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Seaweed Aquaculture 2026: Balancing Carbon Sequestration and Ecosystem Health

Climate Change * Conservation * Energy

Introduction: The Maturation of Macroalgal Blue Carbon Science

By early 2026, marine carbon dioxide removal (mCDR) science has undergone a major paradigm shift centered on macroalgae (seaweed) aquaculture. Historically, "Blue Carbon" frameworks focused on vascular coastal plants -- mangroves, salt marshes, and seagrasses -- that bury organic carbon in root-stabilized sediments. Macroalgae were excluded because they grow on rocky substrates or floating lines and produce labile tissues rapidly respired by bacteria after photosynthesis, cycling carbon back into the atmosphere too quickly to mitigate climate change.

Recent breakthroughs in sediment geochemistry and earth system modeling have redefined macroalgae's role in the global carbon cycle. Research by Fakhraee and Planavsky in Communications Sustainability identified an "alkalinity engine" beneath coastal seaweed farms, showing that anaerobic microbial respiration in sub-farm sediments generates enduring bicarbonate alkalinity that locks carbon away for millennia.[1] Conversely, NEMO-MEDUSA ocean simulations by Anugerahanti et al. warn that scaling open-ocean cultivation and deep-sea biomass sinking to the gigaton level triggers severe surface nutrient robbery -- suppressing wild phytoplankton -- and a deep-ocean deoxygenation debt.[2][11] Synthesizing benthic chemistry, microbial carbon pumping, and 2026 market economics reveals why blue carbon is pivoting from "grow and sink" geoengineering toward targeted biogeochemical cycling.

The Alkalinity Engine and the Microbial Carbon Pump

In oxygenated seawater, aerobic microbes oxidize decaying seaweed back into dissolved CO_2, driving ocean acidification and atmospheric outgassing. Rather than relying on physical biomass burial as a carbon sink, Fakhraee and Planavsky showed that organic detritus shed beneath productive seaweed farms overwhelms aerobic microbes in upper sediment pore water, exhausting dissolved oxygen and establishing localized anoxia.[1]

Under anoxic conditions, a geochemical sequence converts labile carbon into durable alkalinity:[1]

* Sulfate Reduction: Anaerobic bacteria use dissolved seawater sulfate to metabolize deposited macroalgal organic matter, generating Total Alkalinity as stable bicarbonate ions (HCO_3^-).[3][4]

* Carbonate Dissolution: Pore-water chemistry promotes calcium carbonate shell dissolution, consuming dissolved CO_2 and yielding two moles of bicarbonate per mole of carbonate dissolved.[5]

Because bicarbonate is a charged ion that does not outgas, it locks carbon in the oceanic reservoir for 10,000 to 100,000 years regardless of physical seabed

disturbance.[1] Global modeling estimates that the world's existing 3.5 million hectares of seaweed farms already sequester up to 7 million tons of CO2 annually via this benthic alkalinity mechanism.[1]

Simultaneously, in the water column, seaweeds leach Dissolved Organic Carbon (DOC). Forensic carbon accounting demonstrates that ~15% of leached DOC is transformed by the Microbial Carbon Pump -- mediated by taxa such as Clostridia and Kapabacteria -- into Refractory Dissolved Organic Carbon (RDOC) that resists degradation for 4,000 to 6,000 years.[6][8][9] Transported offshore by coastal outwelling currents, ~85% of these RDOC chemical fingerprints remain stable during export into the deep ocean.[8][10]

| Sequestration Mechanism | | Durability (Years) | | Biogeochemical Process | | Primary Constraints & Risks | | Source |

| Deep Biomass Sinking | | 100 - 1,000+ | | Physical transport of whole macroalgae to abyssal depths (>1,000 m). | | Severe deep-sea deoxygenation; nutrient loss; high transport cost. | | [2] |

| Sedimentary POC Burial | | 100 - 1,000 | | Accumulation of particulate organic carbon (POC) in coastal muds. | | Requires high sedimentation; vulnerable to storm/trawling resuspension. | | [17] |

| Refractory DOC (RDOC) | | 1,000 - 5,000 | | Microbial Carbon Pump transforms leached DOC into recalcitrant molecules. | | Challenging open-water MRV verification; dependent on shelf currents. | | [6][8] |

| Bicarbonate Alkalinity | | 10,000 - 100,000 | | Anaerobic sulfate reduction and CaCO3 dissolution generate HCO3 . | | Requires controlled sediment anoxia; site-specific mineral chemistry. | | [1][4] |

The Nutrient Paradox and the Deep-Ocean Oxygen Debt

While coastal sediment chemistry offers millennial durability, NEMO-MEDUSA ocean biogeochemistry simulations show that scaling open-ocean macroalgal cultivation to remove gigatons of carbon triggers acute ecological trade-offs.[2] Acting as nutrient sponges for nitrogen, phosphorus, and iron, simulated global farms depleted surface Dissolved Inorganic Nitrogen (DIN) by 53.1% within farming regions.[2]

This nutrient stripping suppresses wild phytoplankton and zooplankton biomass by nearly 50%, weakening the natural biological pump.[2] Although simulated global farms achieved a gross air-sea CO2 uptake of 11.0 Pg C/year, net additionality was only ~27%; 73% merely offset natural phytoplankton carbon fixation.[2] Moreover, in iron-limited offshore waters, farm yields collapsed by 74% without artificial iron fertilization.[2]

| NEMO-MEDUSA Parameter | | Direction | | Simulated Magnitude | | Earth System Implication | | Source |

| Gross Air-Sea CO2 Uptake | | Increase | | +11.0 Pg C/year | | Substantial gross carbon capture at planetary scale. | | [2] |

| Net mCDR Additionality | | Reduction | | ~27% net efficiency | | 73% of uptake is offset by suppressed wild phytoplankton capture. | | [2] |

| Surface Nutrients (DIN) | | Decrease | | 53.1% in farm regions | | Starves lower trophic levels; displaces commercial fishery productivity. | | [2] |

| Deep-Ocean Dissolved O2 | | Decrease | | 20% global average | | Deep-ocean suffocation from microbial remineralization of sunk kelp. | | [2] |

| Suboxic Seafloor Area | | Expansion | | 0.5% -> 7.9% of abyssal floor | | Smothers benthic coral/sponge communities; risks H2S and CH4 release. | | [2][7] |

| Offshore Yield without Iron | | Collapse | | 74% productivity | | Open-ocean farms require controversial artificial iron fertilization. | | [2] |

Furthermore, intentionally sinking gigatons of seaweed below 1,000 meters creates a severe Deep-Ocean Oxygen Debt. Because abyssal waters ventilate slowly over centuries, microbial respiration of sunk biomass exhausts deep oxygen, driving a 20% global deep-ocean oxygen decline and expanding suboxic seafloor zones from 0.5% to 7.9%.[2][11] Smothering abyssal ecosystem habitats in stagnant anoxic basins also risks generating toxic hydrogen sulfide and methane.[7]

Production Economics, Carbon Markets, and MRV Verification

Technoeconomic analysis of a 1,000-acre offshore Gulf of Maine kelp farm by the University of Maine and Kelson Marine found baseline production costs of $2,618 per ton of fresh kelp, reducible by 85% to $383 per ton via storm-resilient deeper lines and mechanized harvest vessels.[12]

| Economic Metric / Scenario | | Estimated Cost | | Primary Cost & Market Drivers | | Source |

| Baseline Offshore Kelp Farm | | ~$2,618 / ton fresh kelp | | High labor, storm damage, manual line handling (Gulf of Maine). | | [12] |

| Optimized Mechanized Farm | | ~$383 / ton fresh kelp | | 85% cost reduction via deeper lines and mechanized harvest vessels. | | [12] |

| Current Kelp Carbon Cost | | $1,257 - $17,000 / tCO2e | | High water content (~90%) limits carbon mass per harvested ton. | | [13] |

| Target Viability Threshold | | ~$100 / tCO2e | | Required for high-durability carbon removal market competitiveness. | | [13][15] |

Because fresh kelp is ~90% water, unsubsidized sequestration still costs $1,257 to $17,000 per tCO2e against voluntary blue carbon credit prices of $30 to $50/tCO2e.[13][14] Consequently, the 2026 industry has adopted a Cascade Utilization Model: harvesting kelp for high-value nutraceuticals, biostimulants, and food while monetizing non-harvested sedimentary bicarbonate and RDOC fluxes in the >$100/tCO2e high-durability removal tier.[15][16] To verify these invisible chemical fluxes for Monitoring, Reporting, and Verification (MRV),[23] international blue-carbon teams pair radiometric lead-210 and thorium-234 (234Th) sediment tracers with real-time pH and oxygen sensors feeding biogeochemical digital twins.[1][17][24]

Ecological Feedbacks and Regional Scalability

Local ecological risks require careful siting: warming waters and dense monocultures heighten Enterobacterales bacterial outbreaks ("ice-ice" disease),[18][22] canopy

shading blocks up to 40% of light at 5 meters depth while altering surface albedo,[19][21] and excessive organic loading in stagnant bays can induce benthic hypoxia.[19][20] Regionally, China's coastal sector has reached its nutrient ceiling by absorbing nearly all coastal agricultural runoff;[16] Southeast Asian smallholder farms face thermal and pathogen stress;[22] and North American and European operations are scaling mechanized rigs sited for verified alkalinity export.[12][14][20]

Conclusion: From Sinking Biomass to Farming Ocean Chemistry

Macroalgal science in 2026 has replaced "Grow and Sink" geoengineering with "Grow and Cycle" biogeochemical farming. While open-ocean sinking courts deep-ocean deoxygenation and nutrient robbery, coastal farms sited in regions of anthropogenic eutrophication drive a benthic alkalinity engine and microbial RDOC pump that sequester carbon for millennia while supplying harvestable biomass to displace fossil-intensive products.

Updates (Nov 15, 2026): Corrected the Nature Portfolio journal title in Section 1 to Communications Sustainability, updated Anugerahanti et al. (2026) from its EGUsphere preprint to its peer-reviewed publication in Biogeosciences (23, 3735-3754), unnumbered section headings, and replaced ResearchGate, PMC, dead Infofish 404, and 403 publisher URLs with verified CrossRef DOIs.

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