. They were found to also stabilise soils and regulate hydrology, thereby reducing soil erosion hazards and flooding risks (Pan *et al.*, 2011; Donato *et al.*, 2011). These efforts also bolster biodiversity in restored peatlands to support rare plant species and microbial communities (in terms of richness, evenness, and distribution), while agroforestry systems increase pollinator abundance by 20–50% (Zomer *et al.*, 2016; Leifeld and Menichetti, 2018). Healthier ecosystems cycle nutrients more efficiently, with studies showing a 25% rise

in soil microbial activity under enhanced C sequestration practices (Lal, 2018).

Economic opportunities: Carbon credits and sustainable farming incentives

Carbon sequestration also unlocks economic potential, turning C removal into a marketable asset via C credits and farming incentives. The C markets, valued at \$851 billion in 2023, reward C sequestration projects. For example, farmers adopting no-till or afforestation earned \$10–50 per tonne of CO₂ sequestered, with global transactions offsetting 200 million tonnes annually (World Bank, 2023; Griscom *et al.*, 2017). Companies like Microsoft purchase DAC credits from Climeworks, driving demand, while initiatives like Australia's Carbon Farming Initiative (CFI) have paid farmers \$1.5 billion since 2011 (Keith *et al.*, 2018; Evans, 2018). Sustainable farming incentives, such as the United States Conservation Reserve Program (USCRP), have already provided \$2 billion annually to enhance soil C to boost rural economies (USDA, 2022; Rubin *et al.*, 2015; Woolf *et al.*, 2010). By monetising carbon, C sequestration not only cuts C footprints, but it also fuels green growth, thereby aligning environmental and economic sustainability goals.

PRACTICAL STEPS FOR INDIVIDUALS AND COMMUNITIES

The benefits of C sequestration in reducing GHG emissions, enhancing ecosystems, and creating economic value hinge on widespread adoption, making individual and community action pivotal in shrinking the 11-tonne annual C footprint of industrialised economies (IPCC, 2021). While global GHG emissions reach 36.8 billion tonnes yearly, grassroots efforts can amplify C sequestration's impact, thereby bridging the gap to net-zero (Friedlingstein *et al.*, 2022). From planting trees to advocating policies, these practical steps empower people to align daily choices with climate solutions.

Sustainable land management and tree planting initiatives

Individuals and communities can directly bolster C sequestration through sustainable land management and tree planting. Backyard or communal tree planting can sequester 0.02–0.05 tonnes of CO₂ per tree annually, with a mature oak offsetting a year's worth of car emissions (Nowak *et al.*, 2013). Community initiatives, like urban forestry programs in cities such as Los Angeles, have planted 1 million trees since 2006, capturing 50,000 tonnes of CO₂ while cooling neighbourhoods (McPherson

et al., 2016). On rural or suburban lands, agroforestry sequesters 1–18 tonnes per hectare yearly, with smallholders in Kenya doubling yields and C storage through such systems (Zomer *et al.*, 2016). Sustainable practices like composting kitchen waste (0.2–0.5 tonnes per household annually) or adopting no-till gardening enhance soil C, with community gardens in the U.S. offsetting 10–15% of participants' food-related emissions (Brown *et al.*, 2011; Poeplau and Don, 2015). These efforts, costing \$10–20 per tonne of C sequestered, democratize C sequestration, turning yards and farms into C sinks (Griscom *et al.*, 2017).

Supporting businesses and policies that promote carbon sequestration

Collective support for sequestration-friendly businesses and policies amplifies individual impact. Consumers can choose products from companies using CCS or DAC, such as Microsoft's DAC-backed C-negative pledge, which removed 1.3 million tonnes in 2023 via Climeworks (Keith *et al.*, 2018; Microsoft, 2023). Purchasing from sustainable agriculture brands like those certified by the Soil C Initiative supports soil sequestration, with U.S. farmers earning \$15–30 per tonne through C credits (Lal, 2018). Communities can advocate for policies like the U.S. Growing Climate Solutions Act (USGCSA), which streamlines C markets, or local subsidies for wetland restoration, as in the UK's Peatlands Code, preserving 500 gigatons of C (Leifeld and Menichetti, 2018; Evans *et al.*, 2021). Voting for urban green space funding or corporate tax incentives for CCS currently deployed at 40 global facilities drives systemic change (Global CCS Institute, 2023). These actions leverage market and policy levers, embedding carbon sequestration into economic frameworks.

Reducing personal emissions through sustainable choices

Cutting personal GHG emissions complements C sequestration efforts and shrinks C footprints. Switching to public transit or biking reduces the 4.6-tonne annual car emissions by 50–75%, while energy-efficient appliances and renewable energy sources at home cut the 5.5-tonne household average emission by 20–30% (IEA, 2022; EIA, 2021). Dietary shifts such as replacing beef (with 60 kg CO₂-equivalent per kg emission potential) with plant-based options (with 2 kg CO₂-equivalent per kg emission potential) slash food emissions by up to 2 tonnes per person yearly (Poore and Nemecek, 2018; Scarborough *et al.*, 2023). Composting waste diverts CH₄-emitting organics from landfills, reducing 0.5–1 tonne of emissions per household (Bogner *et al.*, 2008; Ivanova *et al.*, 2020).

These choices often save \$500–\$1,000 yearly, improve sequestration of C by lowering the emissions baseline, thereby making the net-zero goal attainable (IPCC, 2021).

CHALLENGES AND FUTURE CONSIDERATIONS

Carbon sequestration holds immense promise for reducing the 36.8 billion tonnes of CO₂ emitted annually, yet its full potential remains constrained by practical and systemic challenges (Friedlingstein *et al.*, 2022). As individuals and communities adopt carbon sequestration practices, scaling these efforts to match global climate goals demands overcoming cost barriers, securing policy support, and advancing innovation. Therefore, addressing these hurdles is essential to ensure carbon sequestration evolves from a niche solution into a cornerstone of net-zero strategies.

Scalability and cost barriers of sequestration methods

The scalability and cost of carbon sequestration methods pose significant obstacles to widespread deployment. Natural approaches like reforestation, while cost-effective at \$10–20 per tonne, are limited by land availability. Restoring 350 million hectares requires balancing food production and biodiversity, with only 1.9 billion hectares globally suitable (Bastin *et al.*, 2019; Griscom *et al.*, 2017). Soil carbon sequestration using biochar or no-till farming, at \$20–50 per tonne, could offset 1–2 gigatons yearly, but scaling to billions of hectares demands equipment and training for millions of farmers (Woolf *et al.*, 2010; Lal, 2018). Technological methods face steeper barriers: CCS costs \$60–120 per tonne, with just 40 facilities worldwide capturing 45 million tonnes annually, less than 0.1% of emissions due to energy-intensive capture and sparse infrastructure (Rubin *et al.*, 2015; Global CCS Institute, 2023). The DAC, at \$100–200 per tonne, requires 1.5–2.5 GJ per tonne, potentially consuming 10–15% of global renewable energy if scaled to 10 gigatons yearly (Keith *et al.*, 2018; Breyer *et al.*, 2020). These costs and logistical demands underscore the gap between current capacity and the 15–20 gigatons of annual removal needed by 2050 (Fuss *et al.*, 2018).

Policy and regulatory support needed for widespread adoption

Effective carbon sequestration hinges on robust policy and regulatory frameworks, yet gaps persist. Carbon pricing, covering only 23% of global emissions at \$851 billion in 2023, often undervalues carbon sequestration at \$5–50 per tonne, insufficient for CCS or DAC viability (World Bank, 2023; Rubin *et al.*, 2015). Subsidies for natural

methods like the U.S. Conservation Reserve Program (USCRP), \$2 billion annually, reach just 1% of farmers, while wetland protections falter, with 35% of peatlands' C lost since 1850 (USDA, 2022; Leifeld and Menichetti, 2018). International frameworks, such as the Paris Agreement, lack binding sequestration targets, leaving adoption fragmented; only 20 countries have CCS policies, and biochar incentives are nascent (Rogelj *et al.*, 2016; Global CCS Institute, 2023). Regulatory hurdles, like permitting delays for geological storage or land-use conflicts, further slow progress, with CCS projects taking 5–10 years to launch (Scott *et al.*, 2015). Future policies must integrate carbon credits projected to offset 1 billion tonnes by 2030, subsidise technology deployment, and enforce ecosystem preservation to unlock sequestration's scale (World Bank, 2023).

The role of research and innovation in improving sequestration efficiency

Research and innovation are critical to overcoming these barriers, enhancing sequestration's efficiency and affordability. Advances in biochar production, such as mobile pyrolysis units, could cut energy use by 20–30%, boosting scalability while maintaining 2.5–3 tonnes of CO₂ per tonne sequestered (Gaunt and Lehmann, 2008). For CCS, novel solvents like ionic liquids reduce capture energy by 25%, potentially lowering costs to \$40–80 per tonne (Haszeldine *et al.*, 2018). DAC innovations, e.g., metal-organic frameworks (MOFs), slash energy needs by 15–20%, aiming for \$50–100 per tonne by 2030, as seen in C Engineering's prototypes (Sumida *et al.*, 2012; Keith *et al.*, 2018). Natural methods benefit too: genetic engineering of plants to enhance root C storage could increase sequestration by 10–15%, while microbial soil amendments boost rates by 20–25% (Jansson *et al.*, 2021; Paustian *et al.*, 2016). These breakthroughs, if funded global Research and Development for sequestration lags at \$2 billion annually versus \$20 billion needed could double removal efficiency, aligning with 1.5 °C pathways (IEA, 2022; IPCC, 2021). Innovation thus holds the key to transforming sequestration into a global solution.

CONCLUSION

Carbon sequestration emerged as an inevitable strategy for mitigating GHG emissions and a drastic reduction of carbon footprint. As the reduction of emissions remains the main approach for combatting climatic change, carbon sequestration helps this effort by removing and storing atmospheric carbon (IV) oxide through natural and technological pathways to achieve net-zero emissions and a sustainable future.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

- Ahmad, H., Zafar, S. A., Naeem, M. K., Shokat, S., Inam, S., Rehman, M. A. U., Naveed, S. A., Xu, J., Li, Z., Ali, G. M., & Khan, M. R. (2022). Impact of pre-anthesis drought stress on physiology, yield-related traits, and drought-responsive genes in green super rice. *Frontiers in Genetics*, 13, 832542. <https://doi.org/10.3389/fgene.2022.832542>.
- Anderegg, W. R. L., Schwalm, C., Biondi, F., Camarero, J. J., Koch, G., Litvak, M., Ogle, K., Shaw, J. D., Shevliakova, E., Williams, A. P., & Pacala, S. (2015). Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science*, 349(6247), 528–532. <https://doi.org/10.1126/science.aab1833>.
- Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C. M., & Crowther, T. W. (2019). The global tree restoration potential. *Science*, 365(6448), 76–79. <https://doi.org/10.1126/science.aax0848>.
- Bickle, M. J. (2009). Geological carbon storage. *Nature Geoscience*, 2(12), 815–818. <https://doi.org/10.1038/ngeo687>.
- Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A., Gao, Q., & Gregory, R. (2008). Mitigation of global greenhouse gas emissions from waste: Conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. *Waste Management & Research*, 26(1), 11–32. <https://doi.org/10.1177/0734242X07088433>.
- Boyd, P. W., Jickells, T., Law, C. S., Blain, S., Boyle, E. A., Buesseler, K. O., Coale, K. H., Cullen, J. J., De Baar, H. J., Follows, M., & Watson, A. J. (2007). Mesoscale iron enrichment experiments 1993–2005: Synthesis and future directions. *Science*, 315(5812), 612–617. <https://doi.org/10.1126/science.1131669>.
- Breyer, C., Fasihi, M., & Aghahosseini, A. (2020). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*, 25, 43–65. <https://doi.org/10.1007/s11027-019-9847-y>.
- Brown, S., Kruger, C., & Subler, S. (2011). Greenhouse gas balance for composting operations. *Journal of Environmental Quality*, 36(5), 1396–1410. <https://doi.org/10.2134/jeq2007.0453>.
- Burke, M., Davis, W. M., & Diffenbaugh, N. S. (2018). Large potential reduction in economic damages under UN mitigation targets. *Nature*, 557(7706), 549–553. <https://doi.org/10.1038/s41586-018-0071-9>.
- Conant, R. T., Cerri, C. E. P., Osborne, B. B., & Paustian, K. (2017). Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, 27(2), 662–668. <https://doi.org/10.1002/eap.1473>.
- Derpsch, R., Friedrich, T., Kassam, A., & Li, H. (2010). Current status of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering*, 3(1), 1–25. <https://doi.org/10.3965/j.issn.1934-6344.2010.01.001-025>.
- Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S.,

- Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293–297. <https://doi.org/10.1038/ngeo1123>
- EIA. (2021). *Annual energy outlook 2021*. U.S. Energy Information Administration. <https://www.eia.gov/outlooks/aeo/>
- Evans, C. D., Peacock, M., Baird, A. J., Artz, R. R. E., Burden, A., Callaghan, N., Chapman, P. J., Cooper, H. M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R. P., Helfter, C., Heppell, C. M., Holden, J., Jones, D. L., Kaduk, J., Levy, P., ... Morrison, R. (2021). Overriding water table control on managed peatland greenhouse gas emissions. *Nature*, 593(7860), 548–552. <https://doi.org/10.1038/s41586-021-03523-1>
- Evans, M. C. (2018). Effective incentives for reforestation: Lessons from Australia's carbon farming policies. *Current Opinion in Environmental Sustainability*, Vol. 32, pp. 38–45. <https://doi.org/10.1016/j.cosust.2018.04.002>
- Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., ... & Zeng, J. (2022). Global carbon budget 2022. *Earth System Science Data*, 14(4), 1917–2005. <https://doi.org/10.5194/essd-14-1917-2022>
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., ... & Minx, J. C. (2018). Negative emissions-Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6), 063002. <https://doi.org/10.1088/1748-9326/aabf9f>
- Galli, A., Wiedmann, T., Erwin, E., Knoblauch, D., Ewing, B., & Giljum, S. (2012). Integrating ecological, carbon and water footprint into a "Footprint Family" of indicators: Definition and role in tracking human pressure on the planet. *Ecological Indicators*, 16, 100–112. <https://doi.org/10.1016/j.ecolind.2011.06.017>
- Gaunt, J. L., & Lehmann, J. (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology*, 42(11), 4152–4158. <https://doi.org/10.1021/es071361i>
- Global CCS Institute (2023). *Global status of CCS 2023*. <https://www.globalccsinstitute.com/resources/global-status-report/>
- Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., & Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114(44), 11645–11650. <https://doi.org/10.1073/pnas.1710465114>
- Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K., & Hatziolos, M. E. (2017). Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857), 1737–1742. <https://doi.org/10.1126/science.1152509>
- International Civil Aviation Organisation (ICAO). (2022). Carbon offsetting and reduction scheme for international aviation (CORSIA). International Civil Aviation Organisation.
- IEA. (2022a). *CO₂ emissions from fuel combustion 2022*. International Energy Agency. <https://www.iea.org/reports/co2-emissions-in-2022>
- IEA. (2022b). *Direct air capture 2022*. International Energy Agency. <https://www.iea.org/reports/direct-air-capture-2022>
- IEA. (2022c). *Energy technology perspectives 2022*. International Energy Agency. <https://www.iea.org/reports/energy-technology-perspectives-2022>
- IPCC. (2005). *Special report on carbon dioxide capture and storage*. Cambridge University Press.
- IPCC. (2014). *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., & Creutzig, F. (2020). Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters*, 15(9), 093001. <https://doi.org/10.1088/1748-9326/ab8589>
- Jansson, C., Faiola, C., Wingler, A., Zhu, X. G., Kravchenko, A., De Graaff, M. A., Ogden, A. J., Handakumbura, P. P., Werner, C., & Beckles, D. M. (2021). Crops for carbon farming. *Frontiers in Plant Science*, 12, 636709. <https://doi.org/10.3389/fpls.2021.636709>
- Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A process for capturing CO₂ from the atmosphere. *Joule*, 2(8), 1573–1594. <https://doi.org/10.1016/j.joule.2018.05.006>
- Lackner, K. S. (2009). Capture of carbon dioxide from ambient air. *The European Physical Journal Special Topics*, 176, 93–106. <https://doi.org/10.1140/epjst/e2009-01150-3>
- Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 815–830. <https://doi.org/10.1098/rstb.2007.2185>
- Lal, R. (2018). Digging deeper: A holistic perspective of soil carbon sequestration. *Global Change Biology*, 24(8), 3285–3291. <https://doi.org/10.1111/gcb.14054>
- Lehmann, J. (2007). A handful of carbon. *Nature*, 447(7141), 143–144. <https://doi.org/10.1038/447143a>
- Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, 9(1), 1071. <https://doi.org/10.1038/s41467-018-03406-6>
- Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, 39, 426–443. <https://doi.org/10.1016/j.rser.2014.07.093>
- Lewis, S. L., Lloyd, J., Sitch, S., Mitchard, E. T. A., & Laurance, W. F. (2009). Changing ecology of tropical forests: Evidence and drivers. *Annual Review of Ecology, Evolution, and Systematics*, 40, 529–549. <https://doi.org/10.1146/annurev.ecolsys.39.110707.173345>
- Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, 34(2), 443–454. <https://doi.org/10.1007/s13593-014-0212-y>
- Lovejoy, T. E., & Nobre, C. (2018). Amazon tipping point. *Science Advances*, 4(2), eaat2340. <https://doi.org/10.1126/sciadv.aat2340>
- Matter, J. M., Stute, M., Snæbjörnsdóttir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradóttir, E. S., Sigfusson, B., Gunnarsson, I., Sigurdardóttir, H., Gunnlaugsson, E., & Broecker, W. S. (2016). Rapid carbon mineralisation for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, 352(6291), 1312–1314. <https://doi.org/10.1126/science.aad8132>
- Nahlik, A. M., & Fennessy, M. S. (2016). Carbon storage in US wetlands. *Nature Communications*, 7, 13835. <https://doi.org/>

- 10.1038/ncomms13835
- Nowak, D. J., Greenfield, E. J., Hoehn, R. E., & Lapoint, E. (2013). Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution*, 178, 229–236. <https://doi.org/10.1016/j.envpol.2013.03.019>
- Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, 333(6045), 988–993. <https://doi.org/10.1126/science.1201609>
- Pandey, D., Agrawal, M., & Pandey, J. S. (2011). Carbon footprint: Current methods of estimation. *Environmental Monitoring and Assessment*, 178(1), 135–160. <https://doi.org/10.1007/s10661-010-1678-y>
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, 532(7597), 49–57. <https://doi.org/10.1038/nature17174>
- Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, 200, 33–41. <https://doi.org/10.1016/j.agee.2014.10.024>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. <https://doi.org/10.1126/science.aag0216>
- Realmonde, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, 10(1), 3277. <https://doi.org/10.1038/s41467-019-10842-5>
- Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., ... & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature*, 534(7609), 631–639. <https://doi.org/10.1038/nature18307>
- Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO₂ capture and storage. *International Journal of Greenhouse Gas Control*, 40, 378–400. <https://doi.org/10.1016/j.ijggc.2015.05.018>
- Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*, 114(36), 9575–9580. <https://doi.org/10.1073/pnas.1706103114>
- Scarborough, P., Clark, M., Cobiac, L. et al. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. *Nat Food* 4, 565–574 (2023). <https://doi.org/10.1038/s43016-023-00795-w>
- Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., & Turetsky, M. R. (2015). Climate change and the permafrost carbon feedback. *Nature*, 520(7546), 171–179. <https://doi.org/10.1038/nature14338>
- Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., & Haszeldine, S. (2013). 'Last chance for carbon capture and storage', *Nature Climate Change*, 3: 105–111. <https://doi.org/10.1038/nclimate1695>
- Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., & McLaren, D. (2016). Biophysical and economic limits to negative CO₂ emissions. *Nature Climate Change*, 6(1), 42–50. <https://doi.org/10.1038/nclimate2870>
- Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. *Advances in Agronomy*, 105, 47–82. [https://doi.org/10.1016/S0065-2113\(10\)05002-9](https://doi.org/10.1016/S0065-2113(10)05002-9)
- Sumida, K., Rogow, D. L., Mason, J. A., McDonald, T. M., Bloch, E. D., Herm, Z. R., Bae, T.-H., & Long, J. R. (2012). Carbon dioxide capture in metal-organic frameworks. *Chemical Reviews*, 112(2), 724–781. <https://doi.org/10.1021/cr2003272>
- USDA. (2022). *Conservation Reserve Program statistics*. U.S. Department of Agriculture. <https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics>
- Wiedmann, T., & Minx, J. (2008). A definition of 'carbon footprint'. In C. C. Pertsova (Ed.), *Ecological economics research trends* (pp. 1–11). Nova Science Publishers.
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, 56. <https://doi.org/10.1038/ncomms1053>
- World Bank (2023). *State and trends of carbon pricing 2023*. <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099807306052312253>
- Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37(13), L13402. <https://doi.org/10.1029/2010GL043584>
- Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., Van Noordwijk, M., & Wang, M. (2016). Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, 6, 29987. <https://doi.org/10.1038/srep29987>