Carbon Sequestration in Soils below Seaweed Farms

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Abstract

The suggestion that seaweed farming contribute to carbon sequestration below the farms was tested by quantifying, combining organic carbon density with sediment accumulation estimates in soils below seaweed farms, in 21 seaweed farms distributed globally, ranging up to 300 years in operation and 15,000 ha in size. One in every four farms sampled was set over environments that exported, rather than retain materials. For the farms that were placed on depositional environments, the thickness of soil layers and stocks of carbon accumulated below the farms increased with farm age, reaching 232 ton C ha^{-1} for the oldest farm, and tended to exceed those in reference soils beyond the farm and/or prior to the operation of the farms. Organic carbon burial rates in the farm soils averaged (± SE) 2.11 ± 0.73 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$ (range 0.06 – 8.99 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$), and tended to increase with increasing yield and the organic content of the unfarmed sediments. These results confirm that, when placed over depositional environments, seaweed farming sequester carbon in the underlying soils and provide the first direct assessment of carbon sequestration below seaweed farms, guiding the design of future farms to generate climate benefits comparable to those of wild blue carbon habitats.

Introduction

Seaweed farming, growing at about 6.5 % $year^{-1}$, accounts for about half of total marine aquaculture production (FAO 2022) and provide a growing opportunity to advance multiple sustainable development goals (Duarte et al. 2021). These include climate action (Duarte et al. 2021), with seaweed farming considered an emerging Blue Carbon option (Lovelock and Duarte 2019). Blue carbon, the strategy to mitigate climate change through the conservation and restoration of vegetated coastal habitats (Duarte et al. 2013), is a growing component of climate action delivered by projects targeting mangroves, seagrass and saltmarshes executed by governments, communities, NGOs and the private sector (Macreadie et al. 2021). However, the total scope for blue carbon projects is limited by the area available to

accommodate mangroves, seagrass and saltmarsh habitats, and is estimated at about ~3% of the removal of global green-house gas emissions required to achieved the goals of the Paris Agreement (Macready et al. 2021). Seaweed farming can be conducted sustainably over an estimated large area, with the area co-opted by seaweed aquaculture by 2050 at the maximum possible expansion rate estimated at 678,000 Km^2, delivering, if achieving this scale, the removal of an estimated 0.24 Pg CO_2-equivalent per year, stored in soils below the seaweed farms (Duarte et al. 2021). However, these estimates are based on indirect assumptions as there is, to-date, not a single published empirical estimate of carbon sequestration in soils below seaweed farms, rendering the estimates of the potential contribution of seaweed farming hypothetical.

Algal forests extend over 7.2 million Km^2 (Duarte et al. 2022), sequestering around 634 Tg CO_2 equivalent per year, as much as mangroves, seagrass and saltmarshes combined (Krause-Jensen and Duarte 2016). Seaweed release a significant fraction of their net primary production (NPP) as both dissolved and particulate organic carbon, exporting, on average, about 43 % of their NPP (Duarte and Cebrian 1996). However, as most algal forests grow on exposed rocky shores, the production exported is advected far away, with seaweed detected in the open sea and deep sea (Krause-Jensen and Duarte 2016, Ortega et al. 2019). In contrast, seaweed farms are often located in sheltered bays suspended over soft sediments, which preclude damages from storms and swells while providing a potential depositional environment where carbon detached from the seaweed can be sequestered in soils below the farm. Assuming seaweed farms to behave as wild seaweed populations, Duarte et al. (2021) calculated that seaweed farms could sequester about 11 % of their exported production (Krause-Jensen and Duarte 2016) or about 3.5 ton CO_2 ha^{-1} $year^{-1}$, at relatively high yields. However, this potential has not yet been quantified.

Here we provide a first assessment of carbon sequestration in soils below seaweed farms. We do so on a global study including 20 farms from 11 nations across all continents, none of which were designed to sequester carbon. Our study supports the hypothesis that most seaweed farms sequester carbon in the underlying soils and provide support for the call to expand seaweed farming globally as a climate change mitigation option that contributes to alleviate hunger and poverty and helps meet several sustainable development goals. Carbon burial in soils below seaweed farming ranged widely, depending on farm yield and farm settings conducive to retain materials in sediments, best reflected in organic-rich muddy to

fine sandy sediments, pointing at opportunities to maximize carbon sequestration by placing seaweed farms in suitable depositional environments.

The farms in our study (Fig. 1) ranged widely in size, from very small farms with one or a few hectares farmed in western nations, where seaweed farming is in an embryonic state, to the 150 Km^2 farm in Ningde, China, which can be seen from space (Tables 1 and 2). They ranged in age from just a couple of years in Western nations to 320 years of operation, with different technologies, in Tokyo Bay, Japan (Tables 1 and 2). Indeed, the farms in the western hemisphere were all very recent and had a small footprint, attesting to the incipient nature of seaweed farming in western nations, except for Chile, due to cultural reasons (Tables 1 and 2). The farms included the most important farmed seaweed species, with the 12 species grown in the farms ranging from large, slow growing kelps (*Sacharina latisima*) to fast-growing sea lettuce (*Ulva pinnatifida*). Yield ranged widely, from 1 to 150 tons fresh weight per ha^{-1} per $year^{-1}$ (Tables 1 and 2), reflecting the number of crops per year, ranging from 1 in high-latitude farms to 8 per year in Indonesia, as well as the convenience of the farmers, as concession size is often much larger than the cropped area, and farmers often chose to have generous spacing among the seaweed lines for ease of navigation with their vessels.

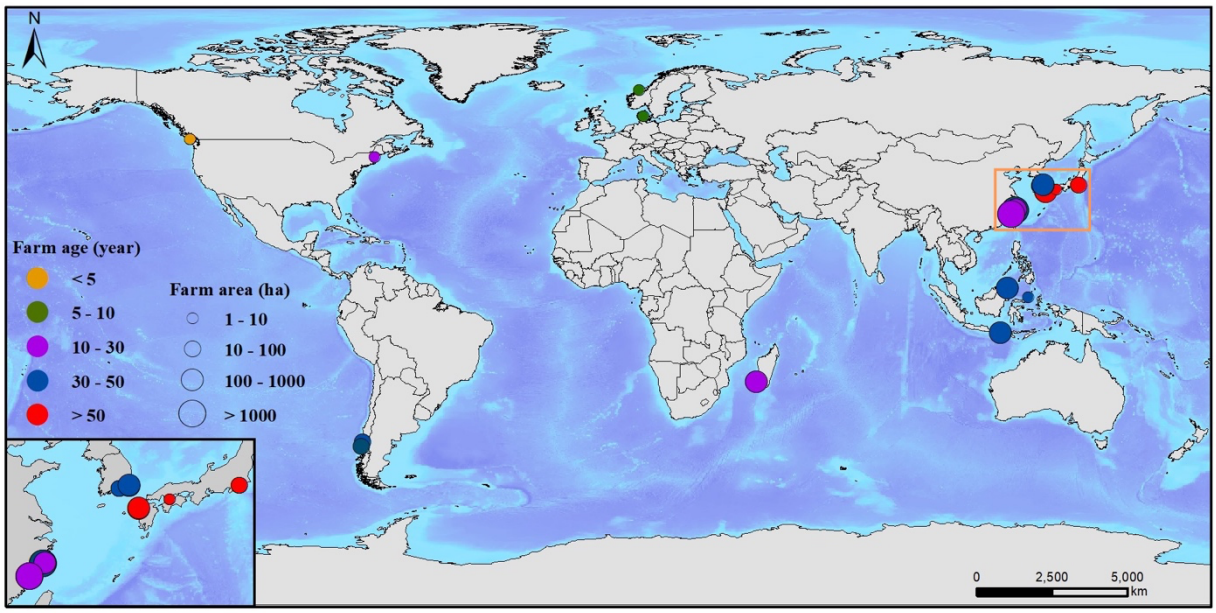

Fig. 1. Location of the sampled seaweed farms, the time (years) elapsed since the onset of farming and the size of harvested area (ha) (Tables 1 and 2). The red square in Asia shows the area highlighted in the insert.

The settings of the farms ranged widely, from sites with strong currents and exposure to waves, in farms in Norway, Korea and Indonesia, which maximize nutrient supply and, therefore, seaweed growth, but export, rather than accumulate, materials, to shelter bays in Canada. Depth also varied from intertidal farms in China and Indonesia to farms located over 30 m of water in Norway and Canada (Tables 1 and 2). Accordingly, the soils below the farms ranged from muddy to gravel, with the presence of coarse sediments suggesting environments exporting rather than retaining materials, including seaweed fragments. Indeed, exposed sites tended to have coarse sediments, compared with sheltered sites, which tended to have muddy sediments, with fine sands dominating in partially sheltered sites (χ^2, P=0.008).

The distance between the center of farms and control sites away from the farm was considerable for the larger farms, which occupied all the suitable environment so that areas away from the farms differed in physical conditions and the nature of sediments. Hence, sediments away from the farm, did not always provide an appropriate reference to compare the effect of seaweed farming on organic carbon stocks and sequestration rates. Where differences in sediment properties suggested reference soils could not be compared to soils below the farm, we used the sediment characteristics prior to farm operations, as determined by ^{210}Pb chronologies, as a proxy for reference soils.

Sedimentation rates could be resolved based on ^{210}Pb concentration profiles in 11 of the 20 farms sampled, with 5 farms showing negligible sedimentation rates, suggesting they were set in environments that exported rather than accumulate materials. Four farms showed ^{210}Pb concentration profiles that denoted either mixing, likely due to bioturbation, or, alternatively, sedimentation rates too high to be resolved with the sediment depth included in the samples retrieved (Arias-Ortiz et al. 2018) (Table 1). The estimated thickness of the soil layer deposited during the operation of the farm ranged widely, increased with farm age (R^2=0.83, $P < 0.0001$, Fig. 2a) for those farms placed within depositional environments. Hence, the sediment layer deposited during farm operations was very thin (0 – 4.7 mm) in farms located

in Europe and North America, where seaweed farming is a recent development. In contrast, we estimated the sediment layer deposited during farm operations to be 183 cm thick in the farm in Ariake Bay, Japan, the oldest (220 years of operation) farm located in a depositional environment (Tables 1 and 2).

Soil organic carbon averaged (±SE) 1.03 ± 0.18 % of dry weight across farms (range from 0.14% to 2.09%) (Table 1). Half of the farms contained elevated organic carbon concentrations in soils below the farm corresponding to the period of operation of the farm relative to those in reference soils beyond the farm or sediment layers deposited prior to the operation of the farms (Wilcoxon ranked paired test, $P < 0.05$). The stock of organic carbon accumulated during farm operations in farms that were set over depositional environments ranged from 0.14 ton C ha^{-1} to 232 ton C ha^{-1}, increasing with the length of time the farms had been in operations ($R^2 = 0.61$, $P = 0.002$, Fig. 2b), and tended to exceed the stock of carbon accumulated over the same time in reference sites away from the farm or prior to farm operations (Wilcoxon ranked paired test, $P < 0.005$). Organic carbon burial rates in the farm soils averaged (± SE) 2.11 ± 0.73 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$ (range 0.06 – 8.99 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$), and tended to increase with increasing yield ($R^2 = 0.56$, $P = 0.0073$, Fig. 2) and exceed organic carbon burial rates in reference sites away from the farm or prior to farm operations (Wilcoxon ranked paired test, $P < 0.005$, Fig. 2d). The best predictors of the organic carbon burial rates in the farm soils included the yield of the seaweed farm together with the organic content of the unfarmed sediments, together accounting for 74% of the variability in carbon sequestration ($R^2 = 0.74$, $F = 11.4$, $P = 0.0045$). The excess organic carbon sequestration relative to reference soils, attributable to the operation of the seaweed farm, averaged (± SE) 1.30 ± 0.72 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$ (range -0.09 - 8.1 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$). The median excess $CO_{2\text{-equiv}}$ sequestration rate below the farms that accumulated sediments represent and additional 11.4% relative to the yield of the farm, in terms of organic carbon retrieved with the seaweed crop.

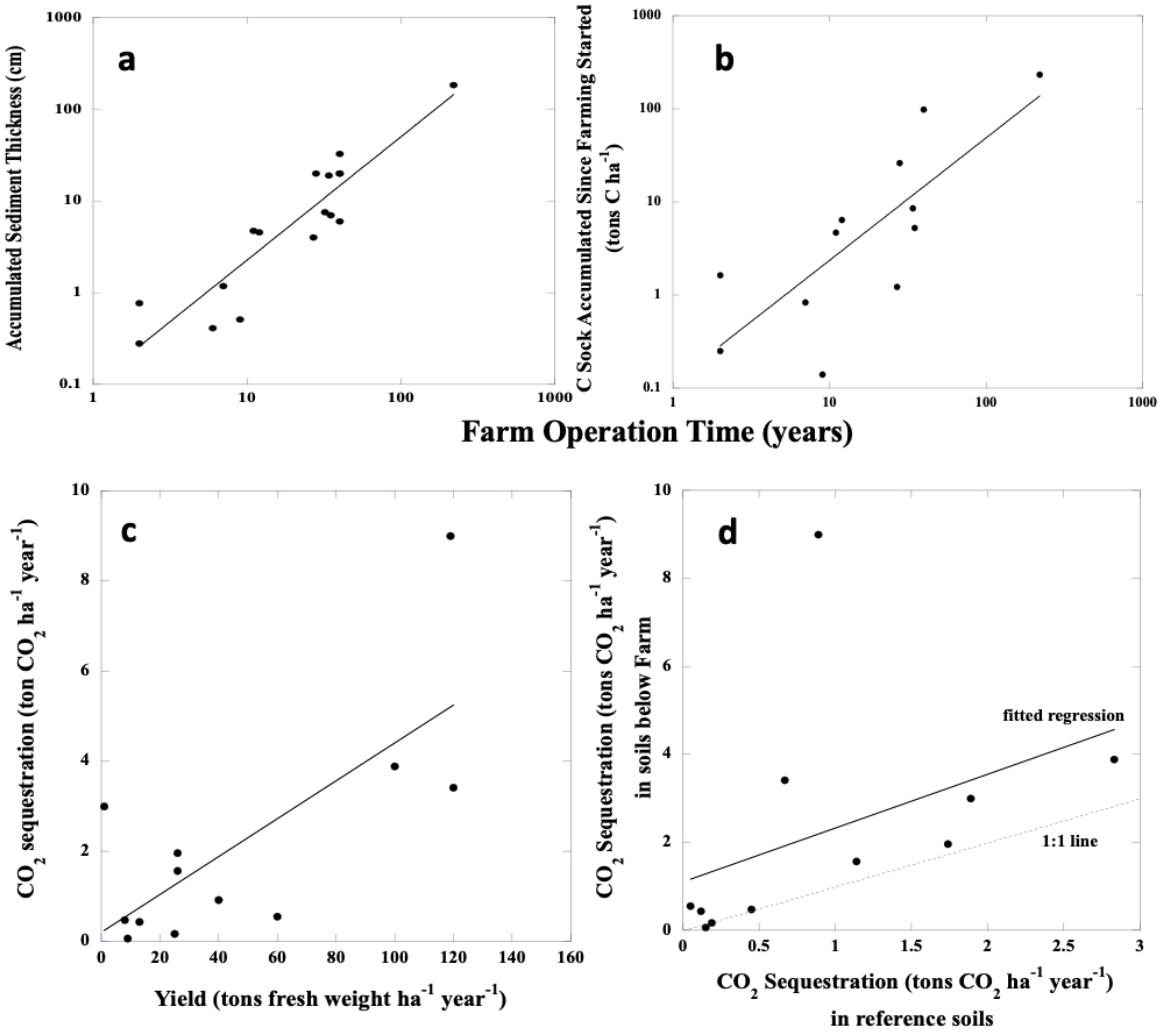

Figure 2. The relationship between the time elapsed since seaweed farming operations were initiated and (a) the thickness of the sediment layer deposited, and (b) the stock of organic carbon accumulated per unit farm area. The relationship between the $CO_{2\text{-equiv}}$ sequestered in soils below the farm and (c) the current farm yield and (d) the $CO_{2\text{-equiv}}$ sequestration in unfarmed soils. The soil lines represent the fitted regression lines: (a) $\log_{10}$ Accumulated Sediment Thickness (cm) = -0.98 + 1.34 (± 0.15) Farm Age (years) (R^2=0.83, P < 0.0001); (b) $\log_{10}$ CO_2 accumulated during farm operation (tons C ha^{-1}) = -2.16 + 3.02 (± 0.76) $\log_{10}$ Farm Age (years) (R^2 = 0.61, P = 0.002); (c) CO_2 sequestration (tons CO2 ha^{-1} yr^{-1}) = 0.20 + 0.042 (± 0.012) Yield (tons FW ha^{-1} yr^{-1}) (R^2 = 0.53, P = 0.0073); (d) CO_2 sequestration below Farm (tons CO_2 ha^{-1} yr^{-1}) = 1.1 + 1.22 (± 0.88) CO_2 sequestration Reference Soils (tons CO_2 ha^{-1} yr^{-1}) (R^2 = 0.18, P = 0.19).

The results presented provide a first estimate of the carbon sequestration below seaweed farms, at an average rate of 2.11 ± 0.73 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$, corresponding to about 39% to 33% of the estimated average carbon sequestration rate in seagrass and mangrove soils, respectively (Duarte et al. 2013). Applying the average carbon sequestration rates found in our study to the estimated present area of seaweed farms of 1,983 Km^2 in 2020 (Duarte et al.

2021) implies that seaweed farming may currently sequester about 0.4 million tons of $CO_{2\text{-equiv}}$ annually, which could grow, following current practice, to 140 million tons of $CO_{2\text{-equiv}}$ annually if seaweed farming expanded at the upper growth rate to reach 667,800 Km^2 by 2050 (Duarte et al. (2021).

Seaweed farming is a recent development in the western world, except Chile, where seaweed farms are small and recent, in contrast to a centenary record of operation in Asia, particularly in Japan, where one of the farms had accumulated an impressive 183 cm layer of sediment containing 232 ton C ha^{-1}, showing that indeed burial is permanent in as long as farming operations are maintained and/or soils are not disturbed. Our findings, therefore, set the conditions to activate seaweed farming as a sink for CO_2 and, eventually, compensate the farmers for the carbon burial services, provided robust verification systems are in place. Assuming seaweed farmers are compensated at US$ 50 per ton of CO_2 removed, with the adequate permanence requirements, this could represent a modest additional income of about US$ 100 per hectare. At an average price of the crop of US$ 0.5 per kg fresh weight of seaweed, as currently paid in some Asian nations, and the average annual yield of 43 ton fresh weight ha^{-1}, carbon sequestration services of farms would only increase gross revenue by 0.4 %, making it unlikely for seaweed farmers to consider carbon sequestration as a relevant benefit. However, the total revenue can be sizeable for large farms, with farms > 100 Km^2 generating revenues in excess of US $ 1.5 million per year.

The calculations above are based, however, on average carbon sequestration rates, whereas our results show that operating seaweed farms at high yield in concessions placed in depositional environments, as reflected in organic-rich sediments, can yield carbon sequestration rates four-fold above the average. The carbon benefits of seaweed farming can be enhanced further if the crop retrieved is used to either displace fossil fuels, such as used as biofuel, biochar or goods embodying the seaweed into durable products, as well as seaweed products, such as the seaweed *Asparagopsis* sp., which reduces methane emissions by ruminants (Duarte et al. 2021, De Angelo et al. 2022). The climate benefits of seaweed farming can be enhanced further by sinking the crop in the deep sea (De Angelo et al. 2022). However, this practice may bring about unintended consequences on the marine ecosystem while depriving society of the benefits to support sustainable development goals that seaweed crops bring about (Duarte et al. 2021). Consequenty, sinking seaweed in the deep sea is not a recommended option (Ricart et al. 2022).

As the value of carbon credits is projected to raise rapidly over the next years (Ernst & Young 2020), the economic benefits of managing seaweed farms for carbon sequestration will increase in the future. These benefits add to additional environmental benefits of seaweed farming for enhancing biodiversity (Theuerkauf et al. 2022) and providing local refugia from ocean acidification and deoxygenation (Xi et al. 2021), along with multiple social benefits, including food supply, poverty alleviation and employment (Duarte et al. 2021). Indeed, the farms involved in this study collectively employ about 27,000 farmers, corresponding to an average of 1.4 employees per farmed hectare. This provides evidence of the significance of seaweed farming in supporting livelihoods and community resilience in many nations, as seaweed farming provided food and much needed economic relieve to the farmers in our study when other sources of income were disrupted by the covid-19 pandemic.

Our results provide the first direct assessment of carbon sequestration below seaweed farms, with an average of 2.11 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$ and a maximum, for the set of farms sampled across the world, of 8.99 ton $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$. Designing seaweed farming to act as a nature-based solution for climate action requires selecting concessions over depositional environments – away from seagrass meadows - and a commitment to avoid disturbance of the sediments below the farm. Provided the scalability of seaweed farming to extend over an ocean space at least 1,000 fold the current area, we conclude that policies should be put in place to enable seaweed farming to match or exceed the contribution of mature blue carbon options to mitigate climate change.

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Methods

Sampling

A network of 20 seaweed farms located around the world was assembled, typically including a local research team operating under standardized protocols. The oldest and largest farms available were selected for sampling. However, this resulted in rather young and small farms in western nations, except for Chile, where seaweed farming is a recent development. For each of the selected farms a "farm" site, representing a site that is likely to receive continuous inputs of any materials detached from the farm, and a ¨reference¨ site, representing a site that is similar in depth and overall environmental conditions (e.g. exposure) as the farm site, but sufficiently away as to be unlikely that materials from the farm may settle there, were established. In the absence of strong currents, the "farm" site was located below the center of the farm area, where "edge" effects will be minimal. Where the farm area shifted over time, the "farm" site represented the area that best represent the center across years (i.e.

consistently covered by the farm). Where significant directional current occurred and depth was significant (> 10 m), the "farm" site was displaced relative to the center of the farm along the direction of current, as settling materials will be advected along that direction, rather than falling vertically. Both sites were also located away from known disturbances to the sediment, that can mix or rework the sediments, such as anchoring systems.

A total of 3 cores, ranging in length from 60 cm to 1 m and 6 to 10 cm in width, were collected by SCUBA divers at each of the farm sites and 2 additional cores at the control sites, just before the crop was harvested. As sampling was set to be initiated in March 2020, covid restrictions led to significant constraints in accessing the sites for research teams due to confinement and restriction measures under covid19, which were severe in some of the participating farms, such as those in China and Japan. Hence, sediment sampling elapsed between March 2020 and June 2022, depending on farms.

The cores retrieved were sliced at at 0.5 cm intervals for the top 10 cm, 1 cm-thick intervals from 10 cm to 20 cm, and 2 cm intervals down to the base of the core. The wet weight of the slices was determined and they were then dried at 60-70 ºC until constant weight. Dried samples were then shipped to the laboratories where organic carbon was determined, at the Andalusian Institute of Earth Sciences (Granada, Spain), and ^{210}Pb concentrations were determined, at Edith Cowan University (Perth, Australia), and the UN International Atomic Energy Agency in Monaco.

Chemical analyses

Sediment samples were dried again at 70 ºC and subsequently pulverized/homogenized. An aliquot was treated with hydrochloric acid (1:1) to remove carbonates. The residual sample was washed (5 times), dried and homogenized again, to be used for the analysis of percentage of organic carbon. Samples were accurately weighed into tin capsules and analyzed in triplicate to calculate the carbon content and the $^{12}C/^{13}C$ ratios by means of a Carlo Elba NC1500 (Milan, Italy) elemental analyzer on line with a Delta Plus XP (Thermo-Finnigan, Bremen, Germany) mass spectrometer (EA-IRMS). Commercial CO_2 was used as the internal standard for the carbon isotopic analyses. Mass area 44, 45 and 46 of CO_2 were used to calculate the carbon content.

The concentrations of ^{210}Pb along each core were determined by alpha spectrometry through the measurement of its granddaughter ^{210}Po, assuming radioactive equilibrium between both radionuclides (Sanchez-Cabeza et al., 1998). Briefly, 300 mg of each sample were spiked with a precisely known amount ^{209}Po and microwave digested with a mixture of concentrated HNO_3 and HF. Boric acid was then added to complex fluorides. The resulting solutions were evaporated and diluted to 100 mL 1M HCl and Po isotopes were plated onto pure silver disks during 8 hours at 70 °C while stirring. Polonium emissions were measured by alpha spectrometry using ULTRA Ion implanted silicon charged particle detectors (ORTEC). The concentrations of supported ^{210}Pb were determined in several evenly distributed samples along each core by measuring the concentrations of ^{226}Ra by gamma spectrometry via its decay products ^{214}Pb and ^{214}Bi (in equilibrium) using well-type, high purity germanium detectors (CANBERRA). Analyses of replicate samples and reference materials (IAEA-447) were carried out systematically to ensure the accuracy and the precision of the results for both alpha and gamma measurements. The excess ^{210}Pb concentration profiles were obtained by subtracting the supported ^{210}Pb from the total ^{210}Pb for each core. Mean sedimentation rates were obtained by modeling the excess ^{210}Pb concentration profiles along the accumulated mass using the CF:CS model (Krishnaswamy et al. 1971, Arias-Ortiz et al., 2018) where possible (i.e. where the excess ^{210}Pb concentration profile presented a decreasing trend with depth).

Calculations

Organic carbon (C_{org}) concentrations were combined with bulk density to calculate carbon density in the soils and integrate C_{org} stocks in sediment layers. For each core where the age model could be calculated (Arias-Ortiz et al., 2018), the C_{org} burial rate since the beginning of activity of the farm was estimated using the mean sedimentation rate and the weighted average concentration of C_{org} from the surface and down to the depth corresponding to the time elapsed based on the age model. Similarly, the C_{org} burial rate during the equivalent amount of time before the farm was operative was estimated using the mean sedimentation rate and the weighted average concentration of C_{org} at deeper layers of each sediment core collected below the seaweed farm. Then, where possible, we could compare the C_{org} burial rates during and before operation of the farm as well with the C_{org} burial rates outside the farms (i.e., determined from samples collected in reference sites).

Table 1. Time (years) since the onset of operation of the seaweed farms, sedimentation rates (mean ± SE), average soil organic content in sediments deposited during the farm operation or reference soils, organic carbon stock accumulated in soils below the farm during the farm operation and CO2equiv. removal rate in sediments deposited during the farm operation or reference soils. BDL: below detection limit.

Country	Farm Name	Farm Age (yr)	Sedimentation rate ($g \cdot cm^{-2} \cdot yr^{-1}$)			C_{org} farm (%)	C_{org} Reference (%)	Stock C_{org} accumulated farm ($Mg\ C \cdot ha^{-1}$)	CO_2 removal rate farm ($Mg\ CO_2 \cdot ha^{-1}\ yr^{-1}$)	CO_2 removal rate Reference ($Mg\ CO_2 \cdot ha^{-1}\ yr^{-1}$)
Japan	Ariake Bay	220	0.45	±	0.11	2.50	2.06	232.86	3.88	2.83
Japan	Seto Inland Sea (Hiuchi Bay)	220	BDL			-			-	-
Japan	Tokyo Bay	320	BDL			-			-	-
USA	Atlantic Sea Farms	11	0.20	±	0.011	2.09	1.52	4.69	1.56	1.14
Malaysia	Semporna	30	BDL			-		6.41	-	-
China	Niyu - Province Zhejiang	40	Mixing/very high sedimentation			0.47	0.41		-	-
China	Dongtou - Province Zhejiang	27	0.11	±	0.035	0.44	0.39		0.17	0.19
China	Ningde - Province Fujian	28	1.20			0.75	0.26	1.22	3.41	0.67
Denmark	Hjarnø Hage	9	0.10	±	0.016	0.51	0.28		0.06	0.15
Norway	Seaweed Solutions AS	7	0.16	±	0.031	0.67	0.18	0.14	0.43	0.12
Indonesia	Nain Island	32	Mixing/very high sedimentation			1.99	1.30		-	-
Indonesia	Seriwe Bay, East Lombok, Nusa Tenggara Barat Province, Indonesia	40	1.93	±	0.41	1.23	1.39	0.83	8.99	0.89
Korea	Myeongji, Gangseo-gu, Busan, Korea	40	Mixing/very high sedimentation			0.14	2.35		-	-
Korea	Dadae, Saha-gu, Busan, Korea	40	Mixing/very high sedimentation			0.42	0.41	98.04	-	-
Korea	Mundong-ri, Ilgwang-myeon, Gijang-gun, Busan, Korea	34	0.60	±	0.24	0.42	0.36		0.92	-
Madagascar	Ocean Farmers (southwest region)	10	BDL			-	-		-	-
Canada	W Vancouver Island, Cascadia Seaweed Danvers	2	0.15	±	0.044	0.80	0.73	8.52	0.47	0.45
Canada	W. Vancouer Island, Cascadia Seaweed Useless	2	0.47	±	0.0017	0.95	1.02		2.99	1.89
Chile	Maullin River	30	BDL			-	-	0.25	-	-
Chile	Pudeto River	35	0.05 - 0.3			0.57	0.29	1.63	0.55	0.05

Table 2. Location (latitude and longitude in decimal degree units), depth range (minimum and maximum) of the farmed area and the current farmed species and the size and yield of the seaweed farm.

Country	Farm	latitude	Longitude	Farmed Species	Farm Size (ha) productive area	Yield (tons fw·ha-1·yr-1)	Range (m).	Min.
Japan	Ariake Bay	33.10713	130.18799	Neopyropia yezoensis f. narawaensis	750	100	1	10
Japan	Seto Inland Sea (Hiuchi Bay)	33.95075	133.13139	Pyropia sp. (Nori)	10	100	1	10
Japan	Tokyo Bay	35.29795	139.78776	Pyropia sp. (Nori)	20	150	5	15
USA	Atlantic Sea Farms	43.72159	-70.14764	Saccharina latissima	1	26	9	12
Malaysia	Semporna	4.34941	118.61631	Kappaphycus striatum	200	25	5	15
China	Niyu - Province Zhejiang	27.87052	121.05833	Porphyra haitanensis	1,800	6	2	3
China	Dongtou - Province Zhejiang	27.86076	121.18308	Sargassum fusiforme	250	25	4	10
China	Ningde - Province Fujian	26.66682	119.76197	Gracilariopsis lemaneiformis	15,000	120	3	20
Denmark	Hjarnø Hage	55.81481	10.11115	Saccharina latissima	2	9	7.5	10
Norway	Seaweed Solutions AS	63.703309	8.86943	Saccharina latissima (sugar kelp) and Alaria esculenta (winged kelp)	5	13	15	45
Indonesia	Nain Island	1.77351	124.78221	Eucheuma denticulatum	10	23	4	12
Indonesia	Seriwe Bay, East Lombok, Nusa Tenggara Barat Province, Indonesia	-8.88854	116.51276	Kappaphycus alvarezii /Eucheuma striatus	305	119	7	8
Korea	Myeongji, Gangseo-gu, Busan, Korea	35.03748	128.89168	Pyropia sp.	20	9	0	15
Korea	Dadae, Saha-gu, Busan, Korea	35.03703	128.89362	Ulva spp.	20	9	0	10
Korea	Mundong-ri, Ilgwang-myeon, Gijang-gun, Busan, Korea	35.30537	129.2708	Undaria pinnatifida, Saccharina japonica	200	40	0	20
Madagascar	Ocean Farmers (southwest region)	-23.50177	43.74472	Kappaphycus alvarezii	400	38	0	8
Canada	W Vancouver Island, Cascadia Seaweed Danvers	48.87851	-125.08619	Saccharina latissima, Alaria marginata	1	8	8	40
Canada	W. Vancouer Island, Cascadia Seaweed Useless	48.89276	-125.08619	Saccharina latissima, Alaria marginata	2	1	6	30
Chile	Maullin River	-41.59132	-73.6414	Agarophyton chilensis	12	-	0	3
Chile	Pudeto River	-41.88254	-73.77307	Agarophyton chilensis	39	60	0	2