

# Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems

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**Coastal seagrass, mangrove and salt-marsh ecosystems—also termed blue-carbon ecosystems—play an important role in the global carbon cycle. Much of the organic carbon they store rests in soils that have accumulated over thousands of years. Rapidly changing climate and environmental conditions, including sea-level rise, warming, eutrophication and landscape development, will impact decomposition and thus the global reservoir of blue soil organic carbon. Yet, it remains unclear how these disturbances will affect the key biogeochemical mechanisms controlling decomposition—mineral protection, redox zonation, water content and movement, and plant-microbe interactions. We assess the spatial and temporal scales over which decomposition mechanisms operate and how their effectiveness may change following disturbances. We suggest that better integration of decomposition mechanisms into blue-carbon models may improve predictions of soil organic carbon stores and facilitate incorporation of coastal vegetated ecosystems into global budgets and management tools.**

Blue-carbon ecosystems play an outsized role in the global carbon cycle. They occupy 0.07–0.22% of the Earth's surface and bury 0.08–0.22 PgC yr<sup>-1</sup>, which is comparable to 0.2 PgC yr<sup>-1</sup> transferred to the seafloor and equivalent to ~10% of the entire net residual land sink of 1–2 PgC yr<sup>-1</sup> (refs. <sup>1,2</sup>). Blue-carbon ecosystems are remarkably efficient at burying organic matter (OM), yet there is considerable spatial heterogeneity in soil stocks that does not reflect latitude, salinity or many other variables<sup>3–7</sup>. Preservation of blue-carbon deposits, which mostly accumulated when sea-level rise (SLR) rates were slower (Box 1)<sup>8</sup>, and the potential for future burial are threatened by anthropogenic and global-change disturbances that reduce macrophyte production and destabilize soils. Disturbances to soils are particularly worrisome because they could cause land subsidence, increase greenhouse-gas concentrations, and exacerbate coastal hypoxia and acidification by promoting the oxidation of buried soil organic carbon (SOC) to CO<sub>2</sub> (refs. <sup>4,5,9,10</sup>).

The magnitude of disturbance effects on blue-carbon decomposition is highly uncertain. Recent studies posit that 25–100% of destabilized blue SOC is eventually respired, producing CO<sub>2</sub> fluxes equivalent to 3–19% of annual global deforestation emissions<sup>5,9,11,12</sup>. Uncertainty surrounding the fate of unearthed, eroded or otherwise destabilized SOC makes it difficult to predict the sustainability of blue-carbon ecosystems and incorporate them into global budgets and management tools. In part, these uncertainties reflect limited understanding of how preservation mechanisms, which have been better characterized in oceanic and terrestrial soils, operate in coastal vegetated ecosystems.

Blue-carbon ecosystems are distinct environments from terrestrial and oceanic ecosystems but share some commonalities. Terrestrial soils are typically oxygenated and well drained, with a low water content, except during heavy precipitation. Oceanic

sediments are saturated, with redox and diffusional gradients, and relatively constant temperature, light and physical conditions. In contrast, soil water content and chemistry vary among blue-carbon ecosystems and over intertidal elevation gradients, reflecting local hydrology. Rhizosphere interactions between plants and microbes further contribute to a dynamic geochemical environment that changes over hourly-to-annual and mm-to-km scales. Because of these differences, soil-decomposition models developed for terrestrial and oceanic ecosystems cannot be directly translated to blue-carbon ecosystems; instead those models offer crucial insights into mechanisms controlling preservation and loss<sup>13–16</sup>. Here, we assess four key biogeochemical controls on blue-carbon decomposition—allochthonous particle deposition and mineral protection, soil water content and movement, redox conditions and plant-microbe interactions—and propose a conceptual framework to improve predictions of SOC storage (Table 1).

## Vulnerability to decomposition

Accumulation of blue-carbon deposits has traditionally been ascribed to the preservation of intrinsically recalcitrant macromolecules (for example, lignin) under waterlogged, anoxic conditions where bacteria rely on energetically poor electron acceptors. Reflecting this, blue-carbon models generally parameterize decomposition as simple, modified decay functions<sup>17–21</sup>. However, recent evidence in oceanic and terrestrial ecosystems reveals that microbes can extensively decompose complex plant macromolecules and degradation products under suitable environmental conditions<sup>14,15,22</sup>. The central role of microbes in controlling decomposition, rather than molecular recalcitrance, also applies to blue-carbon ecosystems because the key factors affecting microbial diversity, activity and access to OM in ocean sediments and terrestrial soils operate in concert along coasts.

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**Box 1 | Evolution of blue-carbon ecosystems**

Blue-carbon ecosystems are common features of estuaries, lagoons and deltas. They developed in subtidal (seagrasses) and intertidal (salt marshes and mangroves) zones in mostly temperate and tropical regions over the past 2,000–6,500 yr, after SLR rates slowed to  $<0.5 \text{ mm yr}^{-1}$  and coastal waters infilled with soil<sup>8,96</sup>. Plant species richness is typically greatest in tropical mangrove forests, with over 70 species in Southeast Asia, lower in temperate latitudes and lowest in Arctic salt marshes<sup>96</sup>. Blue-carbon ecosystems bioengineer soil elevation by trapping fine particles and accumulating undecomposed roots and rhizomes. These processes enable blue-carbon ecosystems to keep pace with SLR and facilitate sequestration of 276–822 Tg  $\text{CO}_2 \text{ yr}^{-1}$ , which is faster than oceanic or terrestrial ecosystems<sup>2,5,11</sup>. Blue-carbon storage and sink capacity are threatened, however, by anthropogenic and climate-related disturbances that cause areal losses of 0.16–7%  $\text{yr}^{-1}$  (refs. <sup>2,95,97</sup>) and may prevent continued vertical elevation gain. Efficient preservation of newly deposited and ancient OM is therefore key to the future sustainability of blue-carbon ecosystems.

Deposition of allochthonous particles increases soil elevation and enhances tidal-wetland resilience against SLR<sup>23,24</sup> while stabilizing OM against decomposition (Fig. 1). Deposited oceanic and terrestrial particles contribute different OM, minerals and microbial communities to blue-carbon soils, thereby increasing complexity<sup>25–27</sup>. Deposited OM increases soil carbon content and stimulates respiration in surface horizons, reducing aerobic decomposition<sup>28</sup>. Mineral associations and narrow pore spaces physically protect OM from decomposition by catalysing condensation reactions, altering molecular structure (for example, folding), and inhibiting enzyme access<sup>29,30</sup>. The strength of organo–mineral sorption interactions varies with bond type and environmental conditions<sup>29</sup>. In the Changjiang estuary system, for example, the fraction of organic carbon (OC) associated with reactive iron was lower in mobile muds, suggesting that repeated resuspension promotes desorption, with a preferential loss of carbon from marine sources<sup>31</sup>.

Soil water content and movement influence decomposition by changing the geochemical environment (Fig. 1). In tidal wetlands, soil water levels and chemistry change over intertidal elevation gradients, with more regularly flushed soils near creekbanks and drier conditions upslope, creating a vertically and laterally complex geochemical environment. Overlaid upon this spatial zonation is temporal variability in flooding duration and extent, which occurs over semi-diurnal and spring–neap tidal cycles. Tides and evapotranspiration affect soil moisture and salinity, thereby influencing OM vulnerability to decomposition<sup>32,33</sup>. Higher water content can cause desorption and enhance microbial access to OM, but accumulation of metabolites between flushing tides can inhibit activity<sup>34</sup>. Soil drying lowers pH, increases salinity, destabilizes organo–mineral aggregates, promotes sorption of hydrophobic molecules, and decreases pore-space connectivity<sup>32</sup>. These changes alter the three-dimensional structure of OM and vulnerability of certain functional groups and bonds to enzymatic degradation<sup>32</sup> and limit interactions between OM and decomposers<sup>15</sup>. Perhaps the strongest effects of changing soil water content and movement on decomposition occur through oscillating redox gradients. For instance, changes in tidal flushing and drainage of a temperate US salt marsh and advection through subtidal North Sea and Baltic Sea sands altered the balance of aerobic and anaerobic metabolisms and contributions from pathways recycling electron acceptors<sup>10,35</sup>.

Plant communities accrete SOC, through primary production and sediment trapping, and affect decomposition by creating a dynamic environment that changes over daily-to-annual cycles

(Fig. 1). Plant-litter biochemistry and input rates vary with species and tissue type, season, latitude and environmental context<sup>36,37</sup>. Thus, the woody stems and waxy leaves of mangroves contribute higher levels of structural compounds to soils than nitrogen- and phosphorus-rich algae<sup>38,39</sup>. Roots affect the soil environment by lowering bulk density, facilitating atmospheric exchange, and releasing gaseous (for example, oxygen), dissolved, and particulate compounds into anoxic horizons. As a result, blue-carbon plant communities influence the composition of OM available to microbes as well as the physical and chemical environment<sup>40</sup>. Root-derived OM can be preserved for millennia<sup>38,41</sup>, form aggregates with older detritus that enhance the stability of both, or be decomposed rapidly<sup>42</sup>. Microbes incorporating root-derived OM or oxygen contribute to decomposition in diverse ways, including nutrient mineralization, which feeds back to plant productivity, electron-acceptor recycling, and priming of refractory detritus<sup>43</sup>. For example, decomposition of tree-derived lignin was linked to the availability of labile compounds, suggesting that production of lignin-degrading enzymes is energy-limited<sup>44</sup>. Although plant–microbe interactions are limited to the rooting zone, their effects on OM transformations may determine whether recently deposited OC is stored for millennia.

The role of microbes in the stability of blue-carbon ecosystems remains poorly understood. Metagenomic analyses of temperate salt marsh and Northern Hemisphere seagrass soils document diverse microbial communities enriched in taxa involved in anaerobic metabolisms<sup>45,46</sup>. This extensive diversity may reflect the dynamic, constantly changing nature of blue-carbon soils. Microbial adaptations to fluctuating environments include phenotypic switching to persist cells to await more favourable conditions<sup>47</sup>. This leads to a large number of inactive taxa that function as a genetic reservoir<sup>46</sup>. Further, recent metagenome-assembled genomes from seagrasses in Portugal and France suggest that some microbial taxa have the genetic capacity to perform an array of metabolic functions to accommodate fluctuating conditions<sup>48</sup>. Numerous factors influencing bacterial metabolism and the fraction of the community that is active, including the supply of biologically available OM and the presence of suitable electron acceptors<sup>49</sup>, vary over temporal and spatial gradients in blue-carbon ecosystems, further exacerbating our ability to predict microbial carbon utilization. Microbes also contribute to SOC accumulation via their own necromass<sup>50</sup>, though the persistence of necromass through time and in response to disturbances is unknown. Understanding how these features of soil microbial communities feed back on carbon cycling is essential for predicting long-term storage.

The dynamic conditions that distinguish coastal vegetated ecosystems from oceanic and terrestrial ecosystems affect the relative importance of different preservation mechanisms across temporal and spatial scales. Assessing the singular and interactive effects of these mechanisms will provide valuable insight into factors driving heterogeneity in SOC stocks<sup>6,11,13</sup>.

**Fate in a changing environment**

Disturbances, including SLR, warming, eutrophication and landscape development, complicate predictions of blue SOC stocks and are estimated to release 0.15–1.02 Pg  $\text{CO}_2 \text{ yr}^{-1}$  (ref. <sup>9</sup>). Characterizing how disturbances affect the balance between decomposition and preservation may help to refine SOC-loss estimates.

SLR elicits complex ecological, geochemical and geomorphic responses, and may initially increase OM production and storage, but, as rates accelerate, will likely cause ecosystem loss (Fig. 2a)<sup>21,24,51</sup>. At moderate SLR rates, shallow seagrasses may migrate towards the shore<sup>52</sup> and emergent wetlands will change along intertidal elevation gradients as species tolerant of greater inundation and higher salinities shift upslope<sup>53</sup>. Seagrass and wetland range expansions increase SOC stocks, through root production and particle trapping, but also alter soil structure, redox, OM composition and microbial

**Table 1 | Conceptual framework of four mechanisms regulating microbial access to OM**

	Particle deposition and mineral protection	Soil water content and movement	Redox zonation	Plant and microbial processes and interactions
Effect on soil microbes	Physical and ionic hindrance	Pore-space connectivity, pore-water chemistry, OM 3D configuration	Electron-acceptor availability	OM composition and input, priming, soil structure, gas diffusion
Effectiveness altered by				
Soil geochemistry	Minerals, grain size, porosity, oxygen, pore-water chemistry	Porosity, grain size, bulk density	Diffusion and advection, soil water content	Pore-water content and chemistry, nutrients, microbial community
Environmental setting	Allochthonous particle input via rivers and estuaries	Wetlands only: tides, ET, precipitation; seagrass only: advection	Particle deposition rate, root oxygen loss, soil drainage	All ecosystems: temperature; wetlands only: tides, drainage; seagrass only: light levels
Disturbances	River damming, soil erosion and aeration, wetland draining, dredging	Wetlands only: SLR, tidal manipulations; seagrass only: waves	All ecosystems: eutrophication, dredging, bioturbation; wetlands only: SLR, draining	SLR, warming, eutrophication, habitat destruction, erosion
Maps to ecosystem characteristic	Ecosystem edges, river-dominated watersheds	Wetlands only: changes with tidal flooding and ET; seagrass only: bed edges, plant density	All ecosystems: root zone; wetlands only: elevation gradients	Root zone, plant species composition
Surface or sub-surface soil horizons	Both	Wetlands only: varies with elevation, distance from creekbank; seagrass only: surface	Variable in rooting zone, more constantly anoxic in sub-surface	Root zone
Timeframe of effects on decomposition	Long term, particularly in deeper horizons	Affects the likelihood that newly deposited OM will be preserved	Affects the likelihood that newly deposited OM will be preserved	Affects new OM inputs, likelihood of long-term preservation

The mechanisms' effectiveness changes in response to the soil geochemical environment, environmental setting and disturbance. These mechanisms map to environmental characteristics and soil depth horizons and vary in effectiveness over shorter- and longer-timescales. Pore-water chemistry includes pH, nutrients, electron acceptors and salinity. ET, evapotranspiration; 3D, three-dimensional structure.

communities. Soil accumulation supports vertical accretion and, consequently, resilience to SLR<sup>23,24</sup>. Yet, seagrass and wetland survival depend on the availability of space for migration, which is limited by coastal development<sup>52,54</sup>.

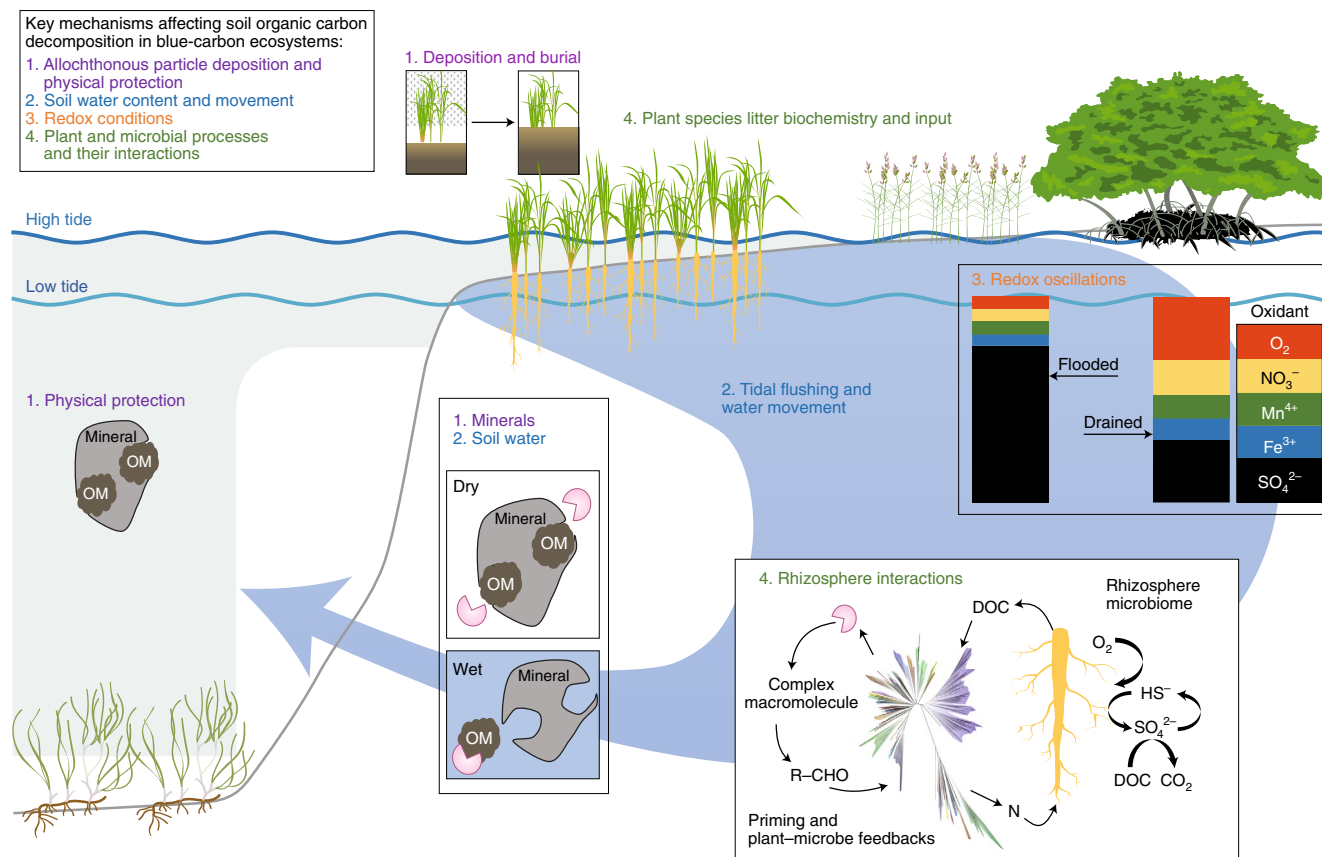
The impacts of SLR on tidal wetland SOC stocks hinge on a changing balance between inputs and losses (Fig. 2a). Higher rates of marsh productivity, under slow-to-moderate SLR<sup>24</sup>, increase deposition but may also catalyse belowground interactions that impact decomposition. A field experiment simulating SLR found that greater marsh-grass biomass production was linked to more oxidizing belowground conditions and higher soil respiration<sup>55</sup>. Root oxygen and OC release likely stimulated aerobic bacteria and metabolisms recycling electron acceptors, thereby priming decomposition of older detritus<sup>55</sup>. Moreover, the oxidation of reduced, toxic sulfides likely had a positive feedback on grass production (Fig. 1). The effects of greater tidal flooding on decomposition are unclear because it will likely increase pore-water connectivity, flush metabolites, and prevent hypersaline and low pH conditions, but also lower redox potentials, which slows respiration and lignin degradation<sup>56</sup> (Fig. 2a). Excessive SLR causes plant dieback, which destabilizes soils. Eroded OM may be redeposited locally<sup>8</sup>, buried nearshore, or oxidized photochemically or microbially<sup>30</sup> while deeper material could remain stored. Predicting changes in SOC stocks is difficult because the net effects on production, decomposition and resuspension are unclear and will vary across intertidal elevation gradients and relative SLR rates.

SLR also causes ecosystem-state changes, by converting tidal freshwater wetlands into salt marshes and mangroves. Rates of land conversion are variable, mirroring relative SLR<sup>57</sup>, but may be substantial. A 52-cm rise in sea level, for example, could shrink tidal

freshwater (−38%) and salt marshes (−8%) but expand brackish (+4%) and transitional (+780%) marshes in the southeast US<sup>57</sup>. Sulfate-rich seawater kills freshwater plants, facilitating colonization by saltwater communities, and shifts the dominant bacterial metabolism from methanogenesis to sulfate reduction<sup>58</sup>. Seawater inundation raises pore-water ionic strength and pH, catalysing abiotic reactions that release inorganic nitrogen and phosphorus from the soil matrix<sup>58</sup>. Consequently, SLR-driven changes in pore-water chemistry can elicit biotic and abiotic responses that result in lower methane emissions but higher decomposition rates and, ultimately, lower SOC concentrations<sup>58</sup>.

Climate warming impacts ecosystem thermodynamics and ecology in complex ways, particularly at higher latitudes<sup>59</sup>, which makes predicting changes in SOC storage challenging. Terrestrial warming studies often observe an initial spike in soil respiration due to greater microbial production and extracellular enzyme activity. This ephemeral response reflects depletion of readily decomposable substrates, inaccessibility of mineral-protected bioavailable OM, and lower bacterial growth efficiencies<sup>59–61</sup>. Larger, refractory compounds are theoretically more destabilized by rising temperatures, however, absolute decomposition rates may be slower<sup>59,62</sup>. The implications for blue-carbon soils, where data are limited, are that warming reduces the likelihood that recently deposited OM will contribute to storage and that older, refractory deposits may become destabilized, particularly if belowground conditions become more oxidizing (Fig. 2b)<sup>63</sup>. Moreover, warming effects may be more pronounced in organic-rich peats, where mineral protection of OM is less likely.

Warming also indirectly affects soil OM cycling by affecting ecological communities. Rising temperatures stimulate primary



**Fig. 1 | Four key mechanisms affect blue SOC decomposition.** (1) Allochthonous particles slow decomposition by increasing burial and through mineral interactions<sup>28,29</sup>. (2) Soil-water effects on OM-particle interactions, and pore-space connectivity and chemistry<sup>32</sup> vary across intertidal elevation gradients. (3) Redox oscillations reflect tides, advection, root oxygen loss and bioturbation<sup>35,74,88</sup>. (4) Plants interact with soil microbes by releasing compounds (for example, DOC and oxygen) into the rhizosphere<sup>55</sup>. Partial circles represent enzymes. DOC, dissolved organic carbon; CHO, an organic molecule. Tree of life image adapted from ref. <sup>93</sup>, Springer Nature Ltd.

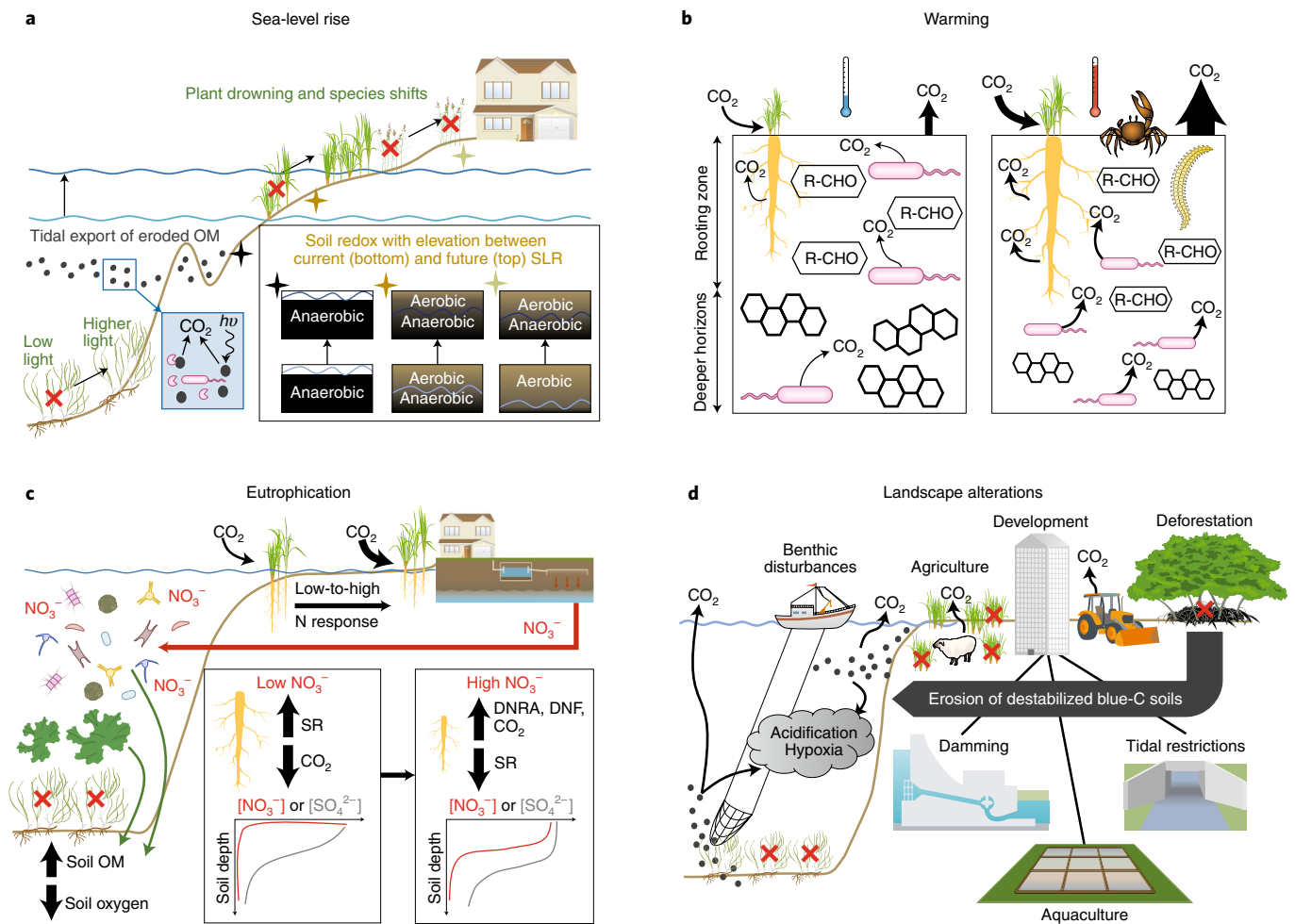
production and catalyse species range shifts, thereby altering OM inputs and composition (Fig. 2b)<sup>64,65</sup>. Rising winter temperatures have facilitated mangrove expansion poleward on five continents into latitudes historically dominated by salt marshes<sup>64,66</sup>. Differences in species-specific productivity and changing inputs of lignin and leaf waxes may, in turn, alter SOC stocks. However, warming and related stressors (for example, drought<sup>67,68</sup>) can reduce plant productivity by exceeding physiological tolerances, increasing soil salinity and altering trophic interactions<sup>69,70</sup>. Warming waters are predicted to cause the highly productive seagrass, *Posidonia oceanica*, to disappear from the western Mediterranean Sea by mid-century<sup>69,71</sup>. Subsequent plant losses destabilize soils, increasing vulnerability to erosion. Range expansion of benthic animals, such as bioturbating fiddler crabs<sup>72</sup>, alters soil redox, and by extension respiration rates and pathways<sup>73,74</sup>. The complexity of warming impacts on SOC challenges us to think about near-term effects on surface horizons and potential long-term destabilization of deeper deposits.

Coastal eutrophication impacts most blue-carbon ecosystems and, like warming, affects OM production and decomposition (Fig. 2c). Global seagrass losses have been attributed to eutrophication as nutrient-fuelled macroalgal and epiphytic growth reduces benthic light levels<sup>75</sup>. Algal deposition and seasonal hypoxia could enhance OM storage; however, seagrass loss increases erodibility<sup>71</sup>. In salt marshes, nutrients stimulate aboveground production at the expense of belowground allocation and may therefore slow OM accumulation<sup>76</sup>. In contrast, nutrient enrichment increased SOC in a Brazilian mangrove forest<sup>77</sup>. Nutrient enrichment promotes

respiration directly, by supplying electron acceptors (that is, nitrate) that are more energetically favourable than sulfate, and indirectly, by increasing inputs from labile algae and increasing the N:C of soils and plant detritus<sup>78</sup>. Percolation of nutrients to deeper horizons could also destabilize older deposits<sup>79</sup>. Consequently, eutrophication will likely result in a net reduction in SOC in some blue-carbon ecosystems, with losses exacerbated by stressors that promote erosion (for example, SLR) and respiration (for example, warming).

Anthropogenic landscape alterations contribute to global losses of blue-carbon ecosystems (Fig. 2d). Expansion of aquaculture, rice and palm-oil production is driving losses of highly diverse mangrove forests in Southeast Asia<sup>11,80</sup>. Habitat destruction removes vegetation and disturbs soils, increasing erodibility and vulnerability to decomposition. The unknown fate of SOC, which varies with habitat type, time-since-disturbance, and disturbance extent, introduces uncertainty in carbon-loss estimates<sup>5,9</sup>. Other alterations, such as river damming, wetland draining, tidal restrictions and even recreation (for example, boat propellers), reduce ecosystem sustainability and SOC storage over longer timeframes by changing plant and soil inputs and belowground geochemistry (for example, redox)<sup>10</sup>. Habitat restoration and creation could counteract lost functions but require decades<sup>81,82</sup>.

Predicting SOC fate in dynamic coastal environments is complicated by multiple, interacting disturbances. Despite the challenges, characterizing how simultaneous disturbances impact decomposition is critical because soil respiration and erosion



**Fig. 2 | Disturbances impact decomposition by changing environmental conditions.** **a**, SLR alters plant communities, destabilizes soils and affects pore-water chemistry<sup>21,24,58</sup>. Red crosses indicate dieback. **b**, Warming theoretically enhances respiration more than production<sup>94</sup>, promoting carbon loss. Species range shifts may alter soil inputs and processing<sup>65</sup>. R-CHO and polycyclic structures represent simple and complex molecules, respectively. **c**, Eutrophication increases plant productivity, soil OM content and electron-acceptor availability. SR, sulfate reduction; DNRA, dissimilatory nitrate reduction to ammonia; DNF, denitrification. **d**, Landscape alterations often reduce plant productivity and destabilize soils<sup>95</sup>.

contribute to land subsidence, raise greenhouse-gas levels, and intensify coastal acidification and hypoxia.

**Conceptual framework for assessing vulnerability**

The future of blue-carbon ecosystems increasingly relies on soil OM preservation. Yet, decomposition models are often parameterized as first-order decay functions with few discrete OM pools and defined limits on loss of the more refractory fraction<sup>17,19–21</sup>. Re-evaluating decomposition within a framework of biogeochemical mechanisms that map onto ecosystem properties could improve predictions of blue SOC stocks (Table 1).

Allochthonous particle deposition and physical protection are likely important in regions with high fine-grained particle delivery and deposition rates<sup>16,30</sup>. Soil OC stocks were twice as high in Australian salt marshes within fluvial compared to marine geomorphic settings<sup>16</sup>. Relationships between soil characteristics and OC content were variable in European<sup>83,84</sup> and Australian<sup>85</sup> seagrass meadows, reflecting geomorphology, hydrology and species-specific deposition. The effectiveness of physical protection is also reduced by disturbances that increase oxygen and light exposure (for example, erosion and resuspension) and alter ionic strength (for example, SLR)<sup>28,31,32,86,87</sup>. Because such disturbances are more likely to affect surface soils, mineral-bound OM that

reaches deeper, more stable horizons will likely be preserved over longer timeframes.

Oscillating redox conditions affect surface soils in seagrass, mangrove and salt-marsh ecosystems. Bioturbation, root oxygen loss and pore-water advection, among other processes, deepen oxygen penetration depth, increasing decomposition via aerobic respiration and pathways recycling electron acceptors<sup>35,55,74</sup>. Deeper horizons are more continuously anaerobic, which favours preservation. In intertidal wetlands, redox conditions vary with tidal inundation across elevation gradients<sup>88</sup>. Disturbances that aerate soils are generally restricted to surface horizons but episodic events, such as storms, could expose deeper deposits<sup>40</sup>.

The effects of soil water content and movement are likely stronger, but more spatially and temporally variable, in surface horizons, permeable soils and wetlands where evapotranspiration and tidal inundation change with elevation gradients and lunar phases<sup>24,35,88</sup>. Creekbanks of meso- and macro-tidal wetlands are more frequently flooded and have greater pore-water turnover than soils at higher intertidal elevations. Seagrass soils are continuously inundated but local hydrodynamics and pore-water advection alter redox gradients<sup>89</sup>.

Disturbance impacts on plant–microbe interactions remain an important unknown. Shifts in plant species cover, and even lineage<sup>90</sup>, change soil OM inputs and composition, affecting

## Box 2 | Integrating blue-carbon ecosystems into large-scale models

Expanding decomposition models to account for parameters, such as soil matrices, thermodynamics, redox oscillations and plant–microbe interactions, will improve predictions of SOC storage and enable identification of emergent properties, which can be utilized for upscaling into spatially explicit Earth systems models (ESMs). Progress has been made regarding terrestrial systems, where ‘reduced complexity models’<sup>98</sup> and models acknowledging microbial and functional diversity, carbon-use efficiency and exoenzyme production have been incorporated into ESMs and improved spatial predictions of soil carbon<sup>99</sup>.

microbial biogeochemistry. Thus, global-change drivers that shift plant community structure or genetic diversity could impact below-ground root–microbe interactions and processes, such as priming, that affect OM preservation<sup>42,43,55,65</sup>.

These four mechanisms operate differently in coastal vegetated ecosystems than in oceanic and terrestrial environments, and impact both the likelihood that recently deposited OM contributes to long-term storage and the fate of unearthed SOC following disturbances. Quantifying how these mechanisms, alone and in concert, affect decomposition over vertical and horizontal gradients and under multi-disturbance scenarios will be critical for building more predictive SOC models.

### Moving forward

Current knowledge-gaps limit the development of realistic SOC and ecosystem-change models. Computational and methodological advances are required to couple our emerging understanding of the soil microbiome with characterizations of OM, in terms of its sources, reactivity and diagenetic state (Box 2). Moving forward also requires more mundane steps, such as adopting standardized field and lab methodologies (for example, the Blue Carbon Initiative), contextualizing soil (for example, grain size and mineralogy), biogeochemical (for example, OM content and composition, and pore-water chemistry), and ecological (for example, plant–microbe interactions) properties, collecting time-series data (for example, Long-Term Ecological Research sites), and developing open-access databases (for example, the Coastal Carbon Atlas). These steps will allow for better synthesis across environmental, disturbance and climatic gradients and will facilitate the evaluation of SOC observations within a framework of ecosystem properties (Table 1), thereby providing mechanistic insight into drivers of spatial heterogeneity<sup>3–6</sup> and moving the field towards a more predictive understanding of preservation mechanisms.

A more mechanistic understanding is needed to improve decomposition models and therefore support effective ecosystem management. Blue-carbon ecosystems provide economic value by buffering communities from coastal storms, providing habitat that supports commercial and recreational fisheries, and sequestering atmospheric CO<sub>2</sub> in soils, among other services<sup>9,91</sup>. Recognizing this, communities invest billions to conserve, restore and create these ecosystems<sup>92</sup>. It is therefore vital to identify high-value blue-carbon ecosystems and take measures to increase their sustainability so that communities can protect infrastructure and plan for future scenarios.

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A.C.S. conceived and wrote initial drafts. All authors contributed to idea development and manuscript writing and editing.

### Competing interests

The authors declare no competing interests.

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