NEW ERA AGRICULTURE MAGAZINE

Seaweed: Jack-of-All-trades in the fight against climate change

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Introduction:

Seaweed (macroalgae) has attracted attention globally given its potential for climate change mitigation. A topical and contentious question is: Can seaweeds' contribution to climate change mitigation be enhanced at globally meaningful scales? There are four categories where seaweed has been suggested to be used for climate change mitigation: 1) protecting and restoring wild seaweed forests with potential climate change mitigation co-benefits; 2) expanding sustainable nearshore seaweed aquaculture with potential climate change mitigation co-benefits; 3) offsetting industrial CO_2 emissions using seaweed products for emission abatement; and 4) sinking seaweed into the deep sea to sequester CO_2.

Challenge 1 - resolving knowledge gaps in the seaweed carbon cycle

The location (e.g. within different coastal geomorphologies, water depths and ocean circulation patterns), and the life cycle of seaweeds (e.g., growth, mortality, and reproduction) determines the magnitude of net primary productivity and the potential for subsequent carbon flows (Fig. 2a; Pessarrodona *et al*., 2018).

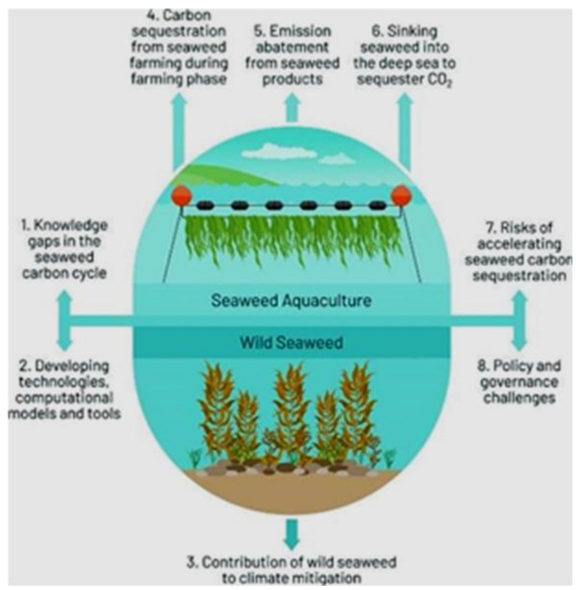

Fig 1 Diagram detailing how the identified research challenges relate to either seaweed aquaculture and/or wild/naturally occurring seaweeds

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The long-distance transport of seaweed biomass and detritus depends on the decomposition rate and physical characteristics of the seaweed material, particularly the buoyancy and density. For example, positively buoyant seaweeds, such as Sargassum, Macrocystis and other Laminariales, can be transported as rafts offshore (Fig. 2c; (Kokubu *et al.*, 2019)). When floating seaweeds lose buoyancy and sink, part of their biomass (OC) may be transported to carbon sinks in shelf sediments or to the deep sea, depending on their size, currents, sinking speed, and distance to the deep sea (Fig. 2h). Likewise non-buoyant seaweed can be exported in the bedload (KrauseJensen and Duarte, 2016). As OC is laterally exported, biotic and abiotic processes continuously fragment the seaweed biomass, resulting in a reduction in the particle size and leading to continuous dispersal of POC, which in turn influences the location of potential POC burial and the efficiency of carbon sequestration (Fig. 2a, b. The decomposition of buried seaweed OC in shelf, coastal and beach sediments also influence carbon sequestration rates (Fig. 2k).

The production and release rates of seaweed DOC (Dissolved organic carbon) has been measured using in situ observations and lab experiments However, the subsequent transport and processes determining the sequestration of DOC are poorly understood and indeed, difficult to determine. One of the mechanisms proposed to contribute to carbon sequestration is the persistence of refractory DOC in the water column (Fig. 2c). (Smale *et al.*, 2021).

CO_2(g) dissolves in water to form CO_2 (aq), which can also be formed from the breakdown of organic matter. As shown below, CO_2 (aq) is in equilibrium with carbonic acid, bicarbonate and carbonate.

CO_2 (g) ↔CO_2 (aq) + H_2O↔H_2CO_3↔HCO_3^- + H+˙↔CO_3^{2-} + $2H^+$

Challenge 2 - developing technologies, computational models and tools to measure seaweed carbon fluxes

Advances in tracing and measuring seaweed carbon fluxes are key for the inclusion of seaweed in the blue carbon framework. While there are available tools to quantify these flows, tracing seaweed carbon fluxes is complex and still unprecise. Detecting the presence and quantifying stored carbon fluxes is complex and still unprecise. Detecting the presence and quantifying stored carbon has often been traced in sediment cores using pigment signatures (e.g., pheophytin and fucoxanthin).

carbon fluxes are complex and still unprecise. Detecting the presence and quantifying stored seaweed carbon is essential to validate whether it reaches sink sites and how much of it arrives in the depositional

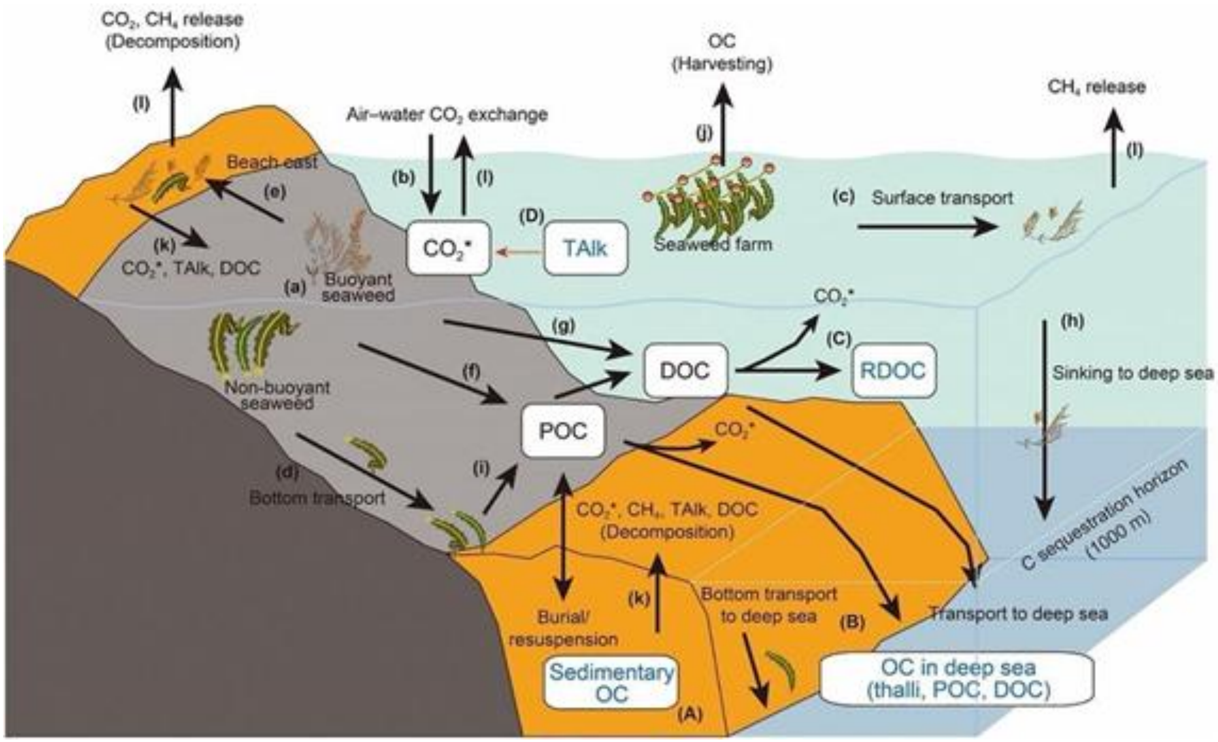

Fig 2 Potential pathways for sequestration of seaweed carbon

Net primary production lowers CO_2 concentration in the surrounding water (a), facilitating atmospheric CO_2 uptake through fixation into macrophyte biomass (b). CO2* indicates the chemical equilibrium between dissolved CO_2, carbonic acid, carbonate ions, and bicarbonate ions in the ocean, which is controlled by total alkalinity (TAlk). Floating thalli (or POC which is usually defined as particles >0.2 μm) of buoyant seaweed can be transported offshore (c), where they sink to the deep sea when buoyancy is lost (h). Non-buoyant seaweeds sink near the sites of origin and are transported via bottom currents and accumulate along bottom slopes (d). A portion of the biomass and detritus of floating and nonbuoyant seaweeds is washed onto beaches (e). Particulate organic carbon (POC) and dissolved organic carbon (DOC) are released and transported offshore (f, g). Seaweed biomass is continuously fragmented during these processes, promoting the dispersal of POC and DOC (i). For seaweed farms, most of the biomass is removed from nearshore waters when seaweed is harvested (j), but about half of their net primary production is released to the environment as DOC and POC before harvest (Duarte et al., 2021). CO_2 and CH_4 gases and TAlk are released to the water column depending on the seaweed decomposition pathways (k) (see text for details of DIC speciation and the role of alkalinity). Degassing of CO_2 and CH_4 gases (l) produced by decomposition (see text for details of DIC speciation). The potential carbon pools that contribute to long-term carbon sequestration are: burial of OC in coastal, shelf and deep sea sediments (A); OC transported to the deep sea (B); and refractory DOC (RDOC) and DOC transported below 1000 m depth, and excess bicarbonate produced from TAlk release (red dashed arrow).

habitats such as the deep ocean (Smith *et al*., 2015).

Challenge 3 - Understanding the potential contribution of wild seaweed to climate change mitigation

Seaweed forests (e.g., kelp, Sargassum) are globally significant ecosystems with high biodiversity. In some regions, wild seaweed is at risk from anthropogenic stressors (Wernberg *et al*., 2019), including pollution and overharvesting of wild populations. Perhaps the most important stressors are ocean warming and the increasing frequency and intensity of marine heat waves, which have led to the mortality of seaweed forests in some areas. Simultaneously at the poles, recent evidence points at a realized and projected poleward expansion of seaweed with climate change.

Challenge 4 - contribution of seaweed aquaculture to undeliberate carbon sequestration during the farming process

Seaweed aquaculture is the fastest-growing component of global food production. Similar to ongoing carbon sequestration by wild seaweed forests, carbon sequestration with seaweed aquaculture could potentially be an additional CO_2 sink due to the incidental shedding of biomass and DOC during growth, some of which would be sequestered in sediments below the farm.

Moreover, farmed seaweed products may have climate change mitigation benefits.

Challenge 5 - Sinking seaweed into the deep sea to sequester CO_2

Sinking seaweed is controversial as both numerical modeling and empirical investigations found high levels of uncertainty regarding its ability to sequester carbon, along with concerns about impacts on deep-sea biology and oxygen budgets. There are also ethical concerns on purposefully sinking biomass that could contribute to alleviating hunger and sustainably producing animal feed.

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