Biological Dynamics for Sustainable Carbon Sequestration

Shahna M. Vakeri[1,2,3], Sami Souissi[5,6,7], Erlantz L. Fernandez[8,9], James MWR. McElhinney[2,3,10]* & Blaise L. Tardy[1,2,3,4]*

1: Research and Innovation Center on CO_2 and Hydrogen, Khalifa University, Abu Dhabi, United Arab Emirates
2: Center for Membrane and Advanced Water Technology, Khalifa University, Abu Dhabi, United Arab Emirates
3: Department of Chemical Engineering, Khalifa University, United Arab Emirates
4: Food Security and Technology Center, Khalifa University, Abu Dhabi, United Arab Emirates
5: Univ. Lille, CNRS, ULCO, IRD, UMR-8187 LOG, F-59000 Lille, France
6: Center of Excellence for Ocean Engineering, National Taiwan Ocean University, Keelung 20224, Taiwan
7: Center of Excellence for the Oceans, National Taiwan Ocean University, Keelung 20224, Taiwan
8: Life Cycle Thinking Group, Department of Graphic Design and Engineering Projects, University of the Basque Country (UPV/EHU), Plaza Ingeniero Torres Quevedo 1, Bilbao, Biscay 48013, Spain
9: BC Materials, Basque Center for Materials, Applications and Nanostructures, Edif. MartinaCasiano, Pl. 3 Parque Científico UPV/EHU, Barrio Sarriena, Leioa, Biscay 48940, Spain
10: Department of Biomedical Engineering, Khalifa University, Abu Dhabi, United Arab Emirates

Corresponding authors:
james.mcelhinney@ku.ac.ae (Tel: +971 2 312 4339) and blaise.tardy@ku.ac.ae (Tel: +971 588 390 281)

The manuscript is a non-peer reviewed preprint submitted to EarthArXiv

The manuscript is under review in *Global Challenges, Wiley, since the 3rd of March 2026.*

Biological Dynamics for Sustainable Carbon Sequestration

Shahna M. Vakeri[1,2,3], Sami Souissi[5,6,7], Erlantz L. Fernandez[8,9], James MWR. McElhinney[2,3,10]* & Blaise L. Tardy[1,2,3,4]*

1: Research and Innovation Center on CO_2 and Hydrogen, Khalifa University, Abu Dhabi, United Arab Emirates
2: Center for Membrane and Advanced Water Technology, Khalifa University, Abu Dhabi, United Arab Emirates
3: Department of Chemical Engineering, Khalifa University, United Arab Emirates
4: Food Security and Technology Center, Khalifa University, Abu Dhabi, United Arab Emirates
5: Univ. Lille, CNRS, ULCO, IRD, UMR-8187 LOG, F-59000 Lille, France
6: Center of Excellence for Ocean Engineering, National Taiwan Ocean University, Keelung 20224, Taiwan
7: Center of Excellence for the Oceans, National Taiwan Ocean University, Keelung 20224, Taiwan
8: Life Cycle Thinking Group, Department of Graphic Design and Engineering Projects, University of the Basque Country (UPV/EHU), Plaza Ingeniero Torres Quevedo 1, Bilbao, Biscay 48013, Spain
9: BC Materials, Basque Center for Materials, Applications and Nanostructures, Edif. MartinaCasiano, Pl. 3 Parque Científico UPV/EHU, Barrio Sarriena, Leioa, Biscay 48940, Spain
10: Department of Biomedical Engineering, Khalifa University, Abu Dhabi, United Arab Emirates

Corresponding authors:
james.mcelhinney@ku.ac.ae (Tel: +971 2 312 4339) and blaise.tardy@ku.ac.ae (Tel: +971 588 390 281)

Keywords: Microbial carbon cycling; Biogeochemical cycles; Soil carbon; Nature-based climate solutions, Equilibrium displacement

Abstract

Earth's atmosphere is shaped by the interplay of biological systems operating across interlinked biogeochemical cycles and, more recently, by anthropogenic emissions. Here, we thoroughly examine the potential for engineering biological systems across ecosystems for sustainable carbon storage. This centralization and comparative analysis of the potential of all key global ecosystems aims to facilitate the integration of nature-based carbon sequestration solutions into the portfolio of solutions currently being explored. Beyond reporting the potential for long-term carbon storage of the various ecosystems present globally, we show that biological equilibria strongly influence biological carbon dynamics. Consequently, routes for the strategic implementation of biological carbon sequestration in out-of-equilibrium systems are put forward. As carbon sequestration by ecosystems is typically linked to other benefits such as food production and expansion of their service value, we expect that the expansion and integration of by-design biological carbon sequestration could significantly contribute to the management of atmospheric carbon.

Introduction

The sustained rise in atmospheric carbon dioxide (CO_2) levels has galvanised the search for effective carbon management solutions[1,2]. Technological approaches such as carbon capture and storage (CCS)[3], where carbon (C) is captured at the source and stored, and renewable energy deployment have both received major investments (exceeding 11 billion USD in 2024[4] and projected to reach 100 billion per year by 2035[5]). In addition to CCS, technologies for carbon capture and utilisation (CCU),

where carbon is reused, and CO_2 removal (CDR), where CO_2 is actively removed from the atmosphere, have received much attention[6].

Key sectors remain hard to abate, with energy and land-use collectively contributing to >70% and 15% of anthropogenic emissions, respectively (**Figure S1**)[7]. Though CDR programs are rapidly growing (750% year-on-year increase in 2022-2023)[8], the IPCC estimates that 100-1000 Gt of CO_2 will need to be removed from the atmosphere by 2100 to limit global warming by 1.5°C[9]. Removal goals are proposed by the IPCC through a diverse portfolio of methodologies spanning Earth systems (land, air and ocean)[6] comprises the carbon management landscape (CCS, CCU and CDR, collectively). Despite significant efforts, however, the scalable success of engineered approaches to carbon management has been limited[3]. Conversely, the natural biological processes regulating the global biogeochemical carbon cycle (**Figure 1**) remain underutilised, even though their yearly carbon exchanges are far exceeding those associated with anthropogenic emissions[8,12,13]. Harnessing biological dynamics, therefore, presents a major opportunity for carbon management. However, there is presently no centralised information on the role of biological systems in carbon sequestration strategies and the associated potential of each ecosystems for long term carbon storage. Here, we synthesise the current knowledge on biological systems in the carbon sequestration landscape and identify strategic pathways for leveraging natural systems for scalable carbon management. By promoting the integration of biological systems into strategic CDR development, we aim to advance the development of sustainable sequestration solutions that align with food production and other ecosystem services.

Overview of carbon capture and global dynamics

Anthropogenic carbon emissions presently exceed the rate at which natural systems integrate atmospheric carbon (**Figure 1**). Indeed, the atmospheric C stock (~910 gigatonnes C (Gt C)), experiences an annual increase of ~0.46% yr^{-1} (**Figure 1**), or cumulative increase of 235.51 Gt C between 1958 and 2025 (per NOAA direct measures, available at https://climate.nasa.gov/vital-signs/carbon-dioxide/), highlighting the need to improve our integration with natural systems. Anthropogenic emissions from the geological C reservoir (4,130 Gt)[14] are primarily attributed to the combustion of fossil fuels at a rate of ~7.0 Gt C yr^{-1} as CO_2 release. Engineered CCS have progressed from the basic strategies such as absorption and catalytic or non-catalytic solvent regeneration[15–17] from pollution point sources, to direct air capture (DAC) that extracts CO_2 directly from the atmosphere[18,19] and sequestration into underground geological formations (estimated capacity of 5,000–10,000 Gt) by injecting CO_2[20]. However, as of 2023, engineered CDR systems sequester around 0.0045 Gt C annually[21], less than 0.01% of global carbon exchanges (**Figure 1**) and 0.4% of the target required to meet the Paris Agreement goals by 2050[22]. In comparison, at 57.3-66.5 Gt C yr^{-1}, net primary production from terrestrial photosynthetic processes account for the largest annual drawdowns of atmospheric carbon, equating to ~13,000× of that achieved with CDR programs[23]. Leveraging, or at least incorporating, the dynamics of biological systems will therefore become increasingly important. For example, given the magnitude of biological dynamics on carbon cycling, shifting them by 0.1% would result in ~13× the cumulative reductions

achieved with engineered CDR approaches. Critically, these processes can be further leveraged via, and integrated into, carbon credit systems if their cost-effectiveness is warranted (Supplementary **Discussion S1**).

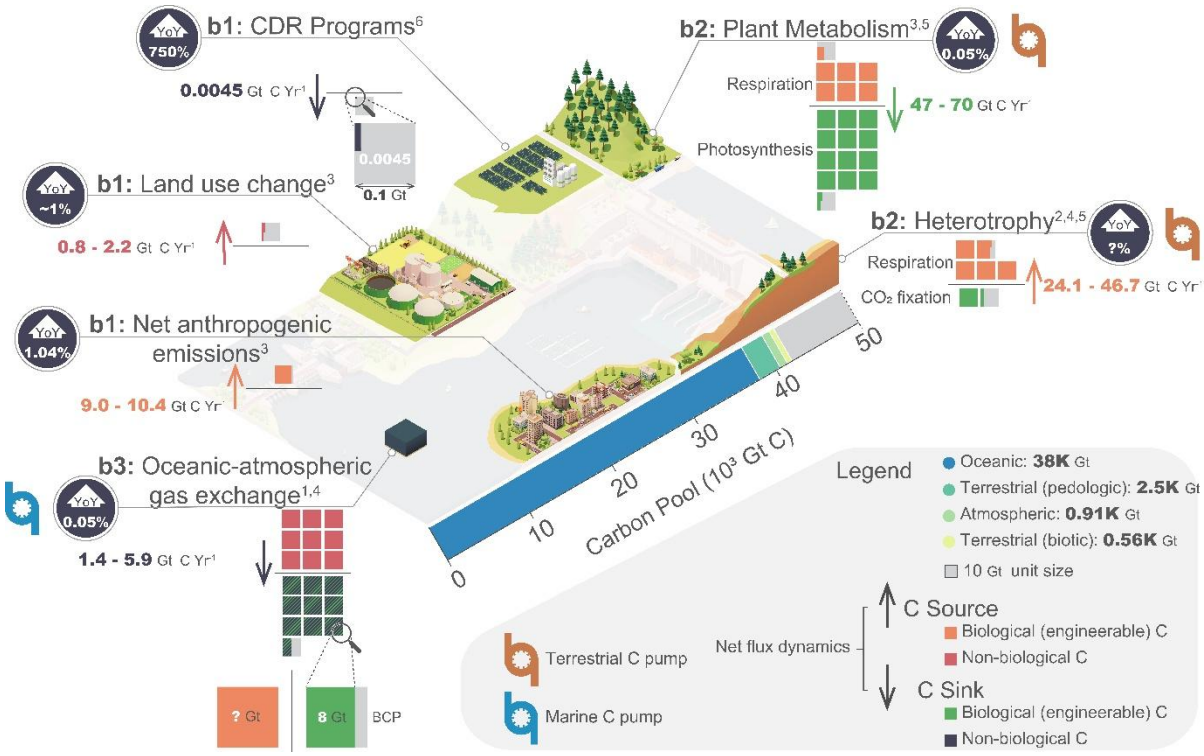

Figure 1 | Major landmarks of the global carbon (C) cycle. For each landmark (CDR Programs, Plant Metabolism, Land use change, Oceanic-atmospheric gas exchange, Heterotrophy and Net anthropogenic emissions). These landmarks are grouped by anthropogenic aspects (b1), terrestrial aspects (b2) and oceanic (b3). The latest year-on-year (YoY) change is presented (as the % against the prior year on record), and net flux is presented explicitly, as the latest ranges in terms of gigatonnes (Gt) per year. Adjacent arrows highlight whether the associated landmark is an overall C sink or source for atmospheric CO_2. Blocks accompanying arrows that are grouped above (CO_2 emission facets) and below (CO_2 absorption facets) the line represent gross units of 10 Gt C (except for CDR programs for which a 0.1 Gt unit is used for clarity) to facilitate comparison of the magnitude of main C landmark facets (for the BCP portion, this line has been made horizontal for illustrative purposes), for oceanic-atmospheric CO_2 absorption the green-blue dashed boxes represent our uncertainty as to the relative contributions of biological/non-biological processes. Blocks are coloured to highlight biological C cycling, which presents opportunities for long-term engineering of the biogeochemical C cycle to favour low atmospheric C. The principal carbon pools (atmospheric, oceanic, and terrestrial (split into pedologic & biotic fractions)) are presented as a stacked bar; explicit values for each pool are given in the legend. Where: GHG – greenhouse gases, BCP – Biological Carbon Pump and CDR – Carbon Dioxide Removal. The year for supporting data for each landmark is indicated where [1] – 2012, [2] – 2019, [3] – 2020, [4] – 2021, [5] – 2022 and [6] – 2023. Further information on data sources can be found in **Discussion S7**.

The four principal pools associated with the biogeochemical carbon cycle (**Figure 1**) are the *oceanic, terrestrial* (*pedologic)*, *atmospheric* and *terrestrial (biotic)* pools. The oceanic pool is the largest (with an estimated 38,000 Gt C), primarily (>90%) stored as dissolved inorganic carbonates (DIC)[24]. Within this pool, the ocean-atmosphere gas exchange accounts for a significant portion of the biogeochemical carbon cycle, playing a critical role in regulating atmospheric CO_2 levels[25]. This exchange is mediated by partial pressure differences between the gas and liquid phases and further shaped by the biological conversion of DIC into particulate inorganic carbon

(PIC). The pelagic transformation of DIC to PIC is intrinsically tied to calcifying marine organisms (notably coccolithophores and foraminifera), which contribute as much as 56% PIC production[26,27].

For terrestrial carbon, the pedologic (soil) pool carries the largest stock of carbon (~2,500 Gt C)[28], accounting for around three times the carbon stored in the atmosphere[29] (**Figure 1b**). Approximately 60% (~1,500 Gt C) of the pedological pool exists as soil organic carbon (SOC)[30] and is therefore derived from biological systems. The remaining 40%, the soil inorganic carbon (SIC), is also thought to be significantly influenced by biological processes, though the relative contributions of these processes across geographies, such as biomineralisation, bioturbation and mineral dissolution, is not yet clear[28,31,32].

The other primary terrestrial pool is the biotic pool (**Figure 1b**), the above-ground fraction of which is the largest and is primarily represented by plant life (comprising ~450 Gt C of a ~550 Gt C biomass pool size[33]). The subsurface fraction (which is comprised of necromass, root systems, fungi, and microbial communities) is smaller than its topside counterpart by several orders of magnitude greater than the aboveground fraction stored in animal and microbial biomass. So, although animal biomass is critical for carbon cycling, it is less well suited for CCS. Notably, the dynamics and relative importance of the natural carbon pools are currently based on broad estimates. Improved quantification of these aspects would clarify the comparative roles of biological and engineered carbon sequestration strategies, supporting the optimisation of more targeted interventions and the development of effective nature-based solutions.

Carbon sequestration lifetime and its association with biological dynamics

Carbon sequestration strategies can be described in terms of six fundamental categories defining storage in 1) waste materials, 2) plant biomass, 3) soils, 4) man-made products, 5) oceans and 6) the deep subsurface (geological) (**Figure 2**). The corresponding BCS actors (including microbes, plants, fungi, and algae), play a fundamental role in many of these strategies (**Figure 2, right**). Their involvement brings both opportunities and challenges, influencing the effectiveness and longevity of CDR and long-term storage. Across these categories of carbon sequestration strategies, each of the products has its own recalcitrance to re-emission, which is proportional to their mean retention time (MRT) (**Figure 2**, **left**). Broadly speaking, waste biomass utilisation of durable goods and storage in certain man-made products (fuels, textiles, engineered woods, bioplastics and composites) possess the shortest MRTs (with reported MRTs often below a year)[34–36]. Of note, there are currently efforts to increase the portion of materials formed from natural carbon sequestration - wood and plant-based materials, for example (**Discussion S2**).

These are followed by landfill sequestration, agricultural approaches, wood construction and ocean fertilisation (ocean fertilisation is notable for its high variability and context dependency and may therefore be underrepresented), where MRTs extended into the order of decades[37,38]. Whilst they are therefore unsuitable for long-term sequestration initiatives, these approaches may yet find utility at local scales as part of holistic frameworks for carbon management. Long-term biomaterial-based (bioconcrete and biochar) methods, ocean alkalinity enhancement, and forestation

approaches begin to approach desirable sequestration timescales (~100s of years)[39–41]. For truly long-term storage (millennia-Ma timespans), methods for C storage in sediments (such as blue carbon ecosystem (i.e., mangroves, salt marshes and seagrasses), and macroalgae cultivation with sinking) and low-turnover peatland soils, mineralisation or deep within geological formations are the primary avenues available[39,42–44]. The geographical and temporal scales surrounding MRT calculations render accurate MRT assessment challenging, as direct observation is impractical. Current long-term MRTs are therefore necessarily limited by their dependence on modelled lifetimes. Nevertheless, at such time horizons, these latter approaches warrant special focus for development. However, it is also important to note that MRT is not the only consideration (an elaborated discussion of CCS MRTs is provided in **Discussion S3**, Supplementary Information), carbon costing, storage capacity, environmental, socioeconomic, and ethical considerations need to be factored into implementation planning. In that regard, each of the available approaches carries its own advantages and challenges.

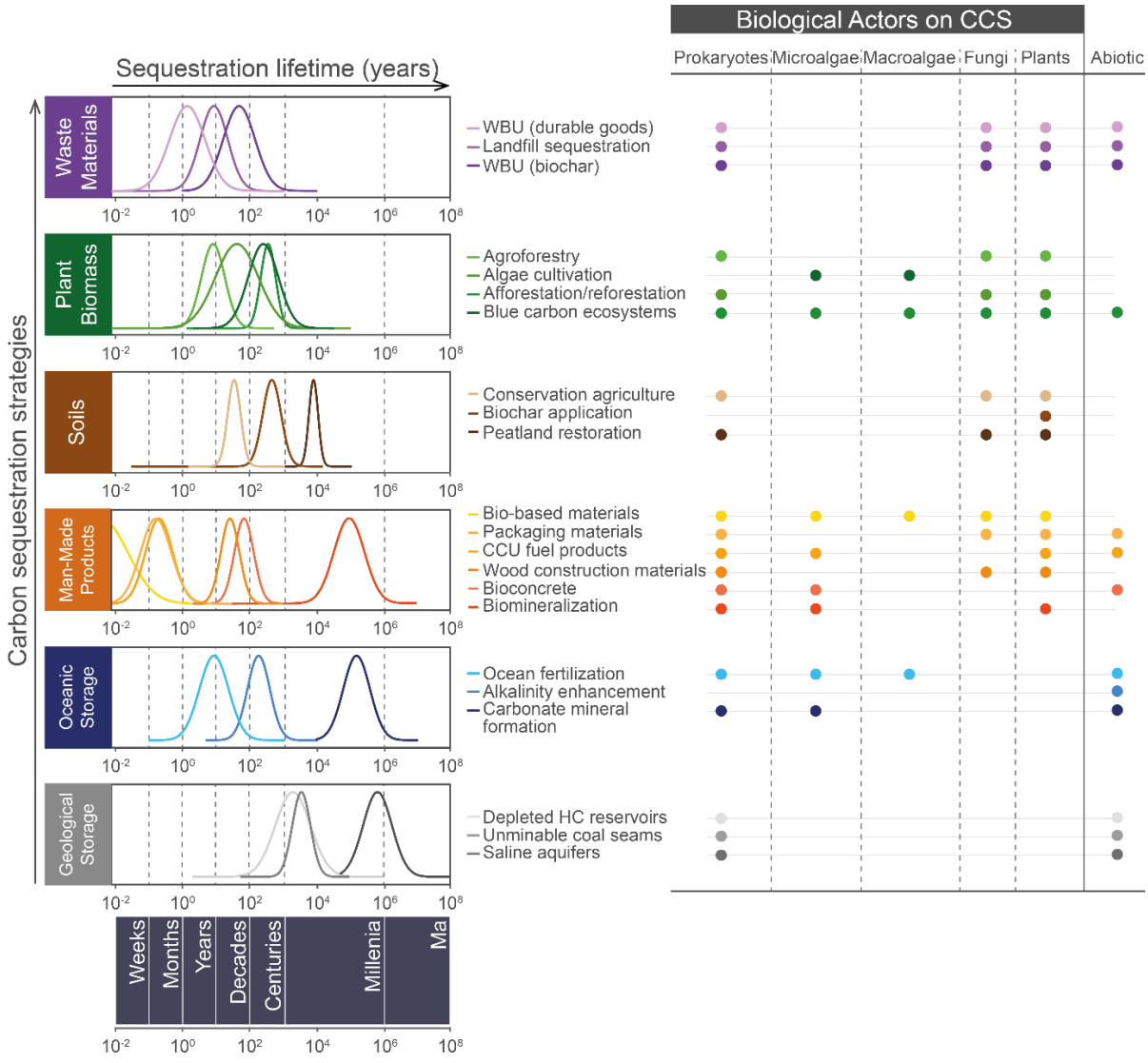

Figure 2 | Sequestration lifetime across ecosystems and anthropogenic sectors as associated to biological systems. Right panel - The representative normalised probability densities (log-normal distributions) for carbon retention lifetimes of carbon sequestration strategies (grouped by shared

approaches). The dotted lines indicate the time horizon, as shown in the bottom-most plot (indigo). Where WBU – waste biomass utilisation; HC - hydrocarbon; CCU carbon capture and utilisation. **Left panel -** Table indicating the involved biological systems (prokaryotes, microalgae, macroalgae, fungi or plant) that are either actively contributing to, or otherwise influencing, the associated sequestration strategy (as indicated by the coloured circles)**.** Circles are also shown for strategies in which abiotic processes are the fundamental aspect. Further information on the data processing for this panel can be found in **Discussion S3**.

Accounting for the net carbon balance for natural systems remains especially challenging due to their complexity and scale. Life cycle assessments (LCA) have become an increasingly popular approach (influencing policy-making, industry, academia) to evaluate carbon sequestration[45]. Until fairly recently, there was a consensus in carbon accounting and LCA modeling that carbon-neutral and climate-neutral were analogous terms. This paradigm accepted the idea that a net flux balance of zero emissions can be reached within a given system if the CO_2 absorbed equals the CO_2 emitted. However, by adopting a dynamic LCA approach[46], and applying it to a system where C rotates between the biosphere, technosphere and atmosphere (e.g., from biomass) the significance factoring in CO_2 molecules that remain in the atmosphere before being incorporated into biomass was revealed[47]. For example, examining the atmospheric decay of a biogenic CO_2 pulse stemming from biomass with rotation and storage periods of 50 and 20 years, respectively (which is then released as a pulse), yields a net area under the curve (corresponding to its global warming potential) that should not be disregarded.

Therefore, it is essential to understand the dynamics of the system and relate how carbon storage in the technosphere, or delayed emissions contribute to climate change[47]. In this sense, the "biogenic global warming potential" (GWP_{bio}) index was introduced to relate biomass growth, emissions from biodynamic fluxes, and the global carbon cycle[47,48]. The characterization factor developed served to quantify the benefits or burdens of storing biomass in the technosphere and the subsequent C release with the radiative forcing integrated within a fixed time window. For instance, for the above example (rotation period of 50 years, 20 years of storage), the GWP_{bio} (for a 100-year time horizon GWP) equals to 0.05, meaning that 5% of the embedded carbon should be considered as emissions. This indicates that despite the storage, a portion of the embedded carbon can impact climate change. We believe this insight is valuable when implementing and studying other CO_2 sequestration and utilization systems to obtain time-resolved global warming metrics[49]. In this process, it is important to underline that the lack of harmonization in assessment methods by LCA practitioners (dynamic *vs.* static approach, cradle-to-gate *vs.* cradle-to-grave, attributional *vs.* consequential, functional unit determination, low transparency in inventory modeling, standard variability) makes it difficult to benchmark across different methods for C sequestration. Consequently, evidencing their climate benefits, the trade-offs to each approach and any potentially occurring co-benefits quickly becomes cumbersome[45,50]. Accordingly, international consortiums may be considered between LCA accounting methodologies that could interact with each other to ensure synergistic improvement

in accounting of sequestration potential of engineered and biosequestration CCS strategies alike.

Bio-sequestration strategies for CCS

Biological carbon sequestration (BCS) emerges from the complex interplay of biocatalytic processes conducted by microbes, plants and animals, including both direct (e.g., carbon fixation)[51] and indirect (e.g., biomineralization)[52] mechanisms. Consequently, in contrast with engineered CCS systems, the impact of BCS is less clearly delineated. Managed interventions on higher plants and microorganisms with the intent of removing CO_2 from the atmosphere is currently the focus. BCS has shown promise for its cost-effectiveness, ease of implementation and potential for long-term continuous sequestration by integrating seamlessly into local ecosystems as well as food production streams. Carbon can then take various forms, such as a richer microbiome, more plant biomass, a richer root network and soil organic matter (SOM), or more recalcitrant carbon forms, inclusive of oceanic sediments and peat, to name a few. Improving stored organic carbon (OC) should prioritize strategies according to effectiveness, permanence, associated ecosystem impact, and feasibility.

Ocean and wetland-based strategies

Many CDR approaches used in coastal, oceanic and wetland settings are based on augmenting the naturally occurring carbon sink processes within these ecosystems (**Figure 3**). Inorganic and organic marine carbon is found either as dissolved (DIC and DOC) or particulate (PIC and POC) forms. Of note, oceanic DIC levels are directly related to the metabolic activities of marine organisms (notably CO_2 uptake by photosynthetic processes of phytoplankton and bioproduction of carbonates by molluscs and coccolithophores). Although the vast majority of the oceanic pool is stored as DIC, marine sediments are still thought to contain approximately 2,322 Gt C in the top 1 m, and these stocks are also effective carbon sinks[53]. Current estimates place ~85% of marine sediment stocks in the deep ocean[53], where they can be expected to remain for at least several thousand years[54], with similar estimates existing for DICs[55]. The oceanic pool is thought to be undergoing an annual increase of 2.3-3.2 Gt C yr^{-1}, and is expected to further increase in the coming years[56,57]. Anoxic marine sediments are also steadily accumulating[58]. The high rate of sediment deposition, low oxygen levels, low hydraulic conductivity of sediment, and slower microbial decomposition rates all contribute to the burial and long-term storage of carbon in these sediments[59,60]. The marine biological carbon pump (BCP), which drives the biological component of oceanic-atmospheric gas exchange and transportation of carbon to deep waters, has received much attention for its significant role in oceanic carbon cycling (**Figure 3a**). The BCP comprises 20 Gt C as particulate organic matter and is thought to account for sequestering 0.23-0.3 Gt C yr^{-1} [61]. The current accounting of carbon in oceanic stocks remains, however, fragmentary with no global totals reported on, e.g., suspended inorganic carbon, suspended organic carbon, or biomass carbon and relative contributions of biotic and abiotic processes driving oceanic carbon fluxes.

Of the emerging man-made strategies for marine BCS, oceanic fertilisation, alkalization and macroalgae cultivation have received the most attention. Ocean

fertilisation exploits the fact that approximately 25% of oceanic surface waters are thought to be high-nutrient, low-chlorophyll waters, where the growth of resident phytoplankton is hampered principally by micronutrient deficiencies due to precipitation of metal ions in their oxide form[62]. Ocean fertilisation approaches seek to sequester CO_2 in the deep ocean by inducing a bloom of phytoplankton with chelated Fe and soluble phosphate supplementation that subsequently sinks to deep waters (**Figure 3b**)[63]. Although potentially inexpensive to implement in near-coastal areas, iron fertilisation carries side-effect risks. These include, for instance, disruption of ecosystem function (contributing to ocean deoxygenation due to increases in bacterial respiration of elevated organic carbon produced by phytoplankton[64]) and pollution from the logistical dependency on maritime vessels.

Oceanic alkalization via the deliberate deposition of minerals (e.g., limestones and olivine) aims to enhance the solubility of CO_2 through the resulting pH shift, thereby raising its uptake into marine waters. This approach benefits from the shear capacity of the oceanic pool and is thought to be capable of housing upwards of 800 Gt additional C by the year 2100[65]. However, the long-term fate of the additional DIC is not entirely clear, though it has been suggested that combining alkalisation with carbon mineralisation may offer a means to circumvent this uncertainty in long-term storage[66]. Importantly, there are considerable energy requirements for alkalisation at scale, and the resulting alterations in marine chemistry are not trivial. Such perturbations can be expected to alter the turbidity and trace metal levels, running the risk of disrupting biogeochemical cycles, biodiversity, and ecosystem services.

Macroalgae may sequester up to 0.166 Gt C yr^{-1} via oceanic burial in coastal and deep-sea sediments[67,68], conceivably surpassing other coastal blue carbon systems in storage potential through cultivation initiatives. However, the impact of large-scale macroalgae cultivation (**Figure 3b**) on BCP equilibrium (due to nutrient sequestration and hypoxia in surrounding waters), warming (from decreased albedo), and mass transport of decaying organic matter to the seafloor sediments poses significant risks that must be carefully evaluated before implementation. Microalgae also contribute significantly to blue carbon (**Discussion S4**) by fixing CO_2 at rates up to 10 times greater than that of higher plants[69,70] while producing valuable biomass products[71] and may therefore find use in biotechnological applications that are carbon negative, though large-scale cultivation remains cost-limited. Chemoautotrophic processes in oceanic sediments are thought to naturally account for and long-term sequestration of carbon in stable mineral form (as much as 0.77 Gt C yr^{-1})[72]. Despite these enticing features, chemoautotrophs in seafloor sediments have been challenging to adapt for BCS, owing to the limited accessibility to their environment and technical challenges associated with their manipulation.

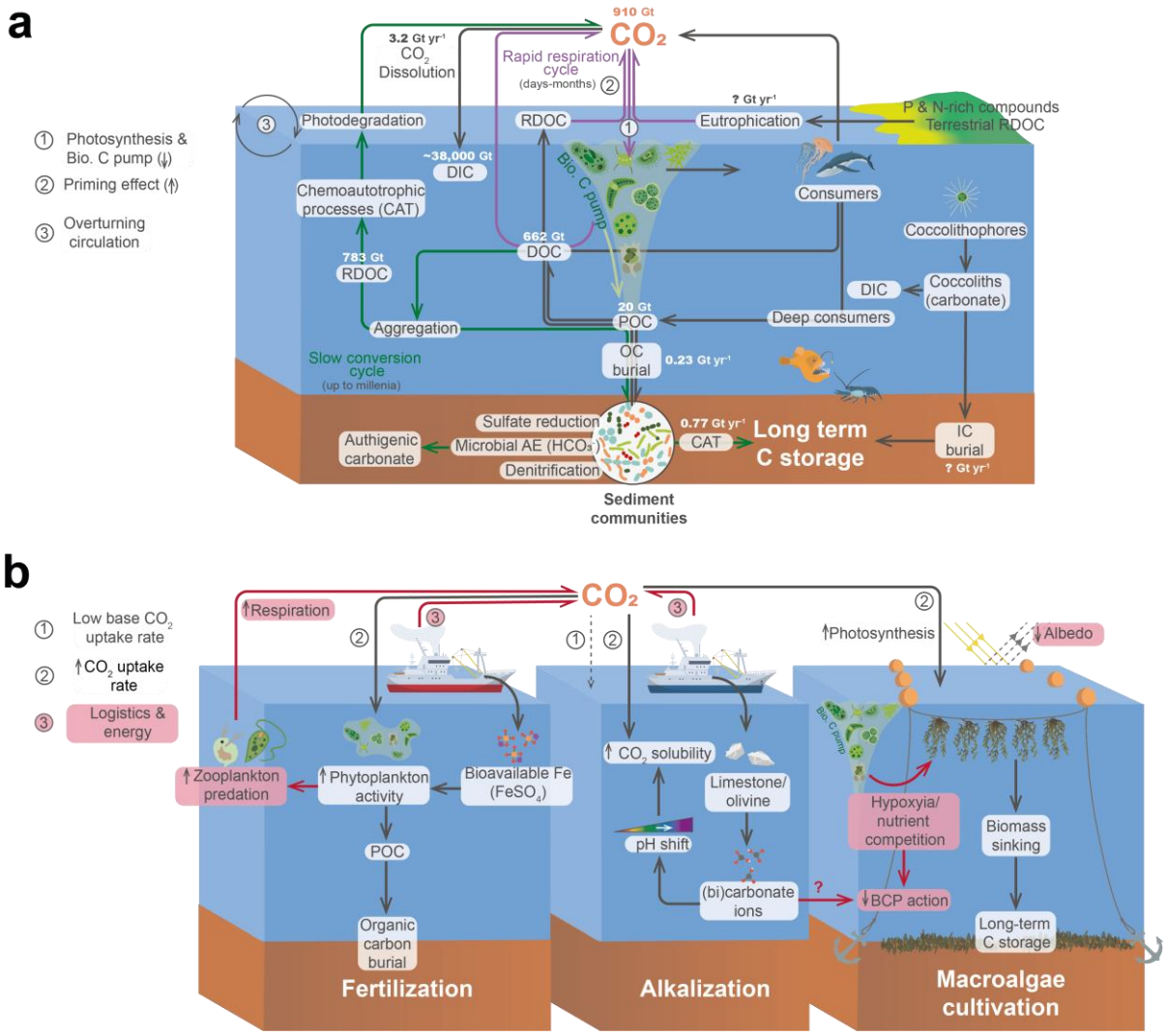

Figure 3 | Dynamics in oceanic carbon cycling and overview of oceanic CCS approaches. a - Ocean carbon cycling dynamics showing the principal mechanisms by which ocean carbon moves through the marine pools (DIC, DOC, RDOC, POC and biomass (comprising plankton and consumers)) and is either locked up for extended periods or released back into the atmospheric pool. Processes forming the rapid respiration cycle or slow conversion cycling are shown in purple and green, respectively. Pools with known magnitudes are presented (using mean values where ranges have been previously reported), and processes with known rates are also given; further information on data sources can be found in **Discussion S7**. Arrows within parenthesis indicate the direction of the process for clarity, where up indicates carbon release, and down indicates carbon uptake. **b** – Summaries of the major oceanic carbon capture and storage approaches (fertilisation, alkalization and macroalgae cultivation), dosing chemistry examples are presented for fertilisation (FeSO4), and alkalization (limestone/olivine), though others also exist. Intended processes for each approach are shown in white boxes, and unintended side effects are indicated in red boxes. Where: P – phosphates, N – nitrogen, DOC – dissolved organic carbon, DIC – dissolved inorganic carbon, OC – organic carbon, IC – inorganic carbon, POC – particulate organic carbon, RDOC – recalcitrant DOC, AE – alkalinity enhancement, CAT – chemoautotrophic processes.

Blue carbon considerations also involve coastal systems such as halophilic flowering plants, namely tidal marshes, mangroves, seagrasses, coral reefs, and others[73,74]. Among these, coastal flowering plants predominantly inhabit depositional shores as rhizophytes[75], where a portion of microbes can be retained as particulate organic

carbon in the root zone[73,74]. Tidal salt marshes provide critical ecological services, including habitat for estuarine organisms, shoreline protection[76], and sequester an estimated 0.0048-0.0872 Gt C annually[73] attributed to their high sedimentation rates, elevated soil carbon content, and efficient burial of organic matter[77], while offering reduced methane emissions [78]. Sediment brought in by tides, coupled with vegetation that acts as a baffle to enhance sediment deposition, supports the accretion process[79]. Seagrass meadows have been highlighted to be able to store up to 19.9 Gt of organic carbon[80,81]. Although seagrass meadows cover a mere 0.1% of the ocean floor, they contribute disproportionately to oceanic carbon burial, accounting for 10–18% of the total, with carbon accumulation rates ranging from 0.048 to 0.112 Gt of carbon annually[58,81]. Coral reefs represent the most biologically diverse marine ecosystems, with an estimated annual global carbon sequestration of approximately 0.9 Gt C yr^{-1}. Their primary productivity spans from 0.3-5 Mg C ha^{-1} yr^{-1}, indicating near-complete utilisation of CO_2 fixed during photosynthesis, primarily by mineralization[82]. It is, however, postulated that the precipitation of 1 mol of calcium carbonate ($CaCO_3$), even when buffered by seawater, results in the release of 0.6 mol of CO_2[83]. CO_2 is utilised in the formation of $CaCO_3$ skeletons, suggesting that organic carbon metabolism can also serve as a net carbon sink whilst providing co-benefits of maintaining biodiversity and marine ecosystem services. Presently, coral restoration and creation efforts are not typically scoped for carbon sequestration. Integrating these initiatives within broader blue carbon strategies may realise as yet untapped synergies for climate mitigation and biodiversity conservation.

Beyond open marine waters, wetlands are effective for sequestering atmospheric CO_2 naturally[84–86] as they possess the highest soil carbon density compared to forests and grasslands [86,87]. Undisturbed wetlands can store carbon for hundreds to thousands of years; their protection, restoration, creation and the alteration of wetland components involved in organic matter decomposition are the main strategies for enhanced wetland C sequestration[88–90]. For example, restoring drained European wetlands (~1.51 × 10^8 hectares[91]) could sequester an average of 0.4 Mg C ha^{-1} yr^{-1} [92] (amounting to 0.06 Gt C yr^{-1} across European wetlands). Biotechnological interventions for BCS in wetlands, such as manipulating soil microbes and vegetation, have been proposed to enhance carbon storage[93]. Amendments such as biochar and humic acid application to wetland peat soils are also considered a viable strategy[94,95]. Mangrove forests have emerged as notable wetland niches for their high-density C accumulation (owing to their capacity to drive C storage in both biomass and surrounding sediments). Indeed, at 738.9 Mg C ha^{-1} on average, mangrove forests store more blue carbon per unit area than any other vegetative ecosystem, accounting for 10-15% of coastal sediment storage despite representing 0.5% of the global coastal area[96]. Implementation of mangroves for BCS will, however, need to manage risks of methane emissions from anaerobic sediments in this niche (which can exceed several thousand μmol m^{-2} h^{-1})[97]. Nevertheless, given their broad ecosystem services in providing habitats for a variety of marine wildlife, supporting nutrient cycling, and preventing coastal erosion, mangroves are an attractive niche for BCS applications. There, mangroves may find additional utility in hybrid nature-based solutions, for instance via restoration or cultivation for coastal and fishery catchment buffering or by integration with aquaculture for sustainable economic benefit provision[98,99].

.

Terrestrial strategies

Naturally occurring soil carbon uptake contributes between 0.4 - 1.2 Gt C yr^{-1}, or 5-15% of worldwide fossil-fuel emissions[100]. The terrestrial sink, including the biotic pool, has been reported to absorb a net ~1.4 ± 0.7 Gt C yr^{-1}, and models suggest this capacity may rise to approximately 5 Gt C per year by 2050[101]. The biotic pool provides the organic material that feeds the largest active source of atmospheric CO_2 from the pedologic pool, i.e., heterotrophic respiration (Rh), which drives the terrestrial pump (**Figure 4a** and **Discussion S5**). Rh releases an estimated net 35.4 ± 11.3 Gt C yr^{-1} [102–104], between 232% and 519% of the emissions released from anthropogenic CO_2 sources. The microbial activities underpinning Rh are governed by a variety of factors (such as solid or gaseous nutrient availability, temperature, and moisture) and remain an active area of research.

Terrestrial strategies for CCS centre on leveraging the biotic and pedologic carbon pools (**Discussion S6**). There, forests account for 40% of below-ground carbon storage[105]. Methods to leverage forests for BCS included afforestation and reforestation. These carry some sequestration potential (up to 0.2 Gt C yr^{-1} on repurposed grazing lands)[106], but they depend on site-specific factors and require substantial land and upfront investment[107,108] which limits their scalability. Other land management practices (e.g., peatland restoration, paludiculture, and conservation agriculture) aim to harness the natural capacity of biological systems to capture and retain atmospheric CO_2 through photosynthetic processes and plant biomass accumulation, thereby stabilising soil carbon. Whereas soil amendments (such as biochar) augment existing stocks of, primarily, SOC with new carbon deposits in stable form. When considering land management practices, SOC plays a key role in the soil and ecosystem health, owing to the role of SOC in making soils more auspicious for biomass growth[109] (**Figure 4a**). Conservation Agriculture (CA) enhances SOC by minimal soil disturbance (no-tillage or minimum tillage), improving crop diversity (to enhance the variety of exudates and rooting depths) and permanent soil cover for increasing deep-seated plants[110]. However, CA is often conflated with reduced-tillage or no-tillage farming, leading to data variability and scepticism regarding its impact on SOC[111] (see also MRTs in **Figure 2**). Additionally, SOC outcomes can vary significantly depending on site-specific factors and management practices[112]. The variability in SOC outcomes from CA highlights the need for further research to better quantify SOC gains and the associated increases in aboveground biomass resulting from improved land management.

Soil amendments (**Figure 4a**) such as compost, livestock manure, green mulches, and particularly biochar can enhance both microbial and plant biomass, nutrient and water retention while introducing degradation-resistant carbon that limits Rh-based turnover[113]. Among these, biochar (which retains >50% of the original biomass carbon[114]), offers one of the most promising mid to long-term CCS strategies, though its effects on SOC vary depending on application rate and soil context[115].

Microbes are the fundamental regulators of SOM dynamics and nutrient availability (**Figure 4a,b**)[116,117]. The management and manipulation of soil microbiomes is

therefore crucial. Biotechnologies centred on soil bioaugmentation, the introduction of pre-cultivated microbial cultures into the soil, have shown promise. Bioaugmentation enhances soil properties, increases plant growth yield, accelerates bioremediation and stabilises SOC (promoting aggregate and humified carbon formation)[118,119]. However, consistency of outcome remains an ongoing research challenge owing to the complexity of soil dynamics and regional soil idiosyncrasies. The potential of specific microbes specifically designed to capture and sequester carbon has also been explored[120]. This includes enhanced CO_2 sequestration via the production of urease- and carbonic anhydrase-producing microbes[121], contribution to soil biomass through fungi's filamentous structures[122,123], and introduction of species capable of converting CO_2 to acetate via the Wood–Ljungdahl pathway[124]. The production of carbonates from oxalate by oxalotrophic bacteria has presented another means for the accumulation of stable mineralised carbon forms like $CaCO_3$, which may be especially beneficial for facilitating CCS in soils cultivating oxalic acid secreting crops (such as Amaranth, Taro, and Spinach)[125,126]. Indeed, we are at the point where the engineering and 3D printing of living materials capable of CO_2 mineralisation-coupled photosynthesis is now possible[127]. Developments of this sort demonstrate that the continued efforts at the nexus of disciplines (e.g. ecology, synthetic biology, materials science) can be expected to yield novel biotechnologies that may contribute meaningfully at the local level as modular tools within a holistic and integrated framework for sustainable habitat integration.

The balance between carbon forms and microbial metabolism (where aerobic pathways favour respiration and anaerobic conditions promote methanogenesis) significantly influences the re-emission of organic carbon. Ideally, captured atmospheric carbon could be stabilised for long-term storage via the intervention of manufactured systems (e.g., pyrolysis), natural carbon pumps or by biotransformation. However, for most carbon-saturated soils, for example, in areas with rich soils such as forests and wetlands (Figure 4b), further introduction of organic carbon typically leads to re-emission, highlighting the need to consider the localised starting C content of soils or ecosystems where BCS strategies are implemented.

Leveraging agro-climatic zones for favourable biological carbon soil equilibria

For carbon-saturated soils (**Figure 4b**), the equilibrium between storage and respiration of carbons is usually stable and further carbon storage involve transforming OC into more stable carbon forms. In contrast, soils that initially have a low carbon content may favour carbon storage from OC given that few organisms are present for re-emission (**Figure 4a, right**). Among the C poor regions, the MENA region, characterised by arid and semi-arid climates, faces distinct challenges for BCS due to water scarcity and land degradation. However, innovative land management practices could offer outstanding BCS benefits. Agroforestry, integrating drought-resistant tree species with crops, might enhance carbon sequestration and provide additional benefits such as improved microclimates and soil stabilisation, particularly in areas with supportive socio-economic frameworks for sustainable agriculture. Coastal areas in the MENA region, particularly along the Red Sea and the Mediterranean, hold potential for blue carbon sequestration through the restoration of mangroves and salt marshes.

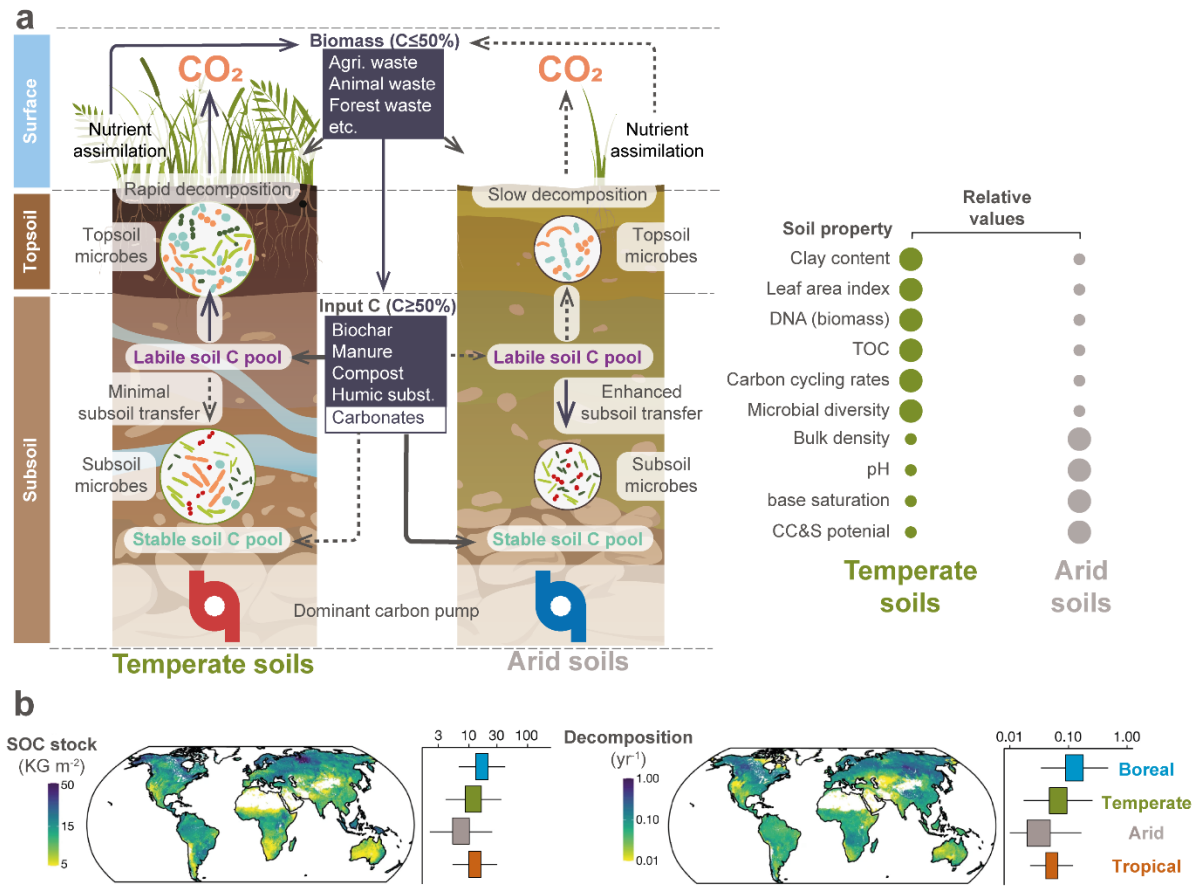

Figure 4 | Carbon saturated (at maximum carbon content equilibrium) and carbon-poor soils (far from maximum equilibrium) and their global predominance. a - responses of temperate and arid soils to input carbon are distinct owing to their respective carbon cycling dynamics which are emergent properties of the local soil-associated biological systems and physicochemical soil properties. Percentages shown refer to the typical carbon content in the biomass and processed input carbon. The dominant carbon pump in temperate soils (red) is microbial (characterized by high carbon turnover, heterotrophic respiration and organics and a correspondingly low capacity for additional carbon input). The dominant carbon pump in arid soil (blue) is the mineral carbon pump (characterized by low carbon turnover mineral adsorption, mineral occlusion and aggregation and a correspondingly higher capacity for additional carbon input). Further details on the mechanisms underpinning these systems are provided in **Figure S1**. Where: Agri. Waste - agricultural waste biomass, Humic subst. - processed humic substances, TOC - total organic carbon and CC&S - carbon capture & storage. **b** - Global heatmaps showing soil organic carbon (SOC) stocks and relative extents of soil decomposition. Adjacent box plots show the breakdown of these values for the four principal soil types (boreal, temperate, tropical, and arid), demonstrating the favourable SOC stocks and decomposition rates in arid soils. Plots adapted from Tao et al 2023[128].

SOC stability is a critical component that is governed through the complex interplay of biological, chemical, and physical factors[129]. The importance of targeting carbon-poor (e.g. arid) areas for a successful BCS implementation is becoming increasingly recognized. For example, studies on the priming effect (PE) describing the rate of organic matter mineralisation, and biochar's influence on this process[130,131], have shown predominantly negative PE values (a reduction in SOC decomposition), except in sandy soils (20.8% positive PE) and other poorly fertile soils[41]. Furthermore, afforestation has greater potential as a carbon sink on barren lands with low initial SOC stocks compared to croplands or pasturelands. In the latter, fresh SOC inputs

(e.g. from tree litter) can recharge the existing SOC pool and prompt the PE, accelerating SOC loss[132,133]. Whereas, in carbon-poor soils, microbial activity is limited due to the lack of bioavailable carbon. There, any new addition tends to exceed the decomposition rate and causes a commensurate increase in SOC stock. Indeed, microbial activities (such as Rh) in arid soils are further restricted by the lack of available water, promoting the retention time for newly added organic matter. However, such regions are also prone to accelerated erosion from wind exposure, which can strip topsoil and undermine SOC accumulation in the long term. Water scarcity must also be carefully considered as it constrains biomass production and microbial establishment, limiting the natural capacity for sustained SOC buildup and thereby hindering the establishment of ecosystem services. Notably, an estimated 36% of tropical land available for afforestation receives only 40% of the necessary water by rainfall, exacerbating local water scarcity[134]. The synergy between BCS and water supply will therefore be critical in realizing gains for the most out-of-equilibrium areas where carbon-poor soils are prevalent.

Shaping of atmospheric composition by biological systems

While equilibrium processes govern carbon storage at local scales, it is the cumulative activities of biological systems across environments that have ultimately shaped the Earth's atmospheric composition. Over geological timescales, biological activity has profoundly altered the atmosphere, driving major shifts in global carbon cycling (**Figure 5**)[135–137]. During the Archean eon, N_2, CO_2 and CH_4, were two to four orders of magnitude higher than today[135]. This composition lasted until the introduction of oxygen, likely through microbial photosynthesis[138]. Indeed, the latest model of CO_2 over the past 485 Ma is consistent with the marked decline in atmospheric CO_2 following the emergence of land plant life[139]. While atmospheric CO_2 has a moderately strong correlation with global mean surface temperature (GMST) across these timespans ($r \approx 0.57$), other climatic factors are clearly also at work in shaping the full climatic signal (**Figure 5a**). Records for other major GHGs (i.e., CH_4 and NO_2) are less complete, owing to their respective instability and lack of geological proxies, though ice-core data are available for the past 800 Ka[140,141]. Across this timespan, a coordinated rise and fall in these GHGs can be seen with a cyclic periodicity of ~100 Ka (**Figure 5b**). This periodicity corresponds to orbital eccentricity, a key aspect of Milankovich cycles, that perturbs climate via insolation-driven orbital forcing[142]. Orbital forcing works globally on GMST, as an external climate driver, influencing climate feedback systems including ice cover, ocean circulation and biogeochemical cycles. This interplay of orbital dynamics and GHGs highlights the importance of developing our understanding of how Earth's systems, both biological and otherwise, modulate responses to astronomic forcing.

Microbiological metabolic networks are central to natural GHG cycling. Key microbial players include: **1)** Syntrophic fermenters, which generate CO_2 and provide the H_2 and acetate for methanogens, which produce CH_4, interfacing with the nitrogen cycle. **2)** Ammonia producers, which inhibit aerobic methanotrophs that would otherwise oxidise CH_4 into CO_2. **3)** Denitrifying methane oxidisers, which consume CH_4 to produce N_2 and CO_2. These microbial systems are complex and deeply intertwined, and yet, are often studied in isolation[143], which limits our capacity to model their role

in atmospheric dynamics or manage their cumulative impacts. Despite their established contemporary impacts and suspected historical roles in shaping atmospheric composition, biological systems remain underutilised in modern CCS strategies, where the focus remains on engineered solutions[144–146]. This is partly due to the relative complexity of biological systems and persistent knowledge gaps surrounding their workings. Notably, the nature of below-ground microbiome responses to dynamics in atmospheric GHGs is poorly understood and challenging to predict[147]. This is further complicated by uncertainties in the coupling of CO_2, CH_4 and NO_2 cycles (**Figure 5**), where, for example, methane emissions offset CO_2 storage in coastal ecosystems due to methanogenic activities in sediment layers[145]. These microbial complexities highlight the need for a cautious and systems-based approach to BCS[143]. Nevertheless, the engineering of biomass and biocatalysis may represent one of the most sustainable avenues for global engineering of atmospheric, soil, and water body compositions while strategically providing for society's needs.

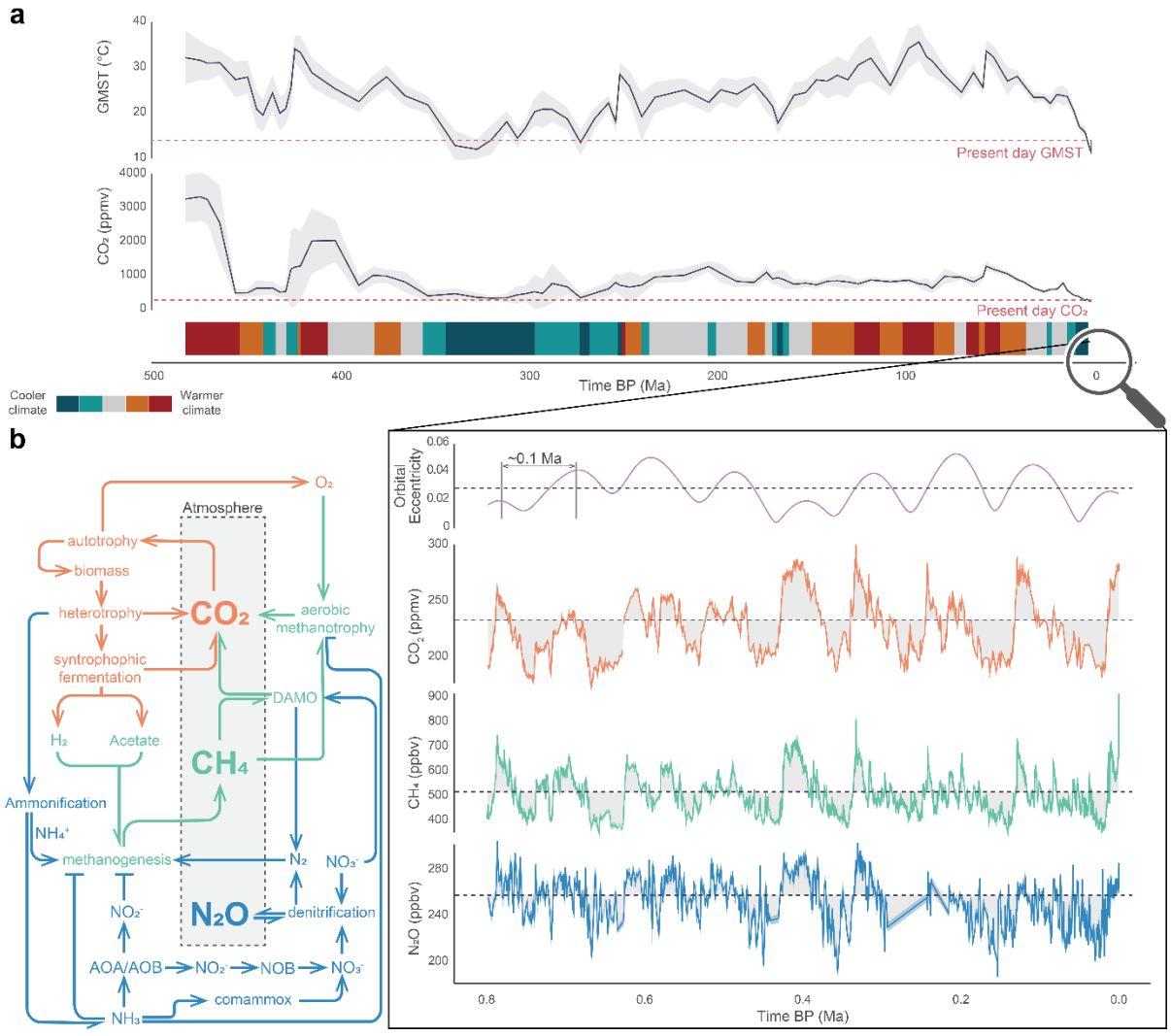

Figure 5 | Highlight of geological impact of biological systems on compositional dynamics of the atmosphere via the balanced interplay of interlinked biogeochemical cycles. **a** - Global mean surface temperature (GMST) together with corresponding CO_2 levels over the past 485 Ma. The coloured bar highlights qualitative climate conditions (from cooler to warmer). **b** - the profiles of Earth's elliptical orbit eccentricity profile alongside major biogenically-produced GHGs (CO_2, CH_4, N_2O) over

the 800 Ka history available from the Vostok and EPICA Dome C ice core records. Cycles in these gases (with a periodicity of ~100 Ka) are highlighted by the cartoon above, the medians are presented as dashed lines to convey a sense of the theoretical equilibria for these GHGs, the fluctuations about which are highlighted by the grey-shaded areas between the data and the median lines. The transparent shading around the data (coloured by gas), depicts the uncertainty range (±1 σ). **c** - are the biogeochemical cycles of these GHGs, emphasising the connections between them (coloured by gas, as in the chart). Where: DAMO - denitrifying anaerobic methane oxidation; AOA/AOB - ammonia-oxidising archaea/bacteria; NOB - nitrite-oxidising bacteria. Details on data sources can be found in **Discussion S7**.

Conclusions

The impact of biological systems on carbon cycling far exceeds that of any current or emerging manufactured CCS system. For example, shifting the balance of carbon exchange associated with natural systems by 0.1% would surpass the total annual impact of current engineered CCS successes to date. Biological processes offer dynamic and often scalable means of capturing carbon across ecosystems. These global processes can be leveraged to inform BCS strategies that enhance carbon capture while delivering ecosystem services, such as food, materials, and other bioproducts. As such, BCS strategies are well-positioned to be embedded in future strategies for food and water security, as well as ecosystem management.

A deeper understanding of how biosystems interact with carbon pools is therefore crucial for assessing the spatial and temporal dynamics of carbon cycling and informing carbon management interventions that are both effective and ecologically sound. In this context, evaluating the interactions between, and the relative impacts of, emerging BCS will be increasingly critical.

The carbon retention timescales of BCS are broad, from decades (as in ocean fertilisation or soil amendments) to millennia (as in peatland restoration and biomineralisation), which offer more permanence. In contrast, abiotic geological storage solutions, such as carbon injection into depleted hydrocarbon reservoirs and saline aquifers, provide near-indefinite sequestration[11] with lower biological interference, but are often energy-intensive and lack ecosystem co-benefits. Nevertheless, both current and future approaches may find their place as part of an integrated, multi-scale, and systems approach to carbon management adopted across diverse settings. However, the contrast between biological and abiotic sequestration pathways highlights a key consideration for integrated carbon management wherein biological processes are leveraged where short- to medium-term sequestration is needed, while ensuring permanent storage options are in place for long-term stability.

A sustainable carbon management framework will require advances in our understanding of biological dynamics, interfaces between biological systems as well as in our ability to monitor carbon transformations and co-emitted gases (CH_4 and N_2O) that reflect microbial activities and co-influence climate. This includes further investment in robust carbon accounting dynamics, improved costing frameworks, and a reduced reliance on uncertain models will be critical. Tailoring strategies for regionally specific settings is equally important, as the variability in “carbon-farming”

and certain other biogenic approaches has shown. Biotechnologies and the creation of circular economies certainly offer promising potential for carbon-based climate management. Nevertheless, large-scale biogeochemical interventions carry unprecedented scope, socioeconomic and ecological implications. The necessary degree of predictive control required for this to be done safely, therefore, requires that restraint, adaptability, and grounding in ongoing observation must be the cornerstones of any responsible carbon strategy. In this way, we can ensure that we are building toward a resilient, regenerative, and sustainable carbon management framework that supports both climate stability and continued ecosystem integrity into the future. Looking ahead, our ability to manage biosphere-atmosphere interactions may prove critical for long-term resilience, not only for climate mitigation, but also in buffering future climate perturbations.

Acknowledgements

The authors extend their gratitude to The Research and Innovation Center on 2D Nanomaterials (RIC2D), Center for Membranes and Advanced Water Technology (CMAT) and The Food Security and Technology Center, at Khalifa University, United Arab Emirates (UAE) as well as The Centers of Excellence for Oceans and Ocean Engineering at The National Taiwan Ocean University, Taiwan for providing support to this study. This work was supported financially by the Abu Dhabi Award for Research Excellence 2020 (ASPIRE Grant No. AARE20–289) and Faculty Start-Up Award (FSU-2022-021/8474000438).

Declaration of interests

We, the authors and our immediate family members, have no financial interests to declare.

References

1. Salehizadeh, H., Yan, N. & Farnood, R. Recent advances in microbial CO2 fixation and conversion to value-added products. *Chem. Eng. J.* **390**, 124584 (2020).

2. Anthropogenic and Natural Radiative Forcing. in *Climate Change 2013 – The Physical Science Basis* (ed. Intergovernmental Panel On Climate Change) 659–740 (Cambridge University Press, 2014). doi:10.1017/CBO9781107415324.018.

3. Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S. & Gilfillan, S. Carbon capture and storage at the end of a lost decade. *One Earth* **4**, 1569–1584 (2021).

4. Ian Tiseo. Global investment in carbon capture and storage 2018-2023. (2024).

5. Susanna Twidale. Global carbon removal market could reach $100 billion/yr from 2030-35, report says. (2024).

6. *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2023).

7. Ritchie, H. Sector by sector: where do global greenhouse gas emissions come from? *Our World Data* (2020).

8. Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I. & Vaughan, N. E. *The State of Carbon Dioxide Removal*. DOI 10.17605/OSF.IO/F85QJ (2024).

9. Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. (Cambridge University Press, Cambridge, 2022). doi:10.1017/9781009157940.

10. Shu, D. Y., Deutz, S., Winter, B. A., Baumgärtner, N., Leenders, L. & Bardow, A. The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment. *Renew. Sustain. Energy Rev.* **178**, 113246 (2023).

11. Ajayi, T., Gomes, J. S. & Bera, A. A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. *Pet. Sci.* **16**, 1028–1063 (2019).

12. Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Arneth, A., Arora, V., Bates, N. R., Becker, M., Bellouin, N., Berghoff, C. F., Bittig, H. C., Bopp, L., Cadule, P., Campbell, K., Chamberlain, M. A., Chandra, N., Chevallier, F., Chini, L. P., Colligan, T., Decayeux, J., Djeutchouang, L. M., Dou, X., Duran Rojas, C., Enyo, K., Evans, W., Fay, A. R., Feely, R. A., Ford, D. J., Foster, A., Gasser, T., Gehlen, M., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Hurtt, G. C., Iida, Y., Ilyina, T., Jacobson, A. R., Jain, A. K., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Kato, E., Keeling, R. F., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Lan, X., Lauvset, S. K., Lefèvre, N., Liu, Z., Liu, J., Ma, L., Maksyutov, S., Marland, G., Mayot, N., McGuire, P. C., Metzl, N., Monacci, N. M., Morgan, E. J., Nakaoka, S.-I., Neill, C., Niwa, Y., Nützel, T., Olivier, L., Ono, T., Palmer, P. I., Pierrot, D., Qin, Z., Resplandy, L., Roobaert, A., Rosan, T. M., Rödenbeck, C., Schwinger, J., Smallman, T. L., Smith, S. M., Sospedra-Alfonso, R., Steinhoff, T., Sun, Q., Sutton, A. J., Séférian, R., Takao, S., Tatebe, H., Tian, H., Tilbrook, B., Torres, O., Tourigny, E., Tsujino, H., Tubiello, F., van der Werf, G., Wanninkhof, R., Wang, X., Yang, D., Yang, X., Yu, Z., Yuan, W., Yue, X., Zaehle, S., Zeng, N. & Zeng, J. Global Carbon Budget 2024. *Earth Syst. Sci. Data* **17**, 965–1039 (2025).

13. Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A.,

Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K. W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I. & Papale, D. Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Science* **329**, 834–838 (2010).

14. Lal, R. Carbon sequestration. *Philos. Trans. R. Soc. B Biol. Sci.* **363**, 815–830 (2007).

15. Alivand, M. S., Mazaheri, O., Wu, Y., Stevens, G. W., Scholes, C. A. & Mumford, K. A. Catalytic Solvent Regeneration for Energy-Efficient CO2 Capture. *ACS Sustain. Chem. Eng.* **8**, 18755–18788 (2020).

16. Saenz Cavazos, P. A., Hunter-Sellars, E., Iacomi, P., McIntyre, S. R., Danaci, D. & Williams, D. R. Evaluating solid sorbents for CO2 capture: linking material properties and process efficiency via adsorption performance. *Front. Energy Res.* **11**, (2023).

17. Tabbi Wilberforce a, Ahmad Baroutaji b, Bassel Soudan e, Abdul Hai Al-Alami c, Abdul Ghani Olabi c d. Outlook of carbon capture technology and challenges. *Sci. Total Environ.* **657**, 56–72 (2019).

18. Terlouw, T., Treyer, K., Bauer, C. & Mazzotti, M. Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources. *Environ. Sci. Technol.* **55**, 11397–11411 (2021).

19. Liu, E., Lu, X. & Wang, D. A Systematic Review of Carbon Capture, Utilization and Storage: Status, Progress and Challenges. *Energies* **16**, 2865 (2023).

20. Fentaw, J. W., Emadi, H., Hussain, A., Fernandez, D. M. & Thiyagarajan, S. R. Geochemistry in Geological CO2 Sequestration: A Comprehensive Review. *Energies* **17**, 5000 (2024).

21. Global CCS Institute. *The Global Status of CCS: 2023*. https://www.globalccsinstitute.com/wp-content/uploads/2024/01/Global-Status-of-CCS-Report-1.pdf (2024).

22. The Paris Agreement | UNFCCC. https://unfccc.int/process-and-meetings/the-paris-agreement?form=MG0AV3.

23. Zhou, T., Hou, Y., Yang, Z., Laffitte, B., Luo, K., Luo, X., Liao, D. & Tang, X. Reducing spatial resolution increased net primary productivity prediction of terrestrial ecosystems: A Random Forest approach. *Sci. Total Environ.* **897**, 165134 (2023).

24. Keppler, L., Landschützer, P., Gruber, N., Lauvset, S. K. & Stemmler, I. Seasonal Carbon Dynamics in the Near-Global Ocean. *Glob. Biogeochem. Cycles* **34**, e2020GB006571 (2020).

25. Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P. & White, J. W. C. Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature* **488**, 70–72 (2012).

26. Grigoratou, M., Monteiro, F., Wilson, J., Ridgwell, A. & Schmidt, D. Exploring the impact of climate change on the global distribution of non-spinose planktonic foraminifera using a trait-based ecosystem model. *Glob. Change Biol.* **28**, 1063–1076 (2021).

27. Meyer, J. & Riebesell, U. Reviews and Syntheses: Responses of coccolithophores to ocean acidification: a meta-analysis. *Biogeosciences* **12**, 1671–1682 (2015).

28. Batool, M., Cihacek, L. J. & Alghamdi, R. S. Soil Inorganic Carbon Formation and the Sequestration of Secondary Carbonates in Global Carbon Pools: A Review. *Soil Syst.* **8**, 15 (2024).

29. Köchy, M., Hiederer, R. & Freibauer, A. Global distribution of soil organic carbon – Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. *SOIL* **1**, 351–365 (2015).

30. Lal, R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* **304**, 1623–7 (2004).

31. Pan, J., Wang, J., Tian, D., Zhang, R., Li, Y., Song, L., Yang, J., Wei, C. & Niu, S. Biotic factors dominantly determine soil inorganic carbon stock across Tibetan alpine grasslands. *SOIL* https://doi.org/10.5194/soil-8-687-2022 (2022) doi:10.5194/soil-8-687-2022.

32. Zeng, X., Bastida, F., Plaza, C., Zhou, G., Vera, A., Liu, Y. & Delgado-Baquerizo, M. The Contribution of Biotic Factors in Explaining the Global Distribution of Inorganic Carbon in Surface Soils. *Glob. Biogeochem. Cycles* **37**, (2023).

33. Bar-On, Y. M., Phillips, R. & Milo, R. The biomass distribution on Earth. *Proc. Natl. Acad. Sci.* **115**, 6506–6511 (2018).

34. Ximenes, F. A., Björdal, C., Kathuria, A., Barlaz, M. A. & Cowie, A. L. Improving understanding of carbon storage in wood in landfills: Evidence from reactor studies. *Waste Manag.* **85**, 341–350 (2019).

35. Folino, A., Karageorgiou, A., Calabrò, P. S. & Komilis, D. Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review. *Sustainability* **12**, (2020).

36. Platnieks, O., Barkane, A., Ijudina, N., Gaidukova, G., Thakur, V. K. & Gaidukovs, S. Sustainable tetra pak recycled cellulose / Poly(Butylene succinate) based woody-like composites for a circular economy. *J. Clean. Prod.* **270**, 122321 (2020).

37. Lorenz, K. & Lal, R. Soil organic carbon sequestration in agroforestry systems. A review. *Agron. Sustain. Dev.* **34**, 443–454 (2014).

38. Robinson, J., Popova, E. E., Yool, A., Srokosz, M., Lampitt, R. S. & Blundell, J. R. How deep is deep enough? Ocean iron fertilization and carbon sequestration in the Southern Ocean. *Geophys. Res. Lett.* **41**, 2489–2495 (2014).

39. Siegel, D. A., DeVries, T., Doney, S. C. & Bell, T. Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environ. Res. Lett.* **16**, 104003 (2021).

40. Nave, L. E., Walters, B. F., Hofmeister, K. L., Perry, C. H., Mishra, U., Domke, G. M. & Swanston, C. W. The role of reforestation in carbon sequestration. *New For.* **50**, 115–137 (2019).

41. Wang, J., Xiong, Z. & Kuzyakov, Y. Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy* **8**, 512–523 (2016).

42. Bachu, S., Gunter, W. D. & Perkins, E. H. Aquifer disposal of CO2: Hydrodynamic and mineral trapping. *Energy Convers. Manag.* **35**, 269–279 (1994).

43. Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., Scott, V., Gilfillan, S. M. V., Ogaya, X. & Haszeldine, R. S. Estimating geological CO2 storage security to deliver on climate mitigation. *Nat. Commun.* **9**, 2201 (2018).

44. Cailleau, G., Braissant, O. & Verrecchia, E. P. Biomineralization in plants as a long-term carbon sink. *Naturwissenschaften* **91**, 191–194 (2004).

45. Butnar, I., Lynch, J., Vetter, S., Gamaralalage, D., Tang, Y., McKechnie, J., Foteinis, S., Rodway-Dyer, S., Röder, M., Sogbesan, S., Hastings, A., Renforth, P., Brander, M. & House, J. A Review of Life Cycle Assessment Methods to Inform the Scale-Up of Carbon Dioxide Removal Interventions. *WIREs Energy Environ.* **13**, e540 (2024).

46. Duval-Dachary, S., Lorne, D., Batôt, G. & Hélias, A. Facilitating dynamic life cycle assessment for climate change mitigation. *Sustain. Prod. Consum.* **51**, 159–168 (2024).

47. CHERUBINI, F., PETERS, G. P., BERNTSEN, T., STRØMMAN, A. H. & HERTWICH, E. CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy* **3**, 413–426 (2011).

48. Guest, G., Cherubini, F. & Strømman, A. H. Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life. *J. Ind. Ecol.* **17**, 20–30 (2013).

49. von der Assen, N., Jung, J. & Bardow, A. Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. *Energy Environ. Sci.* **6**, 2721–2734 (2013).

50. Müller, L. J., Kätelhön, A., Bachmann, M., Zimmermann, A., Sternberg, A. & Bardow, A. A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. *Front. Energy Res.* **Volume 8-2020**, (2020).

51. Braun, A., Spona-Friedl, M., Avramov, M., Elsner, M., Baltar, F., Reinthaler, T., Herndl, G. J. & Griebler, C. Reviews and syntheses: Heterotrophic fixation of inorganic carbon – significant but invisible flux in environmental carbon cycling. *Biogeosciences* **18**, 3689–3700 (2021).

52. Jansson, C. & Northen, T. R. Calcifying cyanobacteria–the potential of biomineralization for carbon capture and storage. *Curr. Opin. Biotechnol.* **21 3**, 365–71 (2010).

53. Atwood, T. B., Witt, A., Mayorga, J., Hammill, E. & Sala, E. Global Patterns in Marine Sediment Carbon Stocks. *Front. Mar. Sci.* **7**, (2020).

54. House, K. Z., Schrag, D. P., Harvey, C. F. & Lackner, K. S. Permanent carbon dioxide storage in deep-sea sediments. *Proc. Natl. Acad. Sci.* **103**, 12291–12295 (2006).

55. Kheshgi, H. S. Ocean carbon sink duration under stabilization of atmospheric CO2: A 1,000-year timescale. *Geophys. Res. Lett.* **31**, (2004).

56. Keppler, L., Landschützer, P., Lauvset, S. K. & Gruber, N. Recent Trends and Variability in the Oceanic Storage of Dissolved Inorganic Carbon. *Glob. Biogeochem. Cycles* **37**, e2022GB007677 (2023).

57. Majkut, J. D., Sarmiento, J. L. & Rodgers, K. B. A growing oceanic carbon uptake: Results from an inversion study of surface pCO2 data. *Glob. Biogeochem. Cycles* **28**, 335–351 (2014).

58. Kennedy, H., Beggins, J., Duarte, C. M., Fourqurean, J. W., Holmer, M., Marbà, N. & Middelburg, J. J. Seagrass sediments as a global carbon sink: Isotopic constraints. *Glob. Biogeochem. Cycles* **24**, 2010GB003848 (2010).

59. Boye, K., Noel, V., Tfaily, M., Bone, S., Williams, K., Bargar, J. & Fendorf, S. Thermodynamically controlled preservation of organic carbon in floodplains. *Nat. Geosci.* **10**, 415–419 (2017).

60. Trevathan-Tackett, S., Seymour, J., Nielsen, D., Macreadie, P., Jeffries, T., Sanderman, J., Baldock, J., Howes, J., Steven, A. & Ralph, P. Sediment anoxia limits microbial-driven seagrass carbon remineralization under warming conditions. *FEMS Microbiol. Ecol.* **93**, (2017).

61. Jiao, N., Herndl, G. J., Hansell, D. A., Benner, R., Kattner, G., Wilhelm, S. W., Kirchman, D. L., Weinbauer, M. G., Luo, T., Chen, F. & Azam, F. Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nat. Rev. Microbiol.* **8**, 593–599 (2010).

62. Basterretxea, G., Font-Muñoz, J., Hernández-Carrasco, I. & Sañudo-Wilhelmy, S. Global variability of high-nutrient low-chlorophyll regions using neural networks and wavelet coherence analysis. *Ocean Sci.* **19**, 973–990 (2023).

63. Markels, M. Sequestration of CO2 by Ocean Fertilization. (2001).

64. Hutchins, D. A. & Fu, F. Microorganisms and ocean global change. *Nat. Microbiol.* **2**, 17058 (2017).

65. Feng, E. Y., Koeve, W., Keller, D. P. & Oschlies, A. Model-Based Assessment of the CO2 Sequestration Potential of Coastal Ocean Alkalinization. *Earths Future* **5**, 1252–1266 (2017).

66. Renforth, P. & Kruger, T. Coupling Mineral Carbonation and Ocean Liming. *Energy Fuels* **27**, 4199–4207 (2013).

67. Krause-Jensen, D. & Duarte, C. M. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* **9**, 737–742 (2016).

68. Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A., Kelleway, J. J., Kennedy, H., Kuwae, T., Lavery, P. S., Lovelock, C. E., Smale, D. A., Apostolaki, E. T., Atwood, T. B., Baldock, J., Bianchi, T. S., Chmura, G. L., Eyre, B. D., Fourqurean, J. W., Hall-Spencer, J. M., Huxham, M., Hendriks, I. E., Krause-Jensen, D., Laffoley, D., Luisetti, T., Marbà, N., Masque, P., McGlathery, K. J., Megonigal, J. P., Murdiyarso, D., Russell, B. D., Santos, R., Serrano, O., Silliman, B. R., Watanabe, K. & Duarte, C. M. The future of Blue Carbon science. *Nat. Commun.* **10**, 3998 (2019).

69. Li, Y., Horsman, M., Wu, N., Lan, C. Q. & Dubois-Calero, N. Biofuels from Microalgae. *Biotechnol. Prog.* **24**, 815–820 (2008).

70. Sanaye Mozaffari Sabet, N. & Golzary, A. CO2 biofixation at microalgae photobioreactors: hydrodynamics and mass transfer study. *Int. J. Environ. Sci. Technol.* **19**, 11631–11648 (2022).

71. San Pedro, A., González-López, C. V., Acién, F. G. & Molina-Grima, E. Marine microalgae selection and culture conditions optimization for biodiesel production. *Bioresour. Technol.* **134**, 353–361 (2013).

72. Middelburg, J. J. Chemoautotrophy in the ocean. *Geophys. Res. Lett.* **38**, (2011).

73. Mcleod, E. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Front Ecol Env.* **7**, 362–370 (2011).

74. Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I. & Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **3**, 961–968 (2013).

75. Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., Pidgeon, E. & Simpson, S. Clarifying the role of coastal and marine systems in climate mitigation. *Front. Ecol. Environ.* **15**, 42–50 (2017).

76. Barbier, E., Hacker, S. & Kennedy, C. The value of estuarine and coastal ecosystem services. *Ecol. Ldots* **81**, 169–193 (2011).

77. Bridgham, S. D., Megonigal, J. P., Keller, J. K., Bliss, N. B. & Trettin, C. The carbon balance of North American wetlands. *Wetlands* **26**, 889–916 (2006).

78. Poffenbarger, H. J., Needelman, B. A. & Megonigal, J. P. Salinity Influence on Methane Emissions from Tidal Marshes. *Wetlands* **31**, 831–842 (2011).

79. Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B. & Cahoon, D. R. Responses of Coastal Wetlands to Rising Sea Level. *Ecology* **83**, 2869–2877 (2002).

80. Greiner, J. T., McGlathery, K. J., Gunnell, J. & McKee, B. A. Seagrass Restoration Enhances “Blue Carbon” Sequestration in Coastal Waters. *PLOS ONE* **8**, e72469 (2013).

81. Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., Apostolaki, E. T., Kendrick, G. A., Krause-Jensen, D., McGlathery, K. J. & Serrano, O. Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* **5**, 505–509 (2012).

82. Crossland, C. J., Hatcher, B. G. & Smith, S. V. Role of coral reefs in global ocean production. *Coral Reefs* **10**, 55–64 (1991).

83. Ware, J. R., Smith, S. V. & Reaka-Kudla, M. L. Coral reefs: sources or sinks of atmospheric CO2? *Coral Reefs* **11**, 127–130 (1992).

84. Lane, C. R. & D’Amico, E. Identification of Putative Geographically Isolated Wetlands of the Conterminous United States. *JAWRA J. Am. Water Resour. Assoc.* **52**, 705–722 (2016).

85. Nahlik, A. M. & Fennessy, M. S. Carbon storage in US wetlands. *Nat. Commun.* **7**, 13835 (2016).

86. Villa, J. A. & Bernal, B. Carbon sequestration in wetlands, from science to practice: An overview of the biogeochemical process, measurement methods, and policy framework. *Ecol. Eng.* **114**, 115–128 (2018).

87. Kayranli, B., Scholz, M., Mustafa, A. & Hedmark, Å. Carbon Storage and Fluxes within Freshwater Wetlands: a Critical Review. *Wetlands* **30**, 111–124 (2010).

88. Mitra, S., Wassmann, R. & Vlek, P. L. G. An appraisal of global wetland area and its organic carbon stock. *Curr. Sci.* **88**, 25–35 (2005).

89. Ezcurra, P., Ezcurra, E., Garcillán, P., Costa, M. T. & Aburto-Oropeza, O. Coastal landforms and accumulation of mangrove peat increase carbon sequestration and storage. **113**, 4404–4409 (2016).

90. Kurnianto, S., Warren, M., Talbot, J., Kauffman, B., Murdiyarso, D. & Frolking, S. Carbon accumulation of tropical peatlands over millennia: a modeling approach. *Glob. Change Biol.* **21**, 431–444 (2015).

91. Davidson, N. C., Fluet-Chouinard, E. & Finlayson, C. M. Global extent and distribution of wetlands: trends and issues. *Mar. Freshw. Res.* **69**, 620–627 (2018).

92. Lamers, L., Vile, M., Grootjans, A. P., Acreman, M., Diggelen, R., Evans, M., Richardson, C., Rochefort, L., Kooijman, A., Roelofs, J. & Smolders, A. Ecological restoration of rich fens in Europe and North America: From trial and error to an evidence-based approach. *Biol. Rev.* **90**, (2014).

93. Hinojosa-Huerta, O., Briggs, M., Carrillo-Guerrero, Y., Glenn, E. P., Lara-Flores, M. & Román-Rodríguez, M. Community-Based Restoration of Desert Wetlands: The Case of the Colorado River Delta. (2005).

94. Gayathri, R., Mahboob, S., Govindarajan, M., Al-Ghanim, K. A., Ahmed, Z., Al-Mulhm, N., Vodovnik, M. & Vijayalakshmi, S. A review on biological carbon sequestration: A sustainable solution for a cleaner air environment, less pollution and lower health risks. *J. King Saud Univ. - Sci.* **33**, 101282 (2021).

95. Olsson, L., Ye, S., Yu, X., Wei, M., Krauss, K. W. & Brix, H. Factors influencing CO_2 and CH_4 emissions from coastal wetlands in the Liaohe Delta, Northeast China. *Biogeosciences* **12**, 4965–4977 (2015).

96. Alongi, D. Global Significance of Mangrove Blue Carbon in Climate Change Mitigation. *Sci* **2**, 67 (2020).

97. Lin, C.-W., Kao, Y.-C., Chou, M.-C., Wu, H.-H., Ho, C.-W. & Lin, H.-J. Methane Emissions from Subtropical and Tropical Mangrove Ecosystems in Taiwan. *Forests* **11**, (2020).

98. Mahmudi, M., Musa, M., Bunga, A., Wati, N. A., Arsad, S. & Lusiana, E. A Water Quality Evaluation of Integrated Mangrove Aquaculture System for Water Treatment in Super-Intensive White Leg Shrimp Pond. *J. Ecol. Eng.* https://doi.org/10.12911/22998993/146746 (2022) doi:10.12911/22998993/146746.

99. Venkatachalam, S., Kandasamy, K., Krishnamoorthy, I. & Narayanasamy, R. Survival and growth of fish (Lates calcarifer) under integrated mangrove-aquaculture and open-aquaculture systems. *Aquac. Rep.* **9**, 18–24 (2018).

100. Lal, R. Carbon sequestration. *Philos. Trans. R. Soc. B Biol. Sci.* **363**, 815–830 (2007).

101. Scholes, R. J. & Noble, I. R. Storing Carbon on Land. *Science* **294**, 1012–1013 (2001).

102. Konings, A. G., Bloom, A. A., Liu, J., Parazoo, N. C., Schimel, D. S. & Bowman, K. W. Global satellite-driven estimates of heterotrophic respiration. *Biogeosciences* **16**, 2269–2284 (2019).

103. Warner, D. L., Bond-Lamberty, B., Jian, J., Stell, E. & Vargas, R. Spatial Predictions and Associated Uncertainty of Annual Soil Respiration at the Global Scale. *Glob. Biogeochem. Cycles* **33**, 1733–1745 (2019).

104. He, Y., Ding, J., Dorji, T., Wang, T., Li, J. & Smith, P. Observation-based global soil heterotrophic respiration indicates underestimated turnover and sequestration of soil carbon by terrestrial ecosystem models. *Glob. Change Biol.* **28**, 5547–5559 (2022).

105. Change in soil carbon following afforestation. *For. Ecol. Manag.* **168**, 241–257 (2002).

106. Follett, R. F. & Schuman, G. E. Grazing land contributions to carbon sequestration. in *Grassland: a global resource* 265–277 (Wageningen Academic, 2005). doi:10.3920/9789086865512_021.

107. Shi, S., Han, P., Zhang, P., Ding, F. & Ma, C. The Impact of Afforestation on Soil Organic Carbon Sequestration on the Qinghai Plateau, China. *PLOS ONE* **10**, 1–18 (2015).

108. Don, A., Schumacher, J. & Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Glob. Change Biol.* **17**, 1658–1670 (2011).

109. Conant, R. T., Ogle, S. M., Paul, E. A. & Paustian, K. Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. *Front. Ecol. Environ.* **9**, 169–173 (2011).

110. Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L. & Grace, P. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **187**, 87–105 (2014).

111. Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., Van Gestel, N., Six, J., Venterea, R. T. & Van Kessel, C. Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365–368 (2015).

112. Liang, C., Schimel, J. P. & Jastrow, J. D. The importance of anabolism in microbial control over soil carbon storage. *Nat. Microbiol.* **2**, 1–6 (2017).

113. Ferri, D., Montemurro, F., Debiase, G., Fiore, A., Convertini, G. & Mastrangelo, M. Application of organic amendments to improve land utilization system of fodder crops. *Fresenius Environ. Bull.* **19**, 1768–1773 (2010).

114. Nan, H., Yin, J., Yang, F., Luo, Y., Zhao, L. & Cao, X. Pyrolysis temperature-dependent carbon retention and stability of biochar with participation of calcium: Implications to carbon sequestration. *Environ. Pollut.* **287**, 117566 (2021).

115. Sun, X., Atiyeh, H. K., Li, M. & Chen, Y. Biochar facilitated bioprocessing and biorefinery for productions of biofuel and chemicals: A review. *Bioresour. Technol.* **295**, 122252 (2020).

116. Buckeridge, K. M., Mason, K. E., McNamara, N. P., Ostle, N., Puissant, J., Goodall, T., Griffiths, R. I., Stott, A. W. & Whitaker, J. Environmental and microbial controls on microbial necromass recycling, an important precursor for soil carbon stabilization. *Commun. Earth Environ.* **1**, 1–9 (2020).

117. King, G. M. Enhancing soil carbon storage for carbon remediation: potential contributions and constraints by microbes. *Trends Microbiol.* **19**, 75–84 (2011).

118. Vishwakarma, K., Kumar, N., Shandilya, C., Mohapatra, S., Bhayana, S. & Varma, A. Revisiting Plant–Microbe Interactions and Microbial Consortia Application for Enhancing Sustainable Agriculture: A Review. *Front. Microbiol.* **11**, (2020).

119. Debiec-Andrzejewska, K., Krucon, T., Piatkowska, K. & Drewniak, L. Enhancing the plants growth and arsenic uptake from soil using arsenite-oxidizing bacteria. *Environ. Pollut.* **264**, 114692 (2020).

120. Hu, G., Li, Y., Ye, C., Liu, L. & Chen, X. Engineering Microorganisms for Enhanced CO2 Sequestration. *Trends Biotechnol.* **37**, 532–547 (2019).

121. Alshalif, A. F., Irwan, J. M., Othman, N., Al-Gheethi, A. A., Shamsudin, S. & Nasser, I. M. Optimisation of carbon dioxide sequestration into bio-foamed concrete bricks pores using *Bacillus tequilensis*. *J. CO2 Util.* **44**, 101412 (2021).

122. Six, J., Frey, S. D., Thiet, R. K. & Batten, K. M. Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems. *Soil Sci. Soc. Am. J.* **70**, 555–569 (2006).

123. Soares, M. & Rousk, J. Microbial growth and carbon use efficiency in soil: Links to fungal-bacterial dominance, SOC-quality and stoichiometry. *Soil Biol. Biochem.* **131**, 195–205 (2019).

124. Jiao, J.-Y., Fu, L., Hua, Z.-S., Liu, L., Salam, N., Liu, P.-F., Lv, A.-P., Wu, G., Xian, W.-D., Zhu, Q., Zhou, E.-M., Fang, B.-Z., Oren, A., Hedlund, B. P., Jiang, H.-C., Knight, R., Cheng, L. & Li, W.-J. Insight into the function and evolution of the Wood–Ljungdahl pathway in Actinobacteria. *ISME J.* **15**, 3005–3018 (2021).

125. Mason, A. R. G., Salomon, M. J., Lowe, A. J. & Cavagnaro, T. R. Microbial solutions to soil carbon sequestration. *J. Clean. Prod.* **417**, 137993 (2023).

126. Syed, S., Buddolla, V. & Lian, B. Oxalate Carbonate Pathway—Conversion and Fixation of Soil Carbon—A Potential Scenario for Sustainability. *Front. Plant Sci.* **Volume 11-2020**, (2020).

127. Dranseike, D., Cui, Y., Ling, A. S., Donat, F., Bernhard, S., Bernero, M., Areeckal, A., Lazic, M., Qin, X.-H., Oakey, J. S., Dillenburger, B., Studart, A. R. & Tibbitt, M. W. Dual carbon sequestration with photosynthetic living materials. *Nat. Commun.* **16**, 3832 (2025).

128. Tao, F., Huang, Y., Hungate, B. A., Manzoni, S., Frey, S. D., Schmidt, M. W. I., Reichstein, M., Carvalhais, N., Ciais, P., Jiang, L., Lehmann, J., Wang, Y.-P., Houlton, B. Z., Ahrens, B., Mishra, U., Hugelius, G., Hocking, T. D., Lu, X., Shi, Z., Viatkin, K., Vargas, R., Yigini, Y., Omuto, C., Malik, A. A., Peralta, G., Cuevas-Corona, R., Di Paolo, L. E., Luotto, I., Liao, C., Liang, Y.-S., Saynes, V. S., Huang, X. & Luo, Y. Microbial carbon use efficiency promotes global soil carbon storage. *Nature* **618**, 981–985 (2023).

129. Doetterl, S., Berhe, A. A., Arnold, C., Bodé, S., Fiener, P., Finke, P., Fuchslueger, L., Griepentrog, M., Harden, J. W., Nadeu, E., Schnecker, J., Six, J., Trumbore, S., Van Oost, K., Vogel, C. & Boeckx, P. Links among warming, carbon and microbial dynamics mediated by soil mineral weathering. *Nat. Geosci.* **11**, 589–593 (2018).

130. El-Naggar, A. H., Usman, A. R. A., Al-Omran, A., Ok, Y. S., Ahmad, M. & Al-Wabel, M. I. Carbon mineralization and nutrient availability in calcareous sandy soils amended with woody waste biochar. *Chemosphere* **138**, 67–73 (2015).

131. El-Naggar, A., Lee, S. S., Awad, Y. M., Yang, X., Ryu, C., Rizwan, M., Rinklebe, J., Tsang, D. C. W. & Ok, Y. S. Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. *Geoderma* **332**, 100–108 (2018).

132. Cao, H., Gao, G., Zhang, Y., Guo, M., Ren, Y. & Ding, G. Soil bacterial approach to assessing afforestation in the desertfied Northern China. *J. Clean. Prod.* **292**, 125935 (2021).

133. Hong, S., Yin, G., Piao, S., Dybzinski, R., Cong, N., Li, X., Wang, K., Peñuelas, J., Zeng, H. & Chen, A. Divergent responses of soil organic carbon to afforestation. *Nat. Sustain.* **3**, 694–700 (2020).

134. Ricciardi, L., D'Odorico, P., Galli, N., Chiarelli, D. D. & Rulli, M. C. Hydrological implications of large-scale afforestation in tropical biomes for climate change mitigation. *Philos. Trans. R. Soc. B Biol. Sci.* **377**, 20210391 (2022).

135. Catling, D. C. & Zahnle, K. J. The Archean atmosphere. *Sci. Adv.* **6**, eaax1420 (2020).

136. Fakhraee, M., Planavsky, N. J. & Reinhard, C. T. The role of environmental factors in the long-term evolution of the marine biological pump. *Nat. Geosci.* **13**, 812–816 (2020).

137. Freire-Zapata, V., Holland-Moritz, H., Cronin, D. R., Aroney, S., Smith, D. A., Wilson, R. M., Ernakovich, J. G., Woodcroft, B. J., Bagby, S. C., Hodgkins, S. B., Mondav, R., E. Cross, J., Fahnestock, M. F., Ferriere, R., Ibba, M., Saleska, S. R., Varner, R. K., Zayed, A. A., Rich, V. I., Sullivan, M. B., Stegen, J. C., Tfaily, M. M., Emerge Field Team & Emerge Biology Integration Coordinators. Microbiome–metabolite linkages drive greenhouse gas dynamics over a permafrost thaw gradient. *Nat. Microbiol.* **9**, 2892–2908 (2024).

138. Sánchez-Baracaldo, P. & Cardona, T. On the origin of oxygenic photosynthesis and Cyanobacteria. *New Phytol.* **225**, 1440–1446 (2020).

139. Judd, E. J., Tierney, J. E., Lunt, D. J., Montañez, I. P., Huber, B. T., Wing, S. L. & Valdes, P. J. A 485-million-year history of Earth's surface temperature. *Science* **385**, eadk3705.

140. Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.-M., Raynaud, D., Stocker, T. F. & Chappellaz, J. Orbital and millennial-scale features of atmospheric CH4 over the past 800,000 years. *Nature* **453**, 383–386 (2008).

141. Schilt, A., Baumgartner, M., Blunier, T., Schwander, J., Spahni, R., Fischer, H. & Stocker, T. F. Glacial–interglacial and millennial-scale variations in the atmospheric nitrous oxide concentration during the last 800,000 years. *Clim. Last Million Years New Insights EPICA Rec.* **29**, 182–192 (2010).

142. Barker, S., Lisiecki, L. E., Knorr, G., Nuber, S. & Tzedakis, P. C. Distinct roles for precession, obliquity, and eccentricity in Pleistocene 100-kyr glacial cycles. *Science* **387**, eadp3491 (2025).

143. Stein, L. Y. & Lidstrom, M. E. Greenhouse gas mitigation requires caution. *Science* **384**, 1068–1069 (2024).

144. Jansson, J. K., McClure, R. & Egbert, R. G. Soil microbiome engineering for sustainability in a changing environment. *Nat. Biotechnol.* **41**, 1716–1728 (2023).

145. Roth, F., Broman, E., Sun, X., Bonaglia, S., Nascimento, F., Prytherch, J., Brüchert, V., Lundevall Zara, M., Brunberg, M., Geibel, M. C., Humborg, C. & Norkko, A. Methane emissions offset atmospheric carbon dioxide uptake in coastal macroalgae, mixed vegetation and sediment ecosystems. *Nat. Commun.* **14**, 42 (2023).

146. Ameray, A., Bergeron, Y. & Cavard, X. Modelling the potential of forest management to mitigate climate change in Eastern Canadian forests. *Sci. Rep.* **13**, 14506 (2023).

147. Yu, Q., He, C., Anthony, M. A., Schmid, B., Gessler, A., Yang, C., Zhang, D., Ni, X., Feng, Y., Zhu, J., Zhu, B., Wang, S., Ji, C., Tang, Z., Wu, J., Smith, P., Liu, L., Li, M.-H., Schaub, M. & Fang, J. Decoupled responses of plants and soil biota to global change across the world's land ecosystems. *Nat. Commun.* **15**, 10369 (2024).

Supplementary Information

Biological Dynamics for Sustainable Carbon Sequestration

Shahna M. Vakeri[1,2,3], Sami Souissi[5,6,7], Erlantz L. Fernandez[8,9], James MWR. McElhinney[2,3,10]* & Blaise L. Tardy[1,2,3,4]*

1: Research and Innovation Center on CO_2 and Hydrogen, Khalifa University, Abu Dhabi, United Arab Emirates
2: Center for Membrane and Advanced Water Technology, Khalifa University, Abu Dhabi, United Arab Emirates
3: Department of Chemical Engineering, Khalifa University, United Arab Emirates
4: Food Security and Technology Center, Khalifa University, Abu Dhabi, United Arab Emirates
5: Univ. Lille, CNRS, ULCO, IRD, UMR-8187 LOG, F-59000 Lille, France
6: Center of Excellence for Ocean Engineering, National Taiwan Ocean University, Keelung 20224, Taiwan
7: Center of Excellence for the Oceans, National Taiwan Ocean University, Keelung 20224, Taiwan
8: Life Cycle Thinking Group, Department of Graphic Design and Engineering Projects, University of the Basque Country (UPV/EHU), Plaza Ingeniero Torres Quevedo 1, Bilbao, Biscay 48013, Spain
9: BC Materials, Basque Center for Materials, Applications and Nanostructures, Edif. MartinaCasiano, Pl. 3 Parque Científico UPV/EHU, Barrio Sarriena, Leioa, Biscay 48940, Spain
10: Department of Biomedical Engineering, Khalifa University, Abu Dhabi, United Arab Emirates

Corresponding authors: james.mcelhinney@ku.ac.ae and blaise.tardy@ku.ac.ae

Keywords: Carbon sequestration; Microbial carbon cycling; Biogeochemical cycles Climate change mitigation; Soil carbon storage; Blue carbon ecosystems; Carbon storage lifetimes; Ecosystem services; Biological carbon pump; Nature-based climate solutions

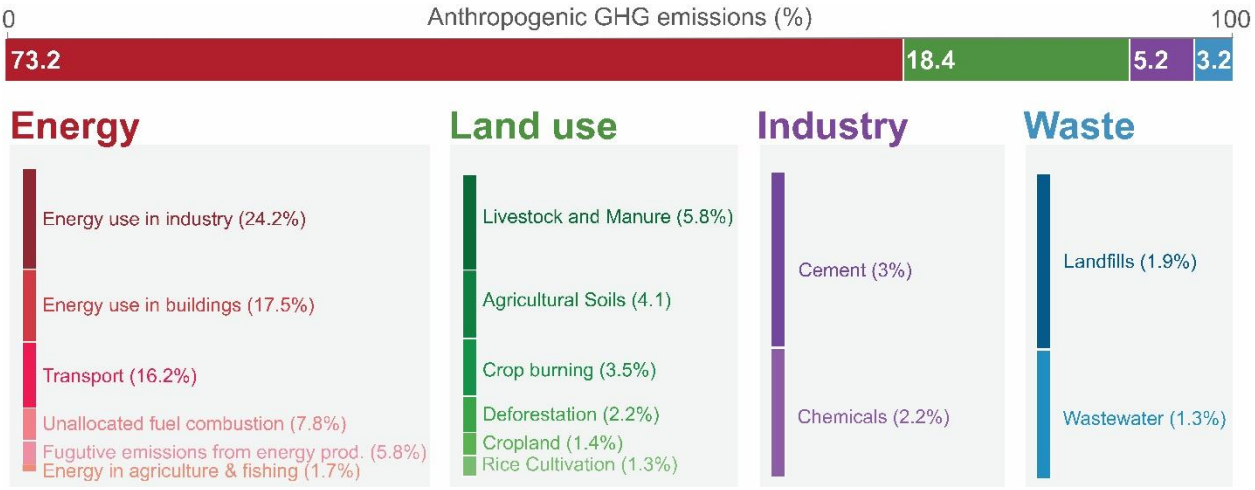

Figure S1 | Major landmarks of the global carbon (C) cycle and opportunities for intervention Summary overview of anthropogenic emissions by sector (as of 2021) as a percentage of the total anthropogenic release. The major subgroups within each sector are presented in the same colour series as normalised bars (with percentages reflecting the associated emissions of the total, such that the subgroup total equates to the value given for the sector). Sector GHG emissions data was taken from[1].

Discussion S1. Carbon costing

Carbon costing is necessary to ensure that selected management practices deliver genuine net benefits by balancing sequestration effectiveness against economic and ecological impacts, thereby guiding policy decisions and management practices toward long-term sustainability. The distribution of costs across time (i.e., upfront, monitoring and maintenance costs) needs to be factored in, particularly when evaluating engineered versus nature-based solutions. Additionally, the discount rates, commonly used for carbon costing, steer policymaking and investments in CCS (with lower rates encouraging stronger regulatory action and prioritising long-term benefits). These discount rates thereby hold strong influence over comparative analyses of engineered (where short-term capture gains may be high) and nature-based (where payoffs may be delayed due to biological dependencies such as biomass growth) solutions. Importantly, carbon costing discounts are not trivial to calculate, are set somewhat arbitrarily and do not account for co-benefits (e.g., environmental) of the capture method. Indeed, small variations can significantly alter the results of cost-benefit analyses, and caution is therefore warranted in their use. Consequently, there is no clear consensus on where they should be set and the degree to which they should be implemented, though they are generally on an upward trend[2].

In any event, levelized costs of carbon capture are a critical determinant of scalability for CDR (S. Table 1). Levelized costs for oceanic sequestration approaches, for example, vary between 7-17K+ USD per tCO_2 mitigated (S. Table 1), which equates to 25.66B – 62.33T USD per Gt C captured (or 0.249T - 605T USD to mitigate the current annual production of 9.7 Gt in anthropogenic CO_2). As with most CDR approaches, current costs are prohibitively high for full scale-up, requiring reductions, in some cases by several orders of magnitude, to approach economic feasibility.

Standardized and effective guidelines for the measurement, monitoring, reporting and verification (MMRV) of CDR programs are still needed for accurate carbon accounting[3]. Universally accepted MMRV guidelines would enable a more holistic consideration of new CDR programs by accounting for unintentional ecological, socioeconomic, and ethical impacts. A key challenge in the construction of MMRV guidelines will be in balancing the costs of acquiring adequate field measurements (to avoid overdependency on predictive models, which may be based on an incomplete view of the CDR setting) whilst ensuring a favourable cost-benefit result.

Supplementary Table 1 | Carbon costing for a selection of biological and engineered CCS approaches

Technology	Costing (USD per tCO_2)	Sources
Direct Air Capture	80-1,133	[4]
Bioenergy with CCS	32-321	[5,6]
Industrial CCS	40-110	[7]
Enhanced weathering	60-200	[8]
Ocean fertilization	7-4,691	[9–11]
Biomass slurry fracture injection	~95	[12]
Kelp aquaculture CCS	1,257-17K	[13]
CCS for power plants	22-56	[14,15]
Biochar	30-139	[16]
Afforestation	220-1,165	[17,18]
Ocean alkalization	130–295	[19]

Discussion S2. Biologically-derived materials for a circular carbon economy

Nearly 106.1 Gt of processed material enter the global economy annually. Carbon constitutes an essential component of many of these materials (e.g. plastics), and its demand is expected to increase at a compound annual growth rate of 2.5%, rising from 0.55 Gt in 2020 (comprising 65% polymers and 35% organic chemicals), to 1.150 Gt in 2050[20]. As a result, modern materials are a relevant source of carbon emissions. However, these materials could become carbon sinks upon model transformation by providing long-term C storage and avoiding carbon-intensive production processes[21]. In this context, while full decarbonization is impractical due to the C-based nature of materials, defossilization strategies that aim to reduce atmospheric fossil-derived carbon (below-ground) levels by progressively phasing it out with alternative feedstocks are more viable. However, certain applications are expected to continue to rely on fossil-derived carbon until viable substitutes are available at scale. Prioritizing sectors where the substitution of fossil-derived carbon is technologically and economically feasible offers promising inroads to prevent the influx of fossil carbon into above-ground systems (atmosphere, technosphere, biosphere), thereby curtailing increases in atmospheric carbon[22].

Unlike most materials currently in use, which originate from fossil-derived carbon sourced from below ground and follow a linear extraction-processing-utilization-waste model, biologically-derived materials contain renewable biogenic carbon that, when kept in use within the technosphere, avoids its release into the atmosphere. Fostering biological material utilization follows the IPCC recommendations and reduces the need for complex carbon capture and storage systems[23]. Wood (and derivatives like cellulose and lignin), chitin and silk are the most representative example of materials containing biogenic carbon. For every kilogram of embedded carbon in these materials, 3.66 kg of CO_2 are prevented from being released into the atmosphere (considering CO_2 and C molecular weight as 44 and 12 $g \cdot mol^{-1}$, respectively)[24]. As biologically-sourced materials typically contain between 36-64 wt% C (depending on species and processing), 1 kg of these materials locks up between 1.30 and 2.33 kg

CO_2 equivalents, providing potential for carbon sequestration in long-term applications[25]. Furthermore, impressive functionalities can be obtained from woody materials, enabling the replacement of existing non-renewable materials in high-tech applications as well[26].

As biologically-derived materials could enable mild processing routes for fabrication, reduced *cradle-to-grave* (considering the entire lifecycle) CO_2 footprint than fossil counterparts are generally realized (Zuiderveen et al. recently reported 45% lower emissions with a 95% confidence interval)[27]. Phasing out fossil-derived materials in favor of renewable C-containing materials (e.g., secondary materials and biomass utilization) would also increase the circularity of the global economy, which has steadily declined from 9.1 % (first Circularity Gap Report in 2018) to 6.9 % (Circularity Gap Report 2025)[28]. Recent estimates suggest that it is feasible to cover 20% of the overall carbon demand of the chemical and derived material sector with agricultural, woody, and biowaste biomass by the year 2050[29]. Therefore, the defossilization of carbon embedded in the materials and chemical industries should be accompanied by the recycling of existing C-containing materials (to keep them within the technosphere), and the implementation of CCU strategies for the materials sector (i.e., copolymerization of CO_2 with epoxides to produce polycarbonates)[30], to establish a truly circular carbon economy[31].

Discussion S3. Carbon retention lifetime distributions

Illustrative log-normal carbon retention lifetime distributions were generated from minimum, maximum, and mean retention times and their standard deviations from data reported previously (S. Table 2). For instances where generalised terms for timeframe were given (e.g., *months*, *decades*), these were handled in a standardised manner using values as laid out in S. Table 3. In the case of the afforestation/reforestation category, minimum retention values were taken as the reported time in years to net C storage, whereas mean and standard deviation in this subgroup were based on an assortment of reported lifetimes of deciduous and coniferous trees of the sort used in such initiatives. In the case of algae cultivation, fuel and feedstock applications were factored in assuming a *weeks* to *months* timeframe for production to utilisation, and this subcategory also includes open ocean macroalgae cultivation and sinking data. Paludiculture (biomass cultivation on wetted peatlands) is an emerging CCS strategy, one that is potentially promising as a nature-based CDR solution. However, there presently appears to be insufficient C retention data to place it alongside the other strategies. Studies measuring the reduction in peatland emissions and the accumulation of biomass are therefore desirable. Log normal distributions were calculated with the *dlnorm* function using the retention time data (extended to 1/10th the minimum retention time and 10× the max retention time, for smooth tails), μ *log* (the adjusted mean of the log transformed retention times, adjusted to account for skews in the distributions by subtracting half of the variance in σ *log*), and σ *log* (the log-space standard deviations) in RStudio[32]. The script to reproduce the plots is available in **Supplementary Information 2**.

Supplementary Table 2 | Carbon Retention Time Data for CCS

Group	Subgroup	Min RT[1]	Max RT[1]	Mean RT[1]	St. Dev. RT[1]	Sources
Waste Materials	Landfill sequestration[2]	0.082	100	34.216	41.974	33–36
	Waste biomass utilization (biochar)[2]	10	999	303	466.325	37–39
	Waste biomass utilization (durable goods)	0.082	99	12.91	23.966	40–47
Plant Biomass	Afforestation/reforestation[3]	13	1,000	532.25	291.091	48–51
	Agroforestry	1	50	28	21.608	52,53
	Algae cultivation[2,4]	0.019	9,999	2,230	4,361.672	54
	Blue carbon ecosystems	21	3,350	1,293	1,797.979	55
Soils	Conservation Agriculture	15	117	47.375	22.295	56,57
	Biochar Application	0.296	1,554	857	600.248	58,59
	Peatland Restoration	5,000	11,700	9,575	3,084	60–63
	Paludiculture	*Data not found*				
Man-made Products	Wood construction materials	25	100	48.75	34.731	64–66
	Bio-based materials[2,5]	0.005	10	0.5	2.499	67
	Bioconcrete	20	280	133.333	98.995	68
	Biomineralization[2]	100	1,000,000	500,050	707,036	69
	Packaging materials[2]	0.019	3	0.8664	1.254	70,71
	CCU fuel products[2,6]	0.019	1.89	0.743	0.884	-
Oceanic Storage	Ocean fertilization	0.986	100	37.8	50.046	72
	Alkalinity enhancement[2]	50	1,000	441	399	55,73
	Carbonate mineral formation[2]	100,000	999,999	550,000	636,395	73
Geological Storage	Depleted HC reservoirs[2]	20	99,999	18,222	33,226	74–77
	Unmineable Coal Seams[2]	550	10,000	6,512	4,505	73,78
	Saline Aquifers[2]	550,000	9,999,999	3,025,000	3,941,034	73,79

1281

1282

[1] Retention times given in years.

[2] Literature includes generalizations, in these cases data is supported using figures from S. Table 3 below.

[3] Data based on lifetimes of trees housing stored carbon (as described in Section 2 above)

[4] Algae cultivation for fuel and feedstocks factored in assuming a weeks to months timeframe for production to utilization and includes open ocean macroalgae cultivation and sinking data.

[5] Short-lived biomaterials such as bioplastics, natural fibres, adhesives, and fungal byproducts.

[6] Assuming fuel storage time of days to months and immediate release upon use.

Supplementary Table 3 | Figures Used for RT Distributions when Handling Generalisations.

Handling generalisations	Min (years)	Max (years)	Mean (years)	SD (years)
Days	0.003	0.036	0.019	0.023
Weeks	0.019	0.134	0.077	0.081
Months	0.082	1.890	0.986	1.279
Years	1	19	10	12.72792206
Decades	10	99	55	63
Centuries	100	999	550	636
Thousands of years/Millenia	1000	9,999	5,500	6,363
Tens of thousands of years	10,000	99,999	55,000	63,639
Hundreds of thousands of years	100,000	999,999	550,000	636,395
Millions of years	1,000,000	9,999,999	5,500,000	6,363,960

Taking waste materials as an example, in landfills, microbes play a crucial role in carbon cycling, converting biodegradable waste into methane (CH_4), carbon dioxide (CO_2), and microbial biomass via both aerobic and anaerobic pathways. In these environments, Rh, methanogenesis and denitrification, are key pathways for carbon transformation [80]. Saprotrophic activities of fungi are also important determinants of carbon cycling and can accelerate the degradation of recalcitrant substrates such as textiles and plastics[81,82]. These processes vary with landfill depth and age, affecting organic matter degradation and carbon sequestration lifetimes[83]. The retention times is affected by complex drivers, e.g. both the composition and nature of the sequestered carbon (e.g. lignin content, bioavailability, chemical treatments etc) and broader conditions of storage. Generally speaking, rapidly degrading products, such as food items, typically release their stored carbon within a year, whereas newspapers and wood items can last for decades or more. Carbon stored as a utilisation of waste biomass (engineered wood, biochar, textiles packing materials and bioplastics), is typically retained for longer (months to decades). However, retention times can be stunted when the biomass is not produced with sequestration applications in mind, as has been seen for waste biochars created from suboptimal pyrolysis and feedstocks, wherein mean retention times (MRTs) can be reduced down to decades versus 10^2-10^3 years of biochar created for CCS applications[84].

Discussion S4. Algae and blue carbon storage

Microalgae and macroalgae are also important drivers of blue carbon (**Figure 3**). Microalgae are estimated to produce approximately half of the atmospheric oxygen while simultaneously utilising CO_2 for their growth[85]. With an airflow containing 4% CO_2, microalgae can fix carbon at a rate of 0.0146 Mg C ha^{-1} /day while growing at 0.0302 Mg [86], up to 10x that of higher plants[87]. CO_2 bio-fixation by algae also yields valuable biomass products. These include proteins, fatty acids, vitamins, minerals,

pigments, dietary supplements for humans and animals, and other bioactive compounds[88]. However, large-scale cultivation projects of microalgae still remain costly, primarily stemming from their comparatively low productivity on a large scale. Initial calculations indicate that macroalgae globally facilitate an export of 0.679 Gt C yr^{-1} [89,90]. Specifically, an estimated 0.014 Gt C yr^{-1} is sequestered in coastal sediments, and 0.152 Gt C yr^{-1} that could potentially be sequestered in the deep sea[89]. It is reported that a part of macroalgae-derived POC is buried in shelf sediments, and a considerably higher amount is sequestered in the deep ocean[91]. These calculations imply that macroalgae might function as a larger sink for carbon than seagrass, tidal marshes, and mangroves combined**.** Nevertheless, macroalgae predominantly inhabit eroding shores, limiting the storage of particulate organic carbon near their production sites.

Discussion S5. Soil dynamics and the microbial carbon pump

Microbes have long been recognised for their vital role in soil carbon cycling. Recent work has led to the conceptualisation of the soil microbial carbon pump (MCP) and carbon use efficiency frameworks[92,93] (**Figure S2**), which essentially serves as a terrestrial counterpart to the more established marine biological carbon pump. The soil MCP describes the microbial processes that collectively convert input soil organics into persistent SOC, thereby contributing to long-term carbon sequestration. This function of the MCP is achieved through the combined effects of anabolic assimilation processes (wherein organics are taken up and converted into microbial biomass)[92], enzyme secretion and exogenous enzymatic carbon transformation (whereby organic matter is converted into metabolic byproducts and biopolymers, as in exudates and biofilms)[94,95], the accumulation of necromass (the cellular debris of dead cells)[96] and the production of recalcitrant carbon (whereby microbially-derived products stabilize carbon via their carbon interactions, often through aggregate formation)[97]. Given the multitude of interfacial dimensions these processes make with other soil components (root systems, soil fauna and the soil matrix), they are complexly interwoven with soil settings. The MCP is therefore influenced by soil chemistry, soil physical conditions, and events above ground (especially those affecting topside flora[98]), and yet highly adaptive to soil perturbations[93,99–101]. Indeed, it is becoming increasingly evident that multimodal analyses (i.e., supporting physicochemical measures with integrative omics microbial measures taken across systems levels, e.g. metabolomics, metaproteomics, metatranscriptomics and metagenomics) are needed to properly capture microbial dynamics in soil systems[102,103].

Microbial communities are distinct across soil compartments and so can vary substantially along the depth[104] and oxygen[105] gradients. This can have pronounced implications for carbon cycling, where topsoils are typically associated with high turnover carbon release from the labile carbon pool[106], most notably via Rh and, in anaerobic settings, methanogenesis, processes which are interlinked with nitrogen cycling (thereby influencing N_2O emission)[107]. Conversely, the subsoil is associated with low carbon turnover and long-term carbon storage through so-called *dark fixation* (principally driven via the chemoautotrophic actions of nitrifying bacteria, and sulphur or iron-oxidizing prokaryotes)[108–111]. Consequently, the soil MCP has a direct bearing on soil carbon fates and soil microbes should therefore be a key consideration in site

selection for soil carbon sequestration initiatives (particularly those based on soil amendments).

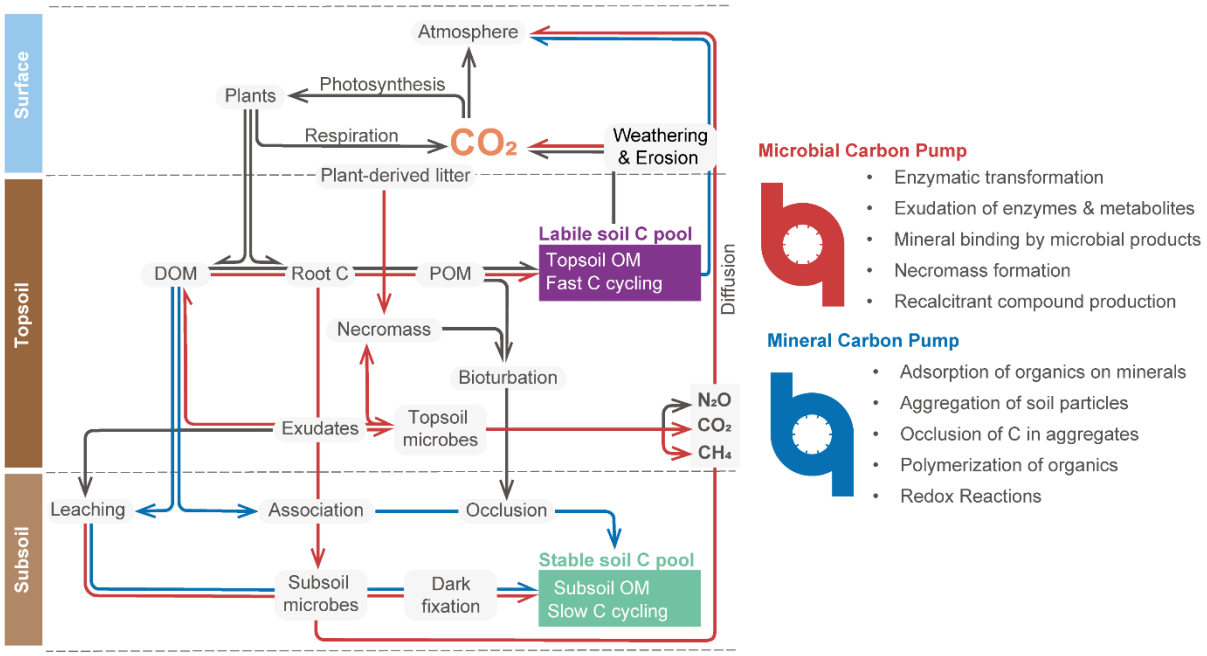

Figure S2 | Soil carbon dynamics are driven by the microbial or mineral carbon pumps. Soil processes are delineated (dashed lines) across soil compartments. Process lines are coloured by carbon pump type (where those in red are driven by the microbial carbon pump and those in blue by the mineral counterpart) remaining processes are in black. On the right, the key features for each pump are summarized in bullet form.

Discussion S6. Forestation, land use and soil capacity

Considering the fact that forests store 40% of all below-ground carbon[112], afforestation, the expansion of forested areas, has been put forward as a CCS approach. Since the late 20th century, global afforestation efforts have increased planted forest areas by approximately 105 million hectares[113]. Afforestation and reforestation, while highly effective at sequestering carbon, require larger land areas and significant upfront investment. CA, afforestation and reforestation are influenced by factors such as tree species, land use history, stand age, climate, and soil type[114–117]. Studies indicate that during the initial 20 years of reforestation, aboveground biomass increases at a rate of 6.2 Mg ha^{-1} yr^{-1}, which slows to 2.9 Mg ha^{-1} yr^{-1} over the next 80 years of regrowth. Globally, there are an estimated 3.5 billion to 3.7 billion hectares of grazing land available[113,118], potentially enabling sequestration of up to 0.2 Gt C yr^{-1} [119], to the extent that ethical and socioeconomic implications are reasonable. Although the optimal approach will vary based on regional factors and the specific dynamics of each ecosystem, effective forest management strategies and adaptive grazing practices (such as high density-short duration grazing)[120], establishing grazing exclusion zones[121], proactive soil intervention[122] and coupling strategic grazing plans with forage species diversification efforts[123] can significantly support both carbon sequestration and ecosystem services.

SOC amendment is an alternative strategy that has the potential to increase soil microbial biomass[92,124], water retention[125], and introduce recalcitrant C. Livestock

manure, compost, biochar, and green mulches are some of the common soil amendments (**Figure 4a**). Additionally, ongoing research on other possible innovative amendments include treated municipal sewage sludge and aluminium or steel slags[126–129]. Biochar amendments also provide stable carbon forms that are resistant to microbial decomposition, limiting Rh-based turnover and standing out as one of the most promising soil amendment approaches for CCS. Biochar is produced through the pyrolysis of organic materials, transforming OC into stable refractory products with a half-life ranging from millennial to centennial timescales. Biochar typically retains 50% C from its original biomass, and up to 100% in idealized conditions, compared to combustion and composting, which retain only around 3% and 10-20%, respectively[130,131]. Furthermore, optimal C sequestration occurs with H/C ratios between 0.38 and 0.44, which is achieved at the highest treatment temperatures (HTT) of 500–550°C across diverse feedstocks[132]. Biochar's impact on soil quality, nutrient availability, and soil carbon mineralization, however, varies, with studies reporting different outcomes[133–135]. For instance, applying biochar at a rate of 30 t ha^{-1} resulted in a 14% decrease in SOC content, whereas application rates of 60 t ha^{-1} and 90 t ha^{-1} led to SOC increases of 18.8% and 8.2%, respectively. The net change in SOC is therefore influenced by complex soil dynamics, necessitating a deep understanding of the target soil.

Soil fungi also present another avenue for increasing stable SOM. For instance, plants allocate up to 20% of their carbon to fungal partners via root exudation and detritus[136], effectively transforming labile organic compounds into more stable SOC. Sclerotia, the hardened masses of fungal hyphae, which typically range from 0.1 mm to 30 cm in diameter, can persist in soil for many years[137,138]. Melanized endophytic fungi may also support this endeavour[139–141] and have been shown to enhance polyaromatic SOC associated with microaggregates and slow decomposition of SOC, potentially increasing the recalcitrant pool of soil carbon[139,140,142].

Discussion S7. Figure data sources

Figure 1 | Major landmarks of the global carbon (C) cycle present opportunities for scalable intervention on atmospheric carbon accumulation. Global annual emissions from land use change and net anthropogenic emissions (and their year on year changes) were taken from the Global Carbon Budget report[143]. Global annual heterotrophic CO_2 fixation is based on the midpoint figure derived from upper and lower bounds estimated in[144]. Global annual heterotrophic respiration is the average of values reported in[145–147]. The average global annual uptake from photosynthesis is based on values reported in[148–151], year on year change in photosynthesis is taken from[150]. Global annual emissions from plant respiration is based on[152]. Global annual carbon removal from the combined CDR programs and the associated year on year change are taken from the 2nd Edition of The State of Carbon Dioxide Removal[153]. Gross global annual ocean-atmosphere CO_2 absorption and emissions totals are taken from[154], the year on year change for ocean-atmosphere exchanges (absorption is taken from[155]). The estimated magnitude of the oceanic biological carbon pump is presented as the midpoint of the accepted range presented in[156]. Oceanic and

terrestrial (biotic) carbon pool sizes are based on values presented in [157] whereas the terrestrial (pedologic) pool size is as reported in[158]. Atmospheric carbon pool size was calculated (using the formula *Total atmospheric C pool size (GtC) = Atmospheric CO_2 concentration (ppm) × 2.12 GtC/ppm*). Atmospheric CO_2 concentration was based on the NOAA recorded atmospheric carbon levels data (taken from https://climate.nasa.gov/vital-signs/carbon-dioxide/), which was 425 ppm at the time of writing.

Figure 2 | Carbon sequestration strategies carry broad sequestration lifetimes and involve a diverse variety of biological systems. Data sources described above, see Discussion S2 and related tables.

Figure 3 | Dynamics in oceanic carbon cycling and overview of oceanic CCS approaches. Pools with known magnitudes are presented (using mean values where ranges have been previously reported) and processes with known rates are also given, data sourced from [159–164].

Figure 5 | Biological systems drive compositional dynamics of the atmosphere via the balanced interplay of interlinked biogeochemical cycles. Global mean surface temperature (GMST) together with corresponding CO_2 levels over the past 485 Ma was adapted from Judd et al. 2024[165]. Eccentricity data were collected using the NASA Goddard Institute for Space Studies ModelE AR5 simulation tool at https://data.giss.nasa.gov/modelE/ar5plots/srorbpar.html. Ice core data was obtained from Luthi et al. 2008[166] for CO_2, Loulergue et al. 2008[167] for CH_4, and Schilt et al. 2010[168] for N_2O.

Supplementary References

1. Ritchie, H. Sector by sector: where do global greenhouse gas emissions come from? *Our World in Data* (2020).

2. Tol, R. S. J. Social cost of carbon estimates have increased over time. *Nature Climate Change* **13**, 532–536 (2023).

3. Doney, S. C., Wolfe, W. H., McKee, D. C. & Fuhrman, J. G. The Science, Engineering, and Validation of Marine Carbon Dioxide Removal and Storage. *Annual Review of Marine Science* vol. 17 55–81 (2025).

4. Chauvy, R. & Dubois, L. Life cycle and techno-economic assessments of direct air capture processes: An integrated review. *International Journal of Energy Research* **46**, 10320–10344 (2022).

5. Langholtz, M. *et al.* The Economic Accessibility of CO2 Sequestration through Bioenergy with Carbon Capture and Storage (BECCS) in the US. *Land* **9**, (2020).

6. Dilute Source CO2 Capture: Management of Atmospheric Coal-Produced Legacy Emissions (Final Technical Report). in (2019).

7. Johnsson, F., Normann, F. & Svensson, E. Marginal Abatement Cost Curve of Industrial CO2 Capture and Storage – A Swedish Case Study. *Frontiers in Energy Research* **Volume 8-2020**, (2020).

8. Strefler, J., Amann, T., Bauer, N., Kriegler, E. & Hartmann, J. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters* **13**, 034010 (2018).

9. Emerson, D., Sofen, L. E., Michaud, A. B., Archer, S. D. J. & Twining, B. S. A Cost Model for Ocean Iron Fertilization as a Means of Carbon Dioxide Removal That Compares Ship- and Aerial-Based Delivery, and Estimates Verification Costs. *Earth's Future* **12**, (2024).

10. Bach, L. T. *et al.* Identifying the Most (Cost-)Efficient Regions for CO2 Removal With Iron Fertilization in the Southern Ocean. *Global Biogeochemical Cycles* **37**, e2023GB007754 (2023).

11. Ward, C., Lee Pereira, R. J., Foteinis, S. & Renforth, P. Techno-economic analysis of ocean iron fertilization. *Frontiers in Climate* **Volume 7-2025**, (2025).

12. Snyder, B. F. Biomass slurry fracture injection as a potential low-cost negative emissions technology. *Environmental Research Letters* **17**, 024013 (2022).

13. Coleman, S. *et al.* Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal. *Frontiers in Marine Science* **Volume 9-2022**, (2022).

14. Crane, C. S. Large-Scale Commercial Carbon Capture Retrofit of the San Juan Generating Station. in (2022).

15. Psarras, P. C. *et al.* Part 1: Cost Analysis of Carbon Capture and Sequestration from U.S. Natural Gas-fired Power Plants. *Environmental science & technology* https://api.semanticscholar.org/CorpusID:216111171 (2020).

16. Ganguly, A., Brown, R. C. & Wright, M. M. Techno-economic and greenhouse gas emission assessment of carbon negative pyrolysis technology†. in (2022).

17. Popp, A. *et al.* Land-use protection for climate change mitigation. *Nature Clim Change* **4**, 1095–1098 (2014).

18. Sathaye, J., Shukla, P. R. & Ravindranath, N. H. Climate change, sustainable development and India: Global and national concerns. *Current Science* **90**, 314–325 (2006).

19. Kowalczyk, K. A. *et al.* Marine carbon dioxide removal by alkalinization should no longer be overlooked. *Environmental Research Letters* **19**, 074033 (2024).

20. Kähler, F., Porc, O. & Carus, M. *RCI Carbon Flows Report 2023, Officially Titled "RCI Carbon Flows Report: Compilation of Supply and Demand of Fossil and Renewable Carbon on a Global and European Level*. (2023).

21. Churkina, G. *et al.* Buildings as a global carbon sink. *Nature Sustainability* **3**, 269–276 (2020).

22. Carbon, R. *Case Studies Based on Peer-Reviewed Life Cycle Assessments – Carbon Footprints of Different Carbon-Based Chemicals and Materials*. (2023).

23. Ding, Y. *et al.* Emerging Engineered Wood for Building Applications. *Chemical Reviews* **123**, 1843–1888 (2023).

24. Yablonovitch, E. & Deckman, H. W. Scalable, economical, and stable sequestration of agricultural fixed carbon. *Proceedings of the National Academy of Sciences* **120**, e2217695120 (2023).

25. Environmental Sustainability of Natural Biopolymer-Based Electrolytes for Lithium Ion Battery Applications. *Advanced Materials* 2416733 (2025) doi:10.1002/adma.202416733.

26. Song, J. *et al.* Processing bulk natural wood into a high-performance structural material. *Nature* **554**, 224–228 (2018).

27. Zuiderveen, E. A. R. *et al.* The potential of emerging bio-based products to reduce environmental impacts. *Nature Communications* **14**, 8521 (2023).

28. The Circularity Gap Report 2025. https://www.circularity-gap.world/2025.

29. *Carus, M., Porc, O., Vom Berg, C., Kempen, M., Schier, F. and Tandetzki, J.: Is There Enough Biomass to Defossilise the Chemicals and Derived Materials Sector by 2050. novaInstitut GmbH (Ed.), Hürth, Germany, 2025-02.*

30. Song, B., Qin, A. & Tang, B. Z. Syntheses, properties, and applications of CO2-based functional polymers. *Cell Reports Physical Science* **3**, 100719 (2022).

31. Sherwood, J. The significance of biomass in a circular economy. *Bioresource Technology* **300**, 122755 (2020).

32. RStudio Team. *RStudio: Integrated Development Environment for R*. (RStudio, PBC., Boston, MA, 2020).

33. Micales, J. A. & Skog, K. E. The decomposition of forest products in landfills. *International Biodeterioration & Biodegradation* **39**, 145–158 (1997).

34. Ximenes, F. A., Gardner, W. D. & Cowie, A. L. The decomposition of wood products in landfills in Sydney, Australia. *Waste Management* **28**, 2344–2354 (2008).

35. Ximenes, F. A., Björdal, C., Kathuria, A., Barlaz, M. A. & Cowie, A. L. Improving understanding of carbon storage in wood in landfills: Evidence from reactor studies. *Waste Management* **85**, 341–350 (2019).

36. Barlaz, M. A. Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochemical Cycles* **12**, 373–380 (1998).

37. Gross, A., Bromm, T. & Glaser, B. Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. *Agronomy* **11**, (2021).

38. Singh, B. P., Cowie, A. L. & Smernik, R. J. Biochar Carbon Stability in a Clayey Soil As a Function of Feedstock and Pyrolysis Temperature. *Environ. Sci. Technol.* **46**, 11770–11778 (2012).

39. Nan, H. *et al.* Pyrolysis temperature-dependent carbon retention and stability of biochar with participation of calcium: Implications to carbon sequestration. *Environmental Pollution* **287**, 117566 (2021).

40. Asgher, M., Qamar, S. A., Bilal, M. & Iqbal, H. M. N. Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Research International* **137**, 109625 (2020).

41. Kakadellis, S. & Harris, Z. M. Don’t scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment – A critical review. *Journal of Cleaner Production* **274**, 122831 (2020).

42. Folino, A., Karageorgiou, A., Calabrò, P. S. & Komilis, D. Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review. *Sustainability* **12**, (2020).

43. T. G., Y. G. *et al.* Biopolymer-Based Composites: An Eco-Friendly Alternative from Agricultural Waste Biomass. *Journal of Composites Science* **7**, (2023).

44. Spiridon, I., Darie-Nita, R. N. & Bele, A. New opportunities to valorize biomass wastes into green materials. II. Behaviour to accelerated weathering. *Journal of Cleaner Production* **172**, 2567–2575 (2018).

45. Bartolucci, L. *et al.* Sustainable Valorization of Bioplastic Waste: A Review on Effective Recycling Routes for the Most Widely Used Biopolymers. *International Journal of Molecular Sciences* **24**, (2023).

46. Haile, A. *et al.* Pulp and paper mill wastes: utilizations and prospects for high value-added biomaterials. *Bioresources and Bioprocessing* **8**, 35 (2021).

47. Platnieks, O. *et al.* Sustainable tetra pak recycled cellulose / Poly(Butylene succinate) based woody-like composites for a circular economy. *Journal of Cleaner Production* **270**, 122321 (2020).

48. Biondi, F., Meko, D. M. & Piovesan, G. Maximum tree lifespans derived from public-domain dendrochronological data. *iScience* **26**, (2023).

49. Laurance, W. F. *et al.* Inferred longevity of Amazonian rainforest trees based on a long-term demographic study. *Forest Ecology and Management* **190**, 131–143 (2004).

50. Nave, L. E. *et al.* The role of reforestation in carbon sequestration. *New Forests* **50**, 115–137 (2019).

51. Lieberman, D. & Lieberman, M. Forest tree growth and dynamics at La Selva, Costa Rica (1969-1982). *Journal of Tropical Ecology* **3**, 347–358 (1987).

52. Lorenz, K. & Lal, R. Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development* **34**, 443–454 (2014).

53. Albrecht, A. & Kandji, S. T. Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems & Environment* **99**, 15–27 (2003).

54. Wu, J., Keller, D. P. & Oschlies, A. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study. *Earth System Dynamics* **14**, 185–221 (2023).

55. Siegel, D. A., DeVries, T., Doney, S. C. & Bell, T. Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environmental Research Letters* **16**, 104003 (2021).

56. West, T. O. & Post, W. M. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. *Soil Science Society of America Journal* **66**, 1930–1946 (2002).

57. Han, P., Zhang, W., Wang, G., Sun, W. & Huang, Y. Changes in soil organic carbon in croplands subjected to fertilizer management: a global meta-analysis. *Scientific Reports* **6**, 27199 (2016).

58. Wang, J., Xiong, Z. & Kuzyakov, Y. Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy* **8**, 512–523 (2016).

59. Zimmerman, A. R. Abiotic and Microbial Oxidation of Laboratory-Produced Black Carbon (Biochar). *Environ. Sci. Technol.* **44**, 1295–1301 (2010).

60. Yu, Z. C. Northern peatland carbon stocks and dynamics: a review. *Biogeosciences* **9**, 4071–4085 (2012).

61. Nichols, J. E. & Peteet, D. M. Rapid expansion of northern peatlands and doubled estimate of carbon storage. *Nature Geoscience* **12**, 917–921 (2019).

62. Kurnianto, S. *et al.* Carbon accumulation of tropical peatlands over millennia: a modeling approach. *Global Change Biology* **21**, 431–444 (2015).

63. Dargie, G. C. *et al.* Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature* **542**, 86–90 (2017).

64. Chang, Y.-S. *et al.* Study on Methods for Determining Half-Life of Domestic Wooden Panel among Harvested Wood Products. *Journal of the Korean Wood Science and Technology* **42**, 309–317 (2014).

65. Puettmann, M. E. Carbon Analysis of Wood Composite Panels. *Forest Products Journal* **72**, 112–115 (2022).

66. Gundimeda, H. A Framework for Assessing Carbon Flow in Indian Wood Products. *Environment, Development and Sustainability* **3**, 229–251 (2001).

67. Geyer, R., Jambeck, J. R. & Law, K. L. Production, use, and fate of all plastics ever made. *Science Advances* **3**, e1700782 (2017).

68. Castro-Alonso, M. J. *et al.* Microbially Induced Calcium Carbonate Precipitation (MICP) and Its Potential in Bioconcrete: Microbiological and Molecular Concepts. *Frontiers in Materials* **Volume 6-2019**, (2019).

69. Cailleau, G., Braissant, O. & Verrecchia, E. P. Biomineralization in plants as a long-term carbon sink. *Naturwissenschaften* **91**, 191–194 (2004).

70. Siracusa, V., Rocculi, P., Romani, S. & Rosa, M. D. Biodegradable polymers for food packaging: a review. *Trends in Food Science & Technology* **19**, 634–643 (2008).

71. Napper, I. E. & Thompson, R. C. Environmental Deterioration of Biodegradable, Oxo-biodegradable, Compostable, and Conventional Plastic Carrier Bags in the Sea, Soil, and Open-Air Over a 3-Year Period. *Environ. Sci. Technol.* **53**, 4775–4783 (2019).

72. Robinson, J. *et al.* How deep is deep enough? Ocean iron fertilization and carbon sequestration in the Southern Ocean. *Geophysical Research Letters* **41**, 2489–2495 (2014).

73. Farrelly, D. J., Everard, C. D., Fagan, C. C. & McDonnell, K. P. Carbon sequestration and the role of biological carbon mitigation: A review. *Renewable and Sustainable Energy Reviews* **21**, 712–727 (2013).

74. Alcalde, J. *et al.* Estimating geological CO2 storage security to deliver on climate mitigation. *Nature Communications* **9**, 2201 (2018).

75. Mkemai, R. M. & Gong, B. Geological performance evaluation of CO2 sequestration in depleted oil reservoirs: A simulation study on the effect of water saturation and vertical to horizontal permeability ratio. *Journal of Natural Gas Science and Engineering* **76**, 103196 (2020).

76. Bagheri, M., Shariatipour, S. M. & Ganjian, E. Parametric study on the integrity of wellbores in CO2 storage sites. *Construction and Building Materials* **268**, 121060 (2021).

77. Myshakin, E. M., Singh, H., Sanguinito, S., Bromhal, G. & Goodman, A. L. Numerical estimations of storage efficiency for the prospective CO2 storage resource of shales. *International Journal of Greenhouse Gas Control* **76**, 24–31 (2018).

78. Mazumder, S., Hemert, P. van, Bruining, J., Wolf, K.-H. A. A. & Drabe, K. In situ CO2–coal reactions in view of carbon dioxide storage in deep unminable coal seams. *Fuel* **85**, 1904–1912 (2006).

79. Bachu, S., Gunter, W. D. & Perkins, E. H. Aquifer disposal of CO2: Hydrodynamic and mineral trapping. *Energy Conversion and Management* **35**, 269–279 (1994).

80. Song, L., Wang, Y., Zhang, R. H. & Yang, S. Microbial Mediation of Carbon, Nitrogen, and Sulfur Cycles During Solid Waste Decomposition. *Microbial Ecology* **86**, 311–324 (2022).

81. Ye, R. *et al.* Fungal diversity and its mechanism of community shaping in the milieu of sanitary landfill. *Frontiers of Environmental Science & Engineering* **15**, (2020).

82. Spina, F. *et al.* Low density polyethylene degradation by filamentous fungi. *Environmental Pollution* **274**, 116548 (2021).

83. Liu, S.-J. *et al.* Succession and diversity of microbial communities in landfills with depths and ages and its association with dissolved organic matter and heavy metals. *The Science of the total environment* **651 Pt 1**, 909–916 (2019).

84. Singh, B. P., Cowie, A. L. & Smernik, R. J. Biochar Carbon Stability in a Clayey Soil As a Function of Feedstock and Pyrolysis Temperature. *Environ. Sci. Technol.* **46**, 11770–11778 (2012).

85. Tabatabaei, M., Tohidfar, M., Jouzani, G. S., Safarnejad, M. & Pazouki, M. Biodiesel production from genetically engineered microalgae: Future of bioenergy in Iran. *Renewable and Sustainable Energy Reviews* **15**, 1918–1927 (2011).

86. Sanaye Mozaffari Sabet, N. & Golzary, A. CO2 biofixation at microalgae photobioreactors: hydrodynamics and mass transfer study. *Int. J. Environ. Sci. Technol.* **19**, 11631–11648 (2022).

87. Li, Y., Horsman, M., Wu, N., Lan, C. Q. & Dubois-Calero, N. Biofuels from Microalgae. *Biotechnology Progress* **24**, 815–820 (2008).

88. San Pedro, A., González-López, C. V., Acién, F. G. & Molina-Grima, E. Marine microalgae selection and culture conditions optimization for biodiesel production. *Bioresource Technology* **134**, 353–361 (2013).

89. Substantial role of macroalgae in marine carbon sequestration | Nature Geoscience. https://www.nature.com/articles/ngeo2790.

90. Duarte, C. M. & Cebrián, J. The fate of marine autotrophic production. *Limnology and Oceanography* **41**, 1758–1766 (1996).

91. Macreadie, P. I. *et al.* The future of Blue Carbon science. *Nat Commun* **10**, 3998 (2019).

92. Liang, C., Schimel, J. P. & Jastrow, J. D. The importance of anabolism in microbial control over soil carbon storage. *Nat Microbiol* **2**, 1–6 (2017).

93. Ren, C. *et al.* Thermal sensitivity of soil microbial carbon use efficiency across forest biomes. *Nature Communications* **15**, 6269 (2024).

94. Chen, J. *et al.* A keystone microbial enzyme for nitrogen control of soil carbon storage. *Science Advances* **4**, (2018).

95. Daunoras, J., Kačergius, A. & Gudiukaitė, R. Role of Soil Microbiota Enzymes in Soil Health and Activity Changes Depending on Climate Change and the Type of Soil Ecosystem. *Biology* **13**, (2024).

96. Ni, H. *et al.* Microbial metabolism and necromass mediated fertilization effect on soil organic carbon after long-term community incubation in different climates. *The ISME Journal* **15**, 2561–2573 (2021).

97. Rabbi, S., Minasny, B., McBratney, A. & Young, I. Microbial processing of organic matter drives stability and pore geometry of soil aggregates. *Geoderma* **360**, 114033 (2020).

98. Liu, T., Peng, D., Tan, Z., Guo, J. & Zhang, Y. Effects of stand density on soil respiration and labile organic carbon in different aged Larix principis-rupprechtii plantations. *Ecological Processes* **10**, 1–15 (2021).

99. Liang, G., Stark, J. & Waring, B. G. Mineral reactivity determines root effects on soil organic carbon. *Nature Communications* **14**, 4962 (2023).

100. Yu, Q. *et al.* Decoupled responses of plants and soil biota to global change across the world's land ecosystems. *Nature Communications* **15**, 10369 (2024).

101. Doetterl, S. *et al.* Links among warming, carbon and microbial dynamics mediated by soil mineral weathering. *Nature Geoscience* **11**, 589–593 (2018).

102. Freire-Zapata, V. *et al.* Microbiome–metabolite linkages drive greenhouse gas dynamics over a permafrost thaw gradient. *Nature Microbiology* **9**, 2892–2908 (2024).

103. McGivern, B. B. *et al.* Microbial polyphenol metabolism is part of the thawing permafrost carbon cycle. *Nature Microbiology* **9**, 1454–1466 (2024).

104. Naylor, D., Mcclure, R. & Jansson, J. Trends in Microbial Community Composition and Function by Soil Depth. *Microorganisms* **10**, (2022).

105. Lipson, D. *et al.* Changes in microbial communities along redox gradients in polygonized Arctic wet tundra soils. *Environmental microbiology reports* **7 4**, 649–657 (2015).

106. Gu, L., Post, W. & King, A. Fast labile carbon turnover obscures sensitivity of heterotrophic respiration from soil to temperature: A model analysis. *Global Biogeochemical Cycles* **18**, (2004).

107. Yin, Y. *et al.* Nitrous oxide inhibition of methanogenesis represents an underappreciated greenhouse gas emission feedback. *The ISME Journal* **18**, (2024).

108. Akinyede, R., Taubert, M., Schrumpf, M., Trumbore, S. & Küsel, K. Dark CO2 fixation in temperate beech and pine forest soils. *Soil Biology and Biochemistry* https://doi.org/10.1016/j.soilbio.2021.108526 (2021) doi:10.1016/j.soilbio.2021.108526.

109. Tong, H. *et al.* Microaerophilic Oxidation of Fe(II) Coupled with Simultaneous Carbon Fixation and As(III) Oxidation and Sequestration in Karstic Paddy Soil. *Environmental science & technology* https://doi.org/10.1021/acs.est.0c05791 (2021) doi:10.1021/acs.est.0c05791.

110. Xiao, K. *et al.* Metagenomic and 14 C tracing evidence for autotrophic microbial CO2 fixation in paddy soils. *Environmental microbiology* https://doi.org/10.1111/1462-2920.15204 (2020) doi:10.1111/1462-2920.15204.

111. Spohn, M., Müller, K., Höschen, C., Mueller, C. & Marhan, S. Dark microbial CO2 fixation in temperate forest soils increases with CO2 concentration. *Global Change Biology* **26**, 1926–1935 (2019).

112. Change in soil carbon following afforestation. *Forest Ecology and Management* **168**, 241–257 (2002).

113. The State of Food and Agriculture 2016 | FAO. https://www.fao.org/family-farming/detail/en/c/447860/.

114. The Impact of Afforestation on Soil Organic Carbon Sequestration on the Qinghai Plateau, China | PLOS ONE. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0116591.

115. Don, A., Schumacher, J. & Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Global Change Biology* **17**, 1658–1670 (2011).

116. Guo, L. B. & Gifford, R. M. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* **8**, 345–360 (2002).

117. Paul, K. I., Polglase, P. J., Nyakuengama, J. G. & Khanna, P. K. Change in soil carbon following afforestation. *Forest Ecology and Management* **168**, 241–257 (2002).

118. Lal, R. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science (New York, N.Y.)* **304**, 1623–7 (2004).

119. Follett, R. F. & Schuman, G. E. Grazing land contributions to carbon sequestration. in *Grassland: a global resource* 265–277 (Wageningen Academic, 2005). doi:10.3920/9789086865512_021.

120. Chaplot, V., Dlamini, P. & Chivenge, P. Potential of grassland rehabilitation through high density-short duration grazing to sequester atmospheric carbon. *Geoderma* **271**, 10–17 (2016).

121. Deng, L., Shangguan, Z.-P., Wu, G.-L. & Chang, X.-F. Effects of grazing exclusion on carbon sequestration in China's grassland. *Earth-Science Reviews* **173**, 84–95 (2017).

122. Terefe, H., Argaw, M., Tamene, L. & Mekonnen, K. Sustainable land management interventions lead to carbon sequestration in plant biomass and soil in a mixed crop-livestock system: the case of Geda watershed, central highlands of Ethiopia. *Ecol Process* **9**, 34 (2020).

123. Sarkar, R., Corriher-Olson, V., Long, C. & Somenahally, A. Challenges and Potentials for Soil Organic Carbon Sequestration in Forage and Grazing Systems. *Rangeland Ecology & Management* **73**, 786–795 (2020).

124. DeLonge, M. S., Miles, A. & Carlisle, L. Investing in the transition to sustainable agriculture. *Environmental Science & Policy* **55**, 266–273 (2016).

125. Mpeketula, P. M. G. & Snapp, S. S. Structural Stability Conditions Soil Carbon Gains from Compost Management and Rotational Diversity. *Soil Science Society of America Journal* **83**, 203–211 (2019).

126. Marko \vCerne *et al.* The effect of stabilization on the utilization of municipal sewage sludge as a soil amendment. *Waste management* **94**, 27–38 (2019).

127. Das, S., Gwon, H. S., Khan, M. I., Jeong, S. T. & Kim, P. J. Steel slag amendment impacts on soil microbial communities and activities of rice (Oryza sativa L.). *Scientific Reports* **10**, 6746 (2020).

128. Tardy, B. L. *et al.* Integrating Arid Areas in the Global Bioeconomy: Opportunities and Challenges toward Sustainable Biomass Generation and Management. *ACS Sustainable Chem. Eng.* **11**, 12177–12193 (2023).

129. Qassem, M. O. *et al.* Slag from steel production as a versatile fertilizer: Evaluation of ladle furnace slag in sandy soils and hydroponics. *Environmental Technology & Innovation* **37**, 103954 (2025).

130. El-Naggar, A. *et al.* Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. *Geoderma* **332**, 100–108 (2018).

131. Rasul, M., Cho, J., Shin, H.-S. & Hur, J. Biochar-induced priming effects in soil via modifying the status of soil organic matter and microflora: A review. *Science of The Total Environment* **805**, 150304 (2022).

132. Rodrigues, L. *et al.* The importance of biochar quality and pyrolysis yield for soil carbon sequestration in practice. *European Journal of Soil Science* **74**, e13396 (2023).

133. Karer, J., Wimmer, B., Zehetner, F., Kloss, S. & Soja, G. Biochar application to temperate soils: effects on nutrient uptake and crop yield under field conditions. *Agricultural and Food Science* **22**, 390–403 (2013).

134. Baronti, S. *et al.* The Biochar Option to Improve Plant Yields: First Results From Some Field and Pot Experiments in Italy. *Italian Journal of Agronomy* **5**, 3–12 (2010).

135. Hussain, M. *et al.* Biochar for crop production: potential benefits and risks. *J Soils Sediments* **17**, 685–716 (2017).

136. Bago, B., Pfeffer, P. E. & Shachar-Hill, Y. Carbon Metabolism and Transport in Arbuscular Mycorrhizas. *Plant Physiology* **124**, 949–958 (2000).

137. The biology of Sclerotinia trifoliorum Erikss. and other species of sclerotium - forming fungi - WILLIAMS - 1965 - Annals of Applied Biology - Wiley Online Library. https://onlinelibrary-wiley-com.libconnect.ku.ac.ae/doi/abs/10.1111/j.1744-7348.1965.tb01234.x.

138. Money, N. P. Chapter 1 - Fungal Diversity. in *The Fungi (Third Edition)* (eds Watkinson, S. C., Boddy, L. & Money, N. P.) 1–36 (Academic Press, Boston, 2016). doi:10.1016/B978-0-12-382034-1.00001-3.

139. Mugerwa, T. T. M., Saleeba, J. A. & McGee, P. A. A variety of melanised root-associated fungi from the Sydney basin form endophytic associations with Trifolium subterraneum. *Fungal Ecology* **6**, 70–82 (2013).

140. McGee, C. F., Byrne, H., Irvine, A. & Wilson, J. Diversity and dynamics of the DNA- and cDNA-derived compost fungal communities throughout the commercial cultivation process for Agaricus bisporus. *Mycologia* **109**, 475–484 (2017).

141. Butler, M. J. & Day, A. W. Destruction of Fungal Melanins by Ligninases of Phanerochaete chrysosporium and Other White Rot Fungi. *International Journal of Plant Sciences* **159**, 989–995 (1998).

142. Lenaers, M. *et al.* Links Between Heathland Fungal Biomass Mineralization, Melanization, and Hydrophobicity. *Microb Ecol* **76**, 762–770 (2018).

143. Friedlingstein, P. *et al.* Global Carbon Budget 2024. *Earth System Science Data* **17**, 965–1039 (2025).

144. Braun, A. *et al.* Reviews and syntheses: Heterotrophic fixation of inorganic carbon – significant but invisible flux in environmental carbon cycling. *Biogeosciences* **18**, 3689–3700 (2021).

145. Konings, A. G. *et al.* Global satellite-driven estimates of heterotrophic respiration. *Biogeosciences* **16**, 2269–2284 (2019).

146. Warner, D. L., Bond-Lamberty, B., Jian, J., Stell, E. & Vargas, R. Spatial Predictions and Associated Uncertainty of Annual Soil Respiration at the Global Scale. *Global Biogeochemical Cycles* **33**, 1733–1745 (2019).

147. He, Y. *et al.* Observation-based global soil heterotrophic respiration indicates underestimated turnover and sequestration of soil carbon by terrestrial ecosystem models. *Global Change Biology* **28**, 5547–5559 (2022).

148. Beer, C. *et al.* Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Science* **329**, 834–838 (2010).

149. Wang, H. *et al.* Towards a universal model for carbon dioxide uptake by plants. *Nature Plants* **3**, 734–741 (2017).

150. Sitch, S. *et al.* Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeosciences* **12**, 653–679 (2015).

151. Wang, J. *et al.* Constraining global terrestrial gross primary productivity in a global carbon assimilation system with OCO-2 chlorophyll fluorescence data. *Agricultural and Forest Meteorology* **304–305**, 108424 (2021).

152. Ito, A. Constraining size-dependence of vegetation respiration rates. *Scientific Reports* **10**, 4304 (2020).

153. Smith, S. M. *et al. The State of Carbon Dioxide Removal*. DOI 10.17605/OSF.IO/F85QJ (2024).

154. Lal, R. Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 815–830 (2007).

155. Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P. & White, J. W. C. Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature* **488**, 70–72 (2012).

156. Brewin, R. J. W. *et al.* Sensing the ocean biological carbon pump from space: A review of capabilities, concepts, research gaps and future developments. *Earth-Science Reviews* **217**, 103604 (2021).

157. Stockmann, U. *et al.* The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment* **164**, 80–99 (2013).

158. Batool, M., Cihacek, L. J. & Alghamdi, R. S. Soil Inorganic Carbon Formation and the Sequestration of Secondary Carbonates in Global Carbon Pools: A Review. *Soil Systems* **8**, 15 (2024).

159. Keppler, L., Landschützer, P., Gruber, N., Lauvset, S. K. & Stemmler, I. Seasonal Carbon Dynamics in the Near-Global Ocean. *Global Biogeochemical Cycles* **34**, e2020GB006571 (2020).

160. Jiao, N. *et al.* The microbial carbon pump and climate change. *Nature Reviews Microbiology* **22**, 408–419 (2024).

161. Jiao, N. *et al.* Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nature Reviews Microbiology* **8**, 593–599 (2010).

162. Keppler, L., Landschützer, P., Lauvset, S. K. & Gruber, N. Recent Trends and Variability in the Oceanic Storage of Dissolved Inorganic Carbon. *Global Biogeochemical Cycles* **37**, e2022GB007677 (2023).

163. Middelburg, J. J. Chemoautotrophy in the ocean. *Geophysical Research Letters* **38**, (2011).

164. Duarte, C. M., Middelburg, J. J. & Caraco, N. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences* **2**, 1–8 (2005).

165. Judd, E. J. *et al.* A 485-million-year history of Earth's surface temperature. *Science* **385**, eadk3705.

166. Lüthi, D. *et al.* High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* **453**, 379–382 (2008).

167. Loulergue, L. *et al.* Orbital and millennial-scale features of atmospheric CH4 over the past 800,000 years. *Nature* **453**, 383–386 (2008).

168. Schilt, A. *et al.* Glacial–interglacial and millennial-scale variations in the atmospheric nitrous oxide concentration during the last 800,000 years. *Quaternary Science Reviews* **29**, 182–192 (2010).