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Potential negative effects of ocean afforestation on offshore ecosystems

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Our scientific understanding of climate change makes clear the necessity for both emission reduction and carbon dioxide removal (CDR). The ocean with its large surface area, great depths and long coastlines is central to developing CDR approaches commensurate with the scale needed to limit warming to below 2 °C. Many proposed marine CDR approaches rely on spatial upscaling along with enhancement and/or acceleration of the rates of naturally occurring processes. One such approach is 'ocean afforestation', which involves offshore transport and concurrent growth of nearshore macroalgae (seaweed), followed by their export into the deep ocean. The purposeful occupation for months of open ocean waters by macroalgae, which do not naturally occur there, will probably affect offshore ecosystems through a range of biological threats, including altered ocean chemistry and changed microbial physiology and ecology. Here, we present model simulations of ocean afforestation and link these to lessons from other examples of offshore dispersal, including rafting plastic debris, and discuss the ramifications for offshore ecosystems. We explore what additional metrics are required to assess the ecological implications of this proposed CDR. In our opinion, these ecological metrics must have equal weight to CDR capacity in the development of initial trials, pilot studies and potential licensing.

There is growing interest in extending seaweed farming into oceanic waters. In this study, we use the term ocean afforestation, defined as 'carbon dioxide removal through basin-scale seaweed farming in the open ocean'[1] and based on 'forests of macroalgae (kelp and other seaweed)'[2]. We consider this distinct from other purposeful occupation of the open ocean with coastal macroalgae, such as macroalgal cultivation[3]. However, many of the potential negative effects we discuss below could also apply in these scenarios. The goal is to expand the 'marine real estate' of coastal seaweed stocks used for blue carbon beyond the relatively narrow nearshore zone[4,5]. In doing so, proponents of ocean afforestation assert that marine carbon dioxide removal (CDR) can be enhanced to contribute substantially to the 'negative emissions' needed to limit warming to <2 °C (refs. [6–8]). The growing interest in ocean afforestation is probably linked to a resurgence in exploring marine CDR approaches after the 2015 Paris Conference of the Parties 21 (https://ec.europa.eu/clima/events/articles/0107_en), at which negative emissions were considered, along with emission reduction, necessary to restrict warming to <2 °C. This revived debate into a climatic role for marine CDR has been further catalysed by the Intergovernmental Panel on Climate Change 1.5 °C special report[9] and Working Group 1 report[10], which reinforced that both emission reduction and CDR are essential.

More than 20 marine CDR approaches have been proposed; all have major knowledge gaps centring on major uncertainties around both side effects and the quantification of their efficacy for carbon sequestration (defined by the Group of Experts on the Scientific Aspects of Marine Environmental Protection Working Group 41 (ref. [11]) in Annex 4 as 'The secure storage of a substance. In the case of sequestration of CO_2, this is generally taken to mean secure storage for a minimum of 100 years'). Our viewpoint in this Perspective is

that we must balance the urgent need to seek and explore all options into approaches to CDR[11] with the need to provide a rigorous scientific assessment of each approach, thus better informing the wider debate on the eventual deployment of the most promising methods[12].

The focus of marine CDR approaches has been on the science and technology needed to develop CDR of sufficient magnitude (gigaton(s) of CO_2) and timescales (multiple decades). However, relatively little effort has been made to assess the potential side effects of marine CDR[11]. Only a few studies have targeted physico-chemical feedbacks from marine CDR, including the inadvertent release of other potent greenhouse gases after ocean iron fertilization (OIF)[13]. Even less scrutiny has been accorded to the potential effects of marine CDR on ocean ecology[14]. Given the growing importance of the oceans to global food security (United Nations sustainable development goals (SDGs))[15,16], more focus on the ecological effects of marine CDR is essential given the likelihood that perturbation of large ocean regions will be needed by marine CDR methods to help to limit warming[11].

Marine CDR approaches
In an ecological context, marine CDR approaches have been divided into two broad categories[14], in which manipulation of ocean properties results in either direct or indirect perturbation of offshore ecosystems (Box 1). A marine CDR technique such as OIF is a prominent example of a direct ecological perturbation as it requires purposeful alteration of the composition of endemic species within offshore ecosystems to succeed (that is, a shift from small to large resident oceanic phytoplankton to enhance the sinking flux of carbon to the oceans' interior[17]) (Box 1b). Examples of indirect ecological perturbations include ocean alkalinity enhancement (OAE) since it must alter ocean carbonate chemistry, not ecology, to

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Box 1 | Examples of three distinct ecological categories for marine CDR methods

Two initial categories, inadvertent and purposeful ecological effects, cover many marine CDR approaches, based on the framework in Russell et al.[14]. In the first ecological category[14], there is an inadvertent reshuffling of the community structure of the resident phytoplankton due to the indirect effects of OAE but one that is not a prerequisite for the success of OAE. OAE is characterized as 'CDR (geochemical)'[11] as it relies on enhanced chemical sequestration of CO_2 driven by accelerated weathering of carbonate or silicate minerals. In Box 1a, purposeful addition of these minerals alters the upper oceans' carbonate chemistry resulting in conditions that may favour calcifying resident phytoplankton over non-calcifiers[18]. Box 1b provides an example of the other category, which is based on the need to purposefully alter ecosystem structure to modify its function in the ocean carbon cycle. In the case of OIF, characterized as 'CDR (biology)'[11], the supply of iron to the ocean results in a floristic shift from the dominant small resident phytoplankton (picophytoplankton and nanophytoplankton) to a bloom of the rarer (iron-stressed) larger resident diatoms. This shift alters the ecological function from a low downward export, high recycling community to a high export, low recycling system that is required to boost marine CDR[17].

By contrast, ocean afforestation does not fit within either of these two ecological categories as it requires purposeful occupation of offshore waters with rafts of coastally derived macroalgae (and their associated organisms denoted by the magnifying glass symbol over the macroalgal blade), as only they have sufficient depth to result in successful carbon sequestration needed for this marine CDR approach (Box 1c). The planned offshore occupation will be transient as the macroalgal rafts are designed to be made of biodegradable materials that will enable their sinking after 6–8 months of growth. However, this time in the open ocean is sufficient to both alter oceanic properties and have an impact on the resident biota (for example, the phytoplankton denoted by the magnifying glass) within offshore ecosystems. Furthermore, it is likely that as such ocean afforestation ventures move towards full deployment, the offshore ocean will become increasingly congested with macroalgal rafts from different consortia for much of the

a Ocean alkalinity enhancement (OAE)

b Ocean iron fertilization (OIF)

c Ocean afforestation
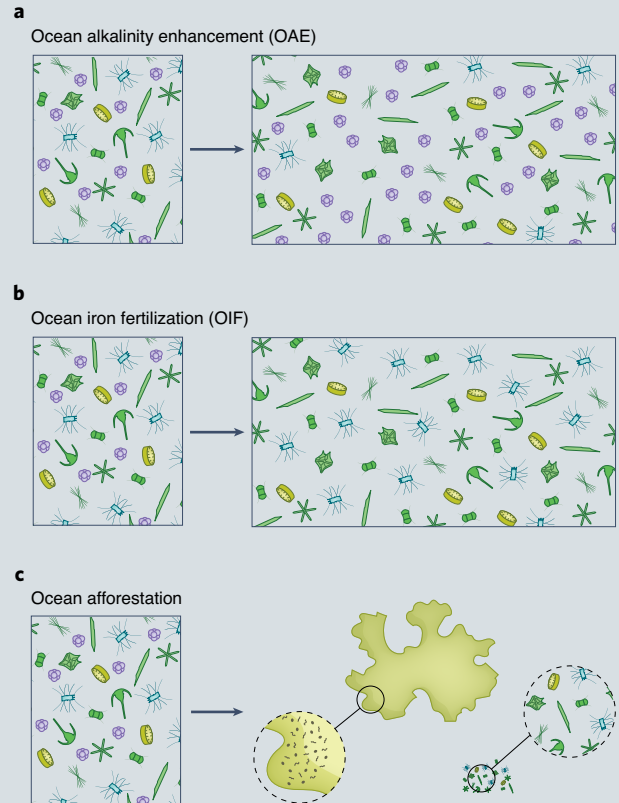
annual cycle, resulting in no respite from occupation of offshore waters. Thus, even in the formulation of pilot studies, the issue of the scale dependency of side effects resulting from full-scale deployment needs careful consideration via 'fore-sighting'[90]. Therefore, such planned occupation of offshore waters will result in a third ecological category and raises broader issues around the role of macroalgae as a 'nature-based' solution.

remove atmospheric CO_2 (Box 1a). However, the alteration of ocean chemistry may cause inadvertent alteration of offshore ecosystems due to side effects such as stimulation of other endemic phytoplankton groups, for example, calcifiers[18].

In both examples, OIF and OAE are designed to enhance or accelerate rates of open ocean processes such as downward export of carbon or enhanced chemical carbon sequestration via alkalinity, along with increasing their areal extent onto large-enough scales to result in substantial marine CDR. For example, iron supply limits the rate of primary production in one-third of the global ocean[19], so that OIF would enhance primary productivity and alter phytoplankton community structure, which would probably boost export flux. OAE aims to speed up cycles of geochemical weathering (thereby enhancing alkalinity) associated with the riverine run-off that is widespread around coastlines[20].

In contrast to the two categories introduced in Box 1a,b, ocean afforestation differs fundamentally, in an ecological context, because it seeks, at basin scales, to populate what some proponents refer to as 'ocean deserts' (https://www.theintrepidfoundation.org/t/seaweed-regeneration) with coastal macroalgae attached to free-drifting platforms. The planned transformation of ocean deserts is without precedent for any proposed marine CDR because it introduces coastal macroalgae and associated nearshore microbes, flora and benthic fauna to offshore waters at scale (Box 1c). Thus,

ocean afforestation cannot be viewed simply as an offshore extension of a 'nature-based solution' (that is, blue carbon[21]) as it is a fundamental alteration of oceanic communities with a coastal assemblage (Box 1c). A major unknown is whether this third ecological category could result in the establishment of new hybrid ecosystems offshore.

This offshore translocation of nearshore biota has many implications for the integrity of oceanic ecosystems. To date, there has been limited discussion about how such a major offshore vector for macroalgae and their associated biota[22–24] might impact offshore food webs. This Perspective delves into wide-ranging ecological issues potentially linked to ocean afforestation that to date have received little attention across a wide range of viewpoints on the potential of ocean afforestation as a viable marine CDR approach[25] (also compare with Krause-Jensen and Duarte[26]). We advocate that improved understanding of the individual and cumulative influence of these many unknowns on oceanic biosecurity must be built into pilots and trials of ocean afforestation with the same rigour and emphasis as those needed to test the detection and attribution of CDR[27] or physicochemical side effects.

Projecting offshore trajectories of macroalgae

Ocean afforestation requires free-drifting macroalgae to be over deep water[28,29] (Fig. 1a) to permit purposeful sinking and hence
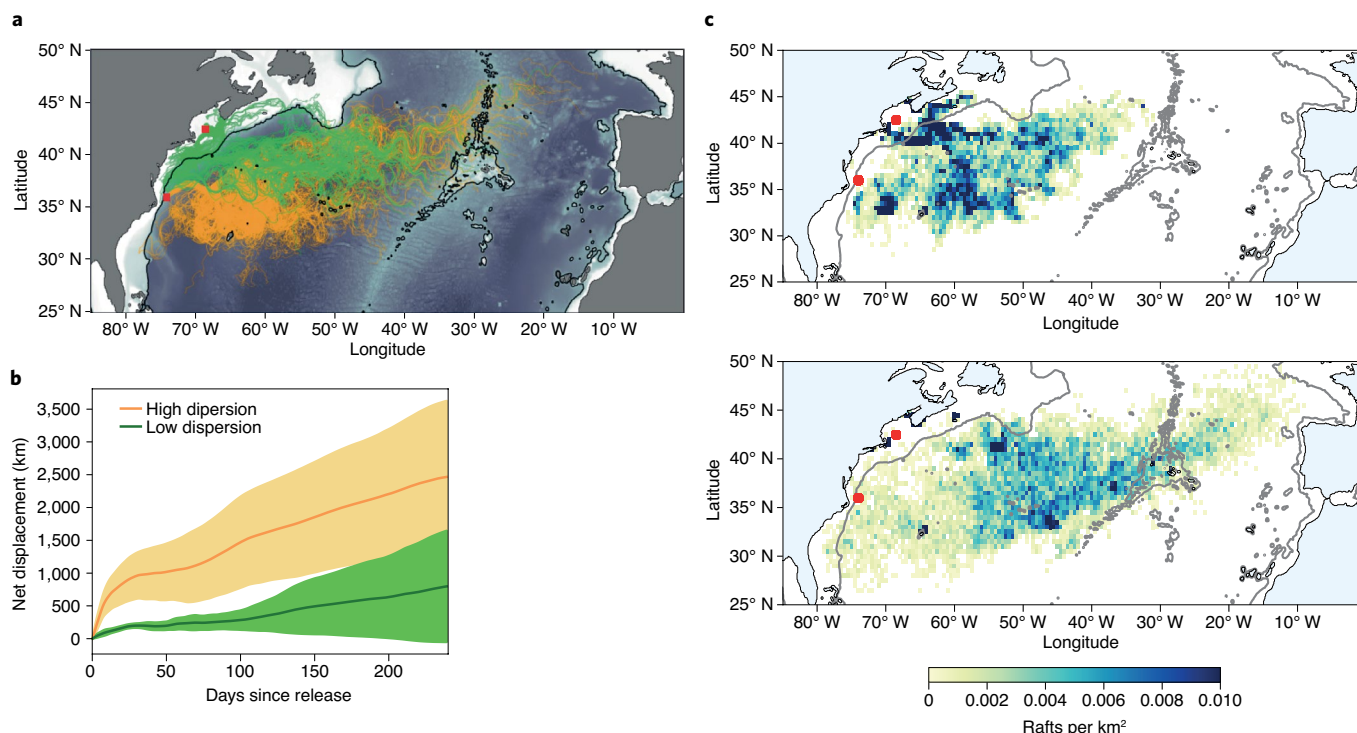
Fig. 1 | Model simulations to explore the potential offshore dispersal and distributions of coastal macroalgae. Seaweed will be purposefully added under the planned ocean afforestation pilot studies[28,29]. **a**, Virtual particle trajectories (free-drifting) represent macroalgal rafts and their density (rafts per km²) for an eight-month growing season after release in March 2013 for high-dispersion (orange, coastal Gulf Stream site) and low-dispersion (green, site further north) regimes. The initial particle release locations are shown in red; the coloured map represents the sea floor topography and the black contour indicates the 2,000-m isobath. Note that the virtual particles mimic macroalgae floating at the oceans' surface (analogous to the GASB), not slightly subsurface on rafts as has been proposed. **b**, A plot of displacement versus time. Mean (solid lines) ±1 s.d. (shaded area) of net displacement of virtual particles over time in the days since release for high (orange trajectories, centred on 36° N, 74° W) and low dispersion (green trajectories, centred on 42.5° N, 68.5° W) regimes in **a**. **c**, Map of the number of virtual particles per km² in each 0.5° latitude by 0.5° longitude bins (top), at the initial time of particle seeding after 120 d (middle) and after 240 d (bottom). Details of the model simulations are provided in the Supplementary Information.

carbon sequestration. Based on information from proponents, rafts (made from biodegradable materials, with pressure sensors to assess their ultimate fate) will initially be seeded with microscopic sporophyte stages of a coastal species such as sugar kelp. The macroalgal rafts on their offshore trajectory will have a projected 6–8 month growth season in the North Atlantic[29]. Macroalgae will probably be biofouled during their six-month passage offshore[22] and will carry an associated suite of 'passenger' organisms both attached (epibionts[30]) and free-living[22]. Hence, the assemblage being transferred offshore will be complex and probably result in additional ecological ramifications for open ocean ecosystems.

Furthermore, macroalgae will also transport their microbiome offshore[31,32], with unknowns about how associated onshore–offshore physicochemical and biological gradients will influence and/or interact with their resident microbes (their microbiome comprises heterotrophic and photosynthetic bacteria and viruses[31,33,34]). To explore the extent of the offshore trajectories of this coastal assemblage, we used a physical oceanographic modelling approach. Using the surface velocity output from a high-resolution ocean model, we seeded virtual kelp rafts at two sites at the surface of the North Atlantic Ocean and tracked the dispersion of these virtual rafts over the course of a growth season. Figure 1a presents the macroalgal dispersal scenarios from two hypothetical sites in the North Atlantic as suggested by proponents[29]. Together, the scenarios provide insights into the timescales of the purposeful occupation of the open ocean by macroalgae (Fig. 1b) along with projections, over time, of their density per km² offshore (Fig. 1c).

Simulated trajectories showed that macroalgae in a high-dispersion scenario have a net displacement of >2,000 km over 8 months (spring to autumn), spreading across the deep North Atlantic Ocean (Fig. 1a). Dispersion is initially rapid, with an average displacement of approximately 1,000 km within 30 d of seeding, and slows thereafter (Fig. 1b). Macroalgae seeded in a lower-dispersion coastal regime were displaced approximately 500 km on average within 8 months but there was wide-ranging dispersal with some particles remaining close to the seeding location throughout. Maps of density of virtual particles per km² (where each particle approximates a macroalgal raft or microfarm[28,29]) show that while densities were generally quite low (and depended on the initial seeding density), after four months particle density remained relatively high along the main dispersion pathways. After eight months of growth, dispersion led to lower particle densities, with the highest densities observed between 55° W and 30° W and in several bands near coastlines and islands (Fig. 1a).

These illustrative simulations are instructive since they reveal the scale of purposeful colonization of offshore waters by afforestation as far as the mid-Atlantic (Fig. 1a,b). They show the heterogeneity of macroalgal dispersion also evident from satellite imagery of the Great Atlantic *Sargassum* Belt (GASB) observed to recur for over a decade[35]. The GASB is a useful basin-scale demonstration of the influence of ocean currents on the distribution of free-drifting natural rafts of floating *Sargassum*[36].

The time series of simulated dispersal (density of macroalgae per km²; Fig. 1c) raises a series of issues. First, the density of rafts

after 4 and 8 months suggests that oceanic side effects (detailed below under direct and indirect effects) will be very limited, that is, <1/100 km². However, due to many unknowns about planned seeding strategies, the density (400 particles, added daily for 30 d) we selected was arbitrary. Second, the density of macroalgae will set both the magnitude of carbon sequestration and the potential for ecological side effects. A high carbon sequestration potential is the desired outcome of marine CDR[11] with ramifications for the magnitudes of associated side effects.

Coastal imprint on oceanic properties

The macroalgal influence on offshore ecosystems is twofold: (1) indirect ecological effects centred on the alteration of oceanic properties including the release of dissolved organic carbon (DOC) and volatile organic compounds (VOCs); (2) direct effects with ramifications for the structure and functioning of the resident (termed 'native' in invasion ecology) community. For example, chemical ecology (allelopathy) can drive competition between the occupying (termed 'adventive' in invasion ecology) macroalgae and native oceanic phytoplankton. We commenced by exploring the indirect ecological effects.

Indirect ecological effects. Much of the open ocean is an oligotrophic nutrient-poor region with intense competition for nitrogen (N) and phosphorus (P) by native phytoplankton, such that nutrient supply is driven by rapid recycling[37] or alternative strategies including N fixation[38]. Nutrient distributions reveal that both N and P are present at the nanomolar range (>1 to <100) over the low latitude ocean[37]. Brown seaweed takes up nitrate (at 5 μM ambient concentration) at 1–5 μmol g⁻¹ dry weight h⁻¹ (tissue N = approximately 1–2.5% dry weight) and phosphate (at 1 μM ambient concentration) at 0.1–0.2 μmol g⁻¹ dry weight h⁻¹ (tissue P = approximately 0.3% dry weight)[39–41]. However, these measurements were made with induced water flow at an unspecified rate relative to the seaweed, which increases the diffusive flux of solutes to the seaweed surface by decreasing the thickness of the diffusion boundary layer (DBL); the rate could well have been greater than the difference in speed of algal rafts and that of surrounding water, decreasing the nitrate and phosphate uptake rates[42].

The purposeful occupation of offshore waters by coastal macroalgae, with relatively high N and P requirements (although no data are available on their uptake rates at nanomolar concentrations) would probably exacerbate the uptake of nutrient stocks (see the model simulations[43]), which are projected to decrease further with climate change due to increased seawater density stratification[44]. In addition, the rapid microbial recycling of N and P over hours to days in offshore waters[37] would probably be hindered by longer-term (months) N and P retention within the macroalgal biomass[45]. Nutrient limitation driven by decreased upper ocean inventories[43], and lower rates of recycling, may cause wide-ranging outcomes including altered phytoplankton community structure[46], increased susceptibility to ocean warming for phytoplankton[47], reduced phytoplankton productivity[1,44] and/or altered nutrient stoichiometry[48]. Proposals for purposeful upwelling, for example, using fabricated 'ocean pipes' to enhance nutrient supply to resident phytoplankton in oligotrophic waters, could potentially be applied to macroalgae[49], with pilot projects emerging (https://www.climate-foundation.org/overview.html). However, artificial upwelling adds additional complexities to the ecological impacts of ocean afforestation as it also upwells higher-CO₂ waters[50,51].

Ocean afforestation will also influence DOC dynamics. Oceanic phytoplankton exude DOC as a strategy to release photosynthate during periods of nutrient limitation[52]. DOC release rates are typically intercompared between species using the metric percentage extracellular release (PER), that is, dissolved organic C release/dissolved organic release plus total particulate organic C[53].

Phytoplankton PER ranges from 2 to 50%[52] owing to multifaceted passive and active controls on exudation including environmental stress[54]. Macroalgal DOC release is also driven by multiple strategies including tissue fragmentation, stoichiometric overflow and herbivory deterrence[55]. A 1–39% range of PER[56,57] has been reported for macroalgae including *Sargassum*[58] for multiple reasons as for phytoplankton. For example, altered nutrient availability may increase PER[55]. Given the wide range of PER estimates above, and unknowns regarding how many macroalgal rafts will be released by proponents (Fig. 1), it is problematic to quantify how much macroalgal DOC could be released into offshore waters. The key driver of cumulative algal DOC release will be oceanic nutrient budgets, which set the magnitude of carbon fixation. Thus, the magnitude of DOC release is unlikely to change, unless there are major differences in PER between these algae, a major unknown for macroalgae under oligotrophic oceanic conditions.

Purposeful macroalgal colonization will also affect DOC quality. Few studies have partitioned the biochemical characteristics of DOC beyond demarcation of labile/recalcitrant/refractory but they revealed wide-ranging biochemicals[59]. Also, macroalgae release more coloured dissolved organic matter (DOM) than phytoplankton; coloured DOM composition is more labile than phytoplankton-derived coloured DOM[60]. In particular, high amounts of coloured DOM can be released by brown seaweed[61], including species being considered for ocean afforestation[28,29]. It is likely that the composition of the labile DOC released by macroalgae has implications for resident ocean microbes (Fig. 2). These include stimulation and inhibition of heterotrophic microbes (that is, due to more or less labile DOC[62]) and alteration of bacterial community structure (different DOC quality). Another unknown centres on changes to DOC exudation rates of macroalgae driven by the transition from nearshore to offshore environmental gradients (in pH, nutrients, optical clarity and photochemistry/bleaching[55]) as they drift offshore. For example, transitions towards warmer waters are reported to alter the biochemistry of DOC released by macroalgae with consequent detrimental effects on marine life[63].

Proposed offshore transport of arrays of free-drifting macroalgae, depending on their deployment depth, could increase the surface oceans' reflectance[1]; the release by macroalgae of VOCs (Fig. 2) will impact particle nucleation in the lower atmosphere and cloud dynamics and incoming solar radiation[64]. The underwater light spectrum may also be influenced by the release of coloured DOM, including phlorotannins. These potential changes have implications for both reradiation of light into space and for reducing incoming radiation (and its spectral characteristics) for the underlying phytoplankton communities (Fig. 2). Such alteration of the light climate will also influence the penetration of incoming short-wave radiation into surface waters[65,66], such that heat is differentially distributed through the water column when incoming radiation is captured by seaweed residing near the surface. This altered distribution of short-wave radiation may impact the temperature and stratification of the upper ocean[67] and thus influence the vertical mixing of nutrients.

Macroalgal attenuation of underwater light fields (see the model simulations[43]) may influence the position (at depth), thickness and ecological functioning of the deep chlorophyll maximum (DCM) (Fig. 2), which comprises a stratified community of photosynthetic picoprokaryotes and eukaryotes[68]. Such shading under macroalgal rafts has parallels, with the roles reversed, in the coastal ocean where nutrient loading leads to phytoplankton blooms that shade benthic macroalgae resulting in decreased macroalgal growth rates[69]. Offshore, macroalga-mediated shading effects may also have ramifications at depth (that is, >100 m) on resident vertical migrators such as mesozooplankton[70]. There may be consequent ecological effects on deep-ocean communities (mesopelagic and benthic)
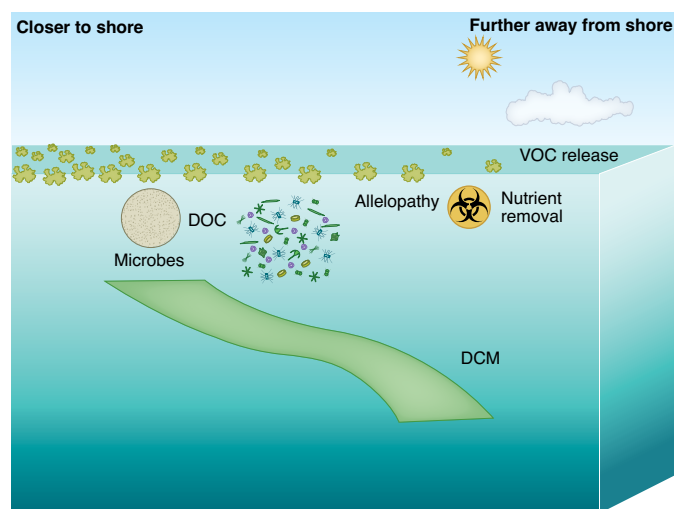
Fig. 2 | Schematic illustrating the potential ecological consequences of the offshore transport and dispersal of macroalgal rafts. These effects will take place during the purposeful multimonth occupation of open ocean waters[28,29]. Ocean afforestation side effects may have direct and indirect influences on offshore food webs. Direct effects include allelopathy (that is, chemical ecological competition between macroalgae and microalgae[73,74] (green cells), represented simplistically by a chemical hazard symbol) and coastal microbial colonization of oceanic waters originating from the macroalgal biome (denoted by the stippled disc symbol). Indirect effects include alteration of seawater properties (nutrient removal), release of macroalgal DOC (impacts on oceanic microbes) and VOCs (cloud symbol), altered light climate (reflectance)[1] and underwater light penetration. Research into the implications of VOC release for lower atmosphere processes is in its infancy[64] and represents a major unknown[1]. Reduced light penetration in the water column due to shading from macroalgal rafts[43] may impact the location and functioning of the DCM, denoted by the green subsurface layer, deepening offshore due to a higher density of macroalgal rafts (more underwater shading). The DCM is a subsurface niche set jointly by underwater irradiance levels and subsurface nutrient supply.

by altered food supply from above, driven by nutrients fuelling macroalgal rather than phytoplankton growth.

These potential imprints resulting from ocean afforestation are scale-dependent; thus, the full extent of the influence of macroalgal occupation on nutrient inventories, DOC dynamics or underwater light climate may not be apparent during any proposed pilot study (Fig. 1c). There is also evidence, from large-scale analogues of marine CDR approaches, of non-linear effects after the upscaling of oceanic perturbations[71]. Hence, the number of arrays per km^2 needed to drive substantial C sequestration (that is, full-scale deployment, not pilot studies) will set both the alteration of the offshore environment and the influence of direct effects of ocean afforestation on open ocean ecosystems.

Direct ecological effects. Direct effects include the competition between macroalgae and phytoplankton for key resources including light and nutrients that can result in both groups deploying chemical ecological strategies termed allelopathy[72]. For example, allelochemicals released by coastal macroalgae caused an inhibition of toxic dinoflagellate growth[73]. Such competition, driven by biochemically mediated inhibition of growth, is commonly observed in modified environments such as eutrophic estuaries[74]. The release of allelochemicals is a putative mechanism that macroalgae use to minimize the overlying shading by phytoplankton blooms fuelled by eutrophication[75]. In offshore environments, phytoplankton groups can outcompete others through allelopathy[76].

In addition to the indirect effects of ocean afforestation on nutrient stocks, there are inherent physiological differences between the nutrient acquisition strategies used by macroalgae and phytoplankton often linked to size and driven by surface area-to-volume ratios[77]. Phytoplankton can take up N more rapidly, per unit biomass, than macroalgae regardless of substrate concentration[77]. Furthermore, the DBLs of macroalgae[42] make them poor competitors for scarce nutrients with native small oceanic phytoplankton such as *Prochlorococcus* and *Ostreococcus*. The DBLs around seaweed blades will probably be even thicker in the open ocean as seaweed will be grown on drifting rafts, so the relative velocity at their surface will be reduced compared to seaweed growing on moored lines in coastal aquaculture systems or natural seaweed beds where they are anchored to rock surfaces[78]. The potential reduction of water movement through the canopy may further reduce their ability to take up nutrients (Fig. 1a). Furthermore, macroalgae exhibit little evidence for associative diazotrophy[79] and have no mechanisms for periodic vertical migration to obtain resources from the nutricline as observed for phytoplankton such as *Ethmodiscus* or *Rhizosolenia*[80].

Macroalgae will carry additional marine life with them as they are transported offshore, both within their microbiome (viruses and heterotrophic bacteria[31], cyanobacteria[34] or encrusting, attached and mobile epibionts[22,30]). Furthermore, they may also have associated free-living biota that drift alongside within their canopy[23,24]. In addition to adventive macroalgae, these groups of associated organisms may interact with the native biota in offshore waters. The microbiome associated with macroalgae is complex with diverse communities of heterotrophic bacteria[33], along with viruses, fungi and protozoa[81], which contribute to the complex interactions with the macroalgae. There is evidence that both microbial interactions[81] and environmental factors such as the availability of exuded DOC influence heterotrophic bacterial dynamics[33]. A further confounding factor in the context of ocean afforestation is that there is a very limited understanding of the functioning of the microbiome in cultivated macroalgae[32], which will probably be used for farmed macroalgal arrays[28,29]. A major risk associated with ocean afforestation is for the offshore transfer of microorganisms associated with macroalgae. An open question is how easy or difficult it is for coastal microorganisms to establish in the open ocean[82] and what will be the ecological effects on native communities and native oceanic food webs. Purposeful biological invasions have seldom been marine ecological successes (Table 1).

Macroalgae carry epifauna including mobile and attached invertebrates, with 1,200 species having been identified on drifting seaweed; these 'passengers' remain viable for multiple generations[22,83]. As such, macroalgal rafts, regardless of their densities offshore, may act as vectors of dispersal for shallow-water communities. Table 1 presents illustrative examples from other offshore dispersal and transport mechanisms that have had widespread effects for offshore and trans-basin biogeography and biosecurity. Examples include communities associated with plastics and other marine debris and species' climate velocities driven by alteration of ocean properties (climate change and radiative dispersal). For example, rafts largely formed by plastic litter carry a wide range of species such as barnacles, bivalves, gastropods, polychaetes and bryozoans, some of which are non-native and invasive[84]. Similar examples of long-distance dispersal and transport of biota come from the consequences of tsunamis and from the interplay of ocean physical circulation with warming oceanic regions and poleward expansion of habitat (Table 1), with the introduction of boreal species having implications for ecosystem structure and function and socioecology in the Arctic Ocean. It is clear from the examples in Table 1 that many unknowns exist, with wider ramifications for the structure and functioning of oceanic ecosystems. These offshore regions, portrayed as 'deserts' by proponents of ocean afforestation, drive

Table 1 | Examples of side effects driven by offshore transport and their ramifications for open ocean biosecurity

Vector	Observations	Side effects and ramifications	Refs.
Drifting kelp arrays—passive rafting	Kelp, which were reproductively viable, and associated biota ('invertebrate passengers') washed up on the Antarctic continent.	Surface-drifting kelp, helped by storms, can penetrate the Polar Front and disperse poleward being washed up on the Antarctic continent.	22–24
Marine anthropogenic litter—passive rafting with 'aquaculture-related passengers'	Aquaculture-related, non-native, invasive species attached to anthropogenic litter items.	These species are well adapted to rafting on artificial surfaces and have a high potential to disperse via this vector.	84,93
Transoceanic dispersal of organisms associated with debris	Japanese tsunami marine debris, including mussels.	Shifts in biogeography of invasive species.	94–96
Climate change radiative dispersal	Dispersal of boreal organisms into polar species habitat.	Physical regime permits poleward advection (much less evident for the Southern Ocean due to presence of the polar front).	97
GASB	Beached macroalgae, including microbiome, attached epibionts and other fauna.	Altered nearshore and littoral ecosystems; associated transboundary effects; ocean carbonate chemistry (alkalinity); altered species associations.	1
Ballast water	Dispersal of toxic dinoflagellates and also some macroalgae such as *Undaria*. Microscopic gametophyte stages (ballast waters) or hull attachment (macroscopic sporophyte or microscopic gametophytes).	Harmful algal blooms and colonization of adventive macroalgae.	89,98–100

Mechanisms include dispersal of biota, including naturally occurring rafts of macroalgae, and biological invasions mediated by changing ocean conditions.

half of global primary productivity[44] and underpin important fisheries, including fast-swimming pelagics such as tuna (table 3 and figure 6 in ref. [85]).

Other examples from Table 1 of offshore or trans-basin dispersal include the 2011 emergence of the GASB, thought to be driven partially by agricultural nutrient run-off from the Amazon[35]. Preliminary findings[86] suggest that *Sargassum* communities associated with the GASB are less diverse than those long-established in the Sargasso Sea. There is also emerging evidence of the heavy metal content of *Sargassum* in the GASB with unknowns about its fate during decomposition[87]. These unknowns call into question the assertion from some advocates for ocean afforestation that offshore macroalgae provide co-benefits such as foraging grounds for fish larvae[2,88]. At the trans-basin scale, ballast water is also a well-known vector for long-distance dispersal of harmful (that is, toxic) phytoplankton species and for invasive species including the kelp *Undaria* (Table 1). Ballast water also serves as a useful illustrative example of how measures have been introduced to curtail the effects of dispersal[89].

Metrics for testing ecological side effects

To conclude, we outlined some metrics that are essential to provide assessment of the ecological implications of occupation of offshore waters during preliminary trials of ocean afforestation. These checks and balances should include targeted measurements to better understand the ramifications of inadvertent transfer of associated microbes and nearshore flora and fauna offshore, exploration of the potential for adventive macroalgae to use allelopathy to compete with native microalgae for scarce offshore nutrients and the influence of alteration of oceanic waters (DOC, VOCs and water column shading) on offshore biota.

All potential side effects, whether direct or indirect, will be scale-dependent, with their magnitude dependent on the density at which macroalgal rafts are deployed (Fig. 1c). This scale dependency cannot be tested using small-scale trials and therefore needs models that consider the relevant ecological processes (that is, models that are fit for purpose). Such modelling should adopt a

fore-sighting approach to "look well beyond a pilot study, so as to uncover the characteristics of the subsequent suite of more advanced and upscaled experiments with respect to efficacy, side-effects, and detection and attribution"[90], as it is likely that many side effects would not be evident during the initial trials (Fig. 1c). In the ocean, upscaling of afforestation will probably be incremental with several proponents being operational. Each may have conducted small-scale trials consistent with their individual deployment scale. However, all proponents in combination may reach a scale of ocean afforestation for which none have planned to test. Furthermore, such carry-over effects may only become conspicuous after upscaling a pilot study to full deployment by one or more proponents. Thus, a key danger in upscaling is that some effects only become conspicuous long after the initial trials, with major issues for the development of adaptive governance. Hence, modelling should tackle the central issue of placing bounds on the critical relationship between the density of macroalgal rafts (Fig. 1c), the CDR potential and the magnitude of potential ecological side effects.

Modelling must be accompanied by a suite of laboratory and field testing to gather fundamental information on wide-ranging unknowns (Fig. 2) using laboratory and enclosed field incubations (mesocosms). Some environmental impacts can be assessed under laboratory conditions, for example, DOC release or nutrient uptake requirements at low nutrient concentrations. Mechanistic understanding acquired in laboratory studies can provide input into models to make them fit for purpose. Other effects such as allelopathic interactions or VOC production will require larger-scale mesocosm experiments. In addition, fundamental research is required for other issues such as DOC quality and the make-up of the microbiome. Mesocosm manipulation experiments may be needed to explore how DOC release, nutrient requirements and the microbiome respond to changes in environmental conditions due to the movement to offshore conditions (such as more optically clear oceanic waters).

Conclusion

A combination of previous examples of the threats posed by other offshore dispersive vectors and the wide range of unknowns around

the consequences of offshore ocean afforestation for ocean biota points to the need to rigorously investigate the wide-ranging direct and indirect potential side effects detailed above. The confounding issue of scale dependency, as this ocean afforestation is scaled up from pilot studies to deployment, means that a combination of modelling (at full deployment scales), laboratory assays and offshore surveys will be required to holistically assess environmental risks across many scales. Assessment of the risk of major large-scale detrimental effects to the structure and functioning of offshore ecosystems is probably of equal importance as that of the efficacy of the CDR[27] with regard to seeking social licence for ocean afforestation. Any unforeseen detrimental effects on food security due to the inadvertent restructuring of offshore ecosystems is indicative of the need to carefully map the multiple usage of the ocean commons[91]. Such ocean-scale marine spatial planning is a key step as we move towards a growing range of anthropogenic pressures on Earth, reflected by the concept of planetary boundaries[92], including climate change and food insecurity, and the need for United Nations SDGs to address these pressing issues[15,16].

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Author contributions

P.W.B., L.T.B., C.L.H., E.P., J.A.R. and V.T. discussed the topics included within this perspective and the selection of display items. P.W.B. wrote the first draft based on contributions from all authors. Subsequent drafts were reviewed by P.W.B., L.T.B., C.L.H., E.P., J.A.R. and V.T. V.T. designed and performed the dispersion modelling analysis.

Competing interests

The authors declare no competing interests.

Additional information

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