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Optimizing pelagic Macroalgae growth for effective ocean-based carbon dioxide removal

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Abstract

Macroalgae, superior to phytoplankton, **excel in carbon transportation due to heightened carbon fixation**. However, pointing to ideal locations and timing for optimal macroalgae cultivation faces challenges due to the dynamic environmental changes across seasons. **This study identifies suitable cultivation locations and seasons using a 1-D macroalgae growth model** coupled with an ocean dynamics and ecosystem model. Green (Ulva) and brown (Sugar kelp) macroalgae thrive in subarctic regions, with Ulva also showing growth potential in warmer subtropical areas. Shorter cultivation periods favor faster-growing Ulva in summer and early fall, while sugar kelp thrives in early spring. **This seasonal segregation underscores macroalgae's versatility for Carbon Dioxide Removal (CDR) across diverse seasons and locations**, highlighting the crucial role of species selection and cultivation timing in open ocean environments.

Introduction

Rising atmospheric carbon dioxide (CO_2) levels prompt exploration of carbon sequestration solutions. **Macroalgae cultivation enhances photosynthesis and the biological pump, offering biomass production and Carbon Dioxide Removal (CDR) benefits**. With a higher carbon-to-nitrate (CN) ratio in photosynthesis than phytoplankton, macroalgae sequester more carbon and sink faster, transporting it into the deep ocean.

However, **macroalgae growth is sensitive to environmental conditions like insolation, ocean temperature, and nitrate availability, complicating optimal cultivation location and timing**. Understanding factors controlling macroalgae growth aids in tailoring cultivation techniques for maximum productivity. Seasonal fluctuations in location, temperature, and nutrient availability significantly affect macroalgae growth patterns. While winter-spring seasons exhibit high nutrients from ocean mixing, summer-fall seasons face nutrient limitations due to thermal stratification. Despite its benefits, macroalgae growth inhibits **a feedback mechanism altering nutrient availability and phytoplankton populations**, impacting carbon uptake efficiency in marine ecosystems.

This study aims to overview optimal macroalgae cultivation from selected North Atlantic and Pacific sites (**Figure 1**), considering critical physical and biogeochemical processes, including ecosystem feedback loops.

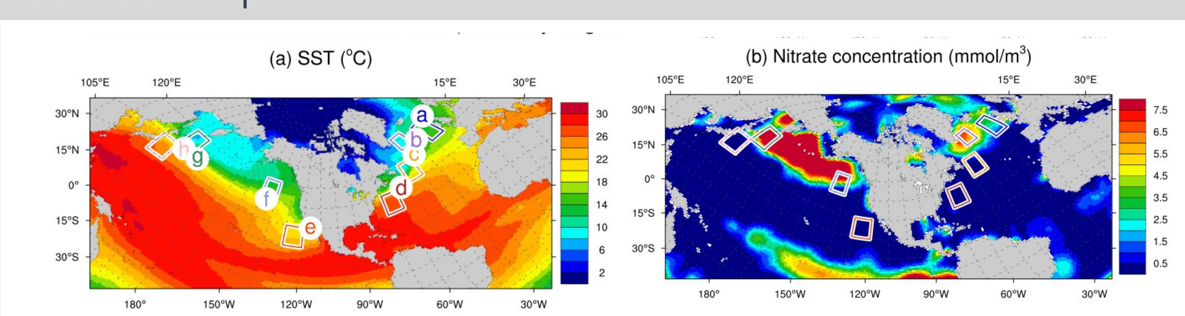


Figure 1: Selected North Atlantic and Pacific sites and observational data of sea surface temperature (SST) and nitrate concentrations.

Methodology

This study employs **a one-dimensional ocean ecosystem model integrating macroalgae functions** to analyze marine pelagic ecosystem dynamics (**Figure 2**).

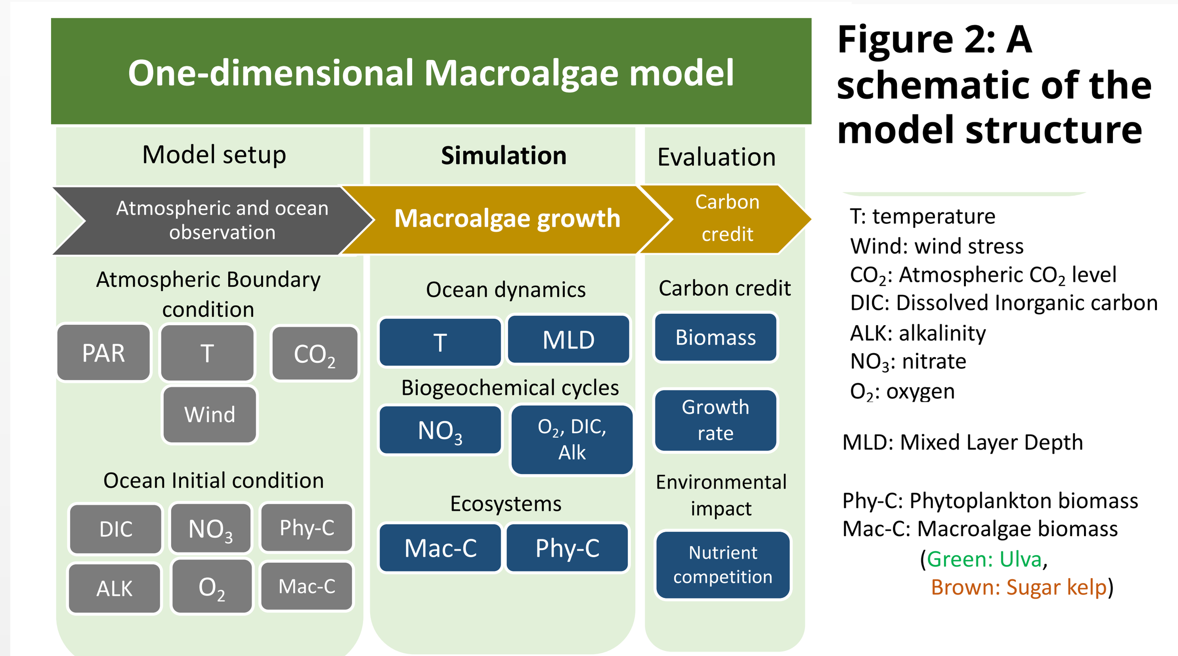
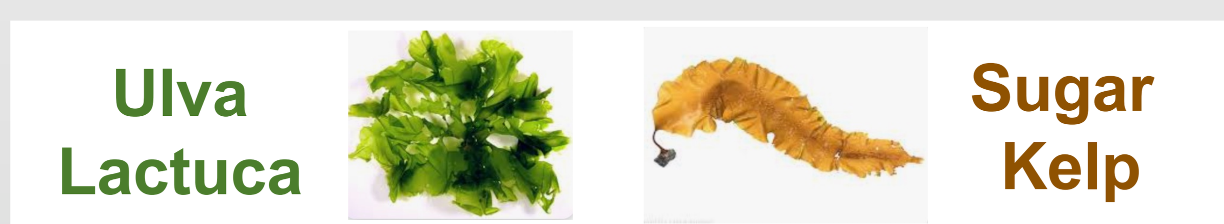


Figure 2: A schematic of the model structure

Macroalgae-Ecosystem model

The model integrates 105 vertical layers and includes nitrate and carbon cycles alongside simplified ecosystem functions (NPZD) to evaluate seasonal phytoplankton blooms influenced by insolation, temperature, and nutrient availability (Sasai et al., 2016). **The model integrates macroalgae functions** to deepen understanding of marine pelagic macroalgae responses, **including green (Ulva) and brown (Sugar Kelp) species**. Their growth dynamics depend on insolation, temperature, and nutrient availability akin to phytoplankton photosynthesis under Michaelis-Menten kinetics.

Sasai, Y. et al. (2016). Journal of Oceanography, 72(3), 509–526. https://doi.org/10.1007/s10872-015-0341-1



Boundary and initial conditions

The essential boundary conditions for the simulation are the daily dataset of **JRA55** reanalysis data (radiation, temperature, wind, precipitation, and sea surface temperature). Monthly data sets from WOA were used for biogeochemistry, and for carbon chemistry, initial values were created from **CDIAC**.

Simulation Design

Eight locations were selected to analyze macroalgae responses to subtropical and subarctic water variations in the North Atlantic and Pacific Oceans. The model underwent a 5-year spin-up without macroalgae (phytoplankton control run). **Subsequent simulations with macroalgae functions (macroalgae run), starting deployments from January to October**, explored optimal growth months for Ulva and Sugar Kelp.

Results

Optimal Site Selection for Algae Cultivation

Optimal locations for Ulva and Sugar Kelp growth exhibit subarctic regions with high nitrate and cold temperatures (Sites a, b, g, and h), including the western North Pacific (Site h) (**Figure 3**). In these sites, macroalgae present significant growth potential, such as the biomass increase from the initial one of 0.4. wet gram m^{-2} to several hundred grams per year. In contrast, subtropical regions characterized by summer temperatures above 20 °C and nitrate deficit inhibit Ulva and Sugar Kelp growth (**Figures 3**).

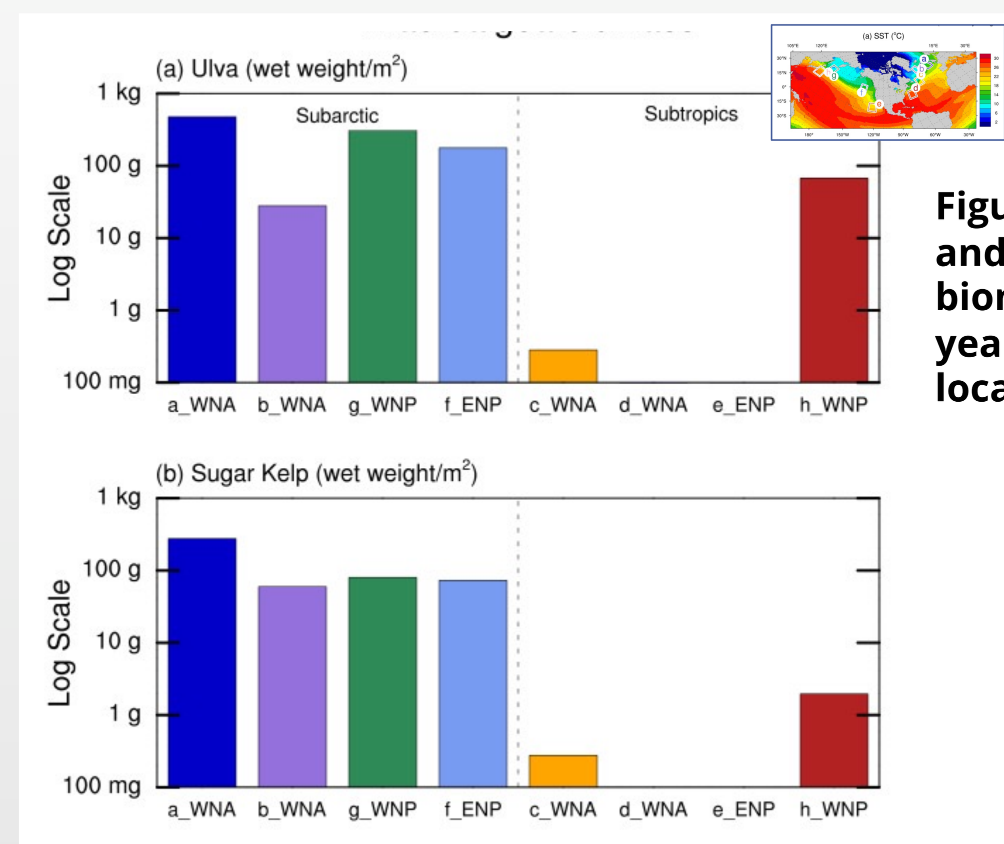


Figure 3: Ulva and Sugar Kelp biomass for a year at eight locations.

Growth Controlling factors

Ulva growth at the most productive site (site a) is primarily controlled by water temperature in the spring and nitrate availability in the summer and fall seasons (**Figure 4**). **Eutrophic conditions, characterized by abundant nutrients, sustain macroalgae biomass during summer, contrasting with the nutrient-deficient subtropical regions where biomass drastically drops**. For sugar kelp, growth is limited by water temperature throughout the year, indicating sufficient nutrients for growth in this area.

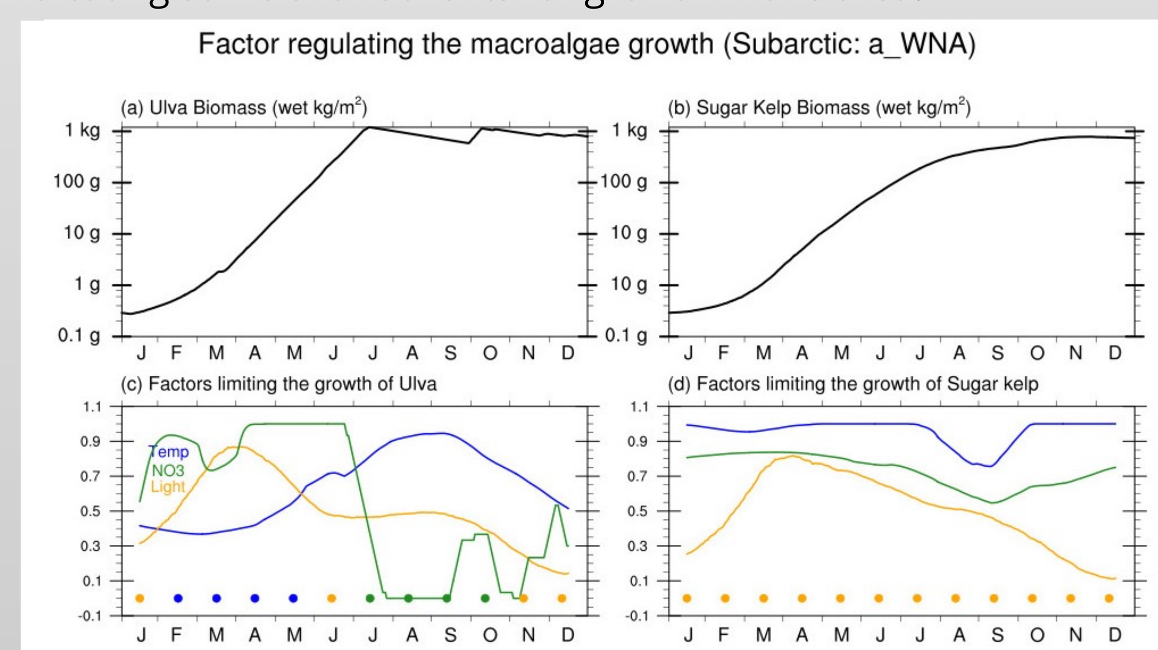


Figure 4: Controlling factors for growth potential at site a. The biomass and limited factors for Ulva and Sugar Kelp.

Best Cultivation Seasons

Ulva and Sugar Kelp demonstrate distinct optimal timing for three-month deployments on productive sites. **Ulva thrives when cultivations begin in the summer and early fall months, whereas Sugar Kelp exhibits optimal growth potential when deployed commercially in spring** (**Figure 5**). This is attributed to light availability, as shown in **Figure 4**, where solar input and biomass shading maximize growth during this season. Ulva benefits from avoiding nutrient consumption until early summer, fostering favorable conditions of high insolation, appropriate temperatures, and available nutrients, thereby boosting growth later on.

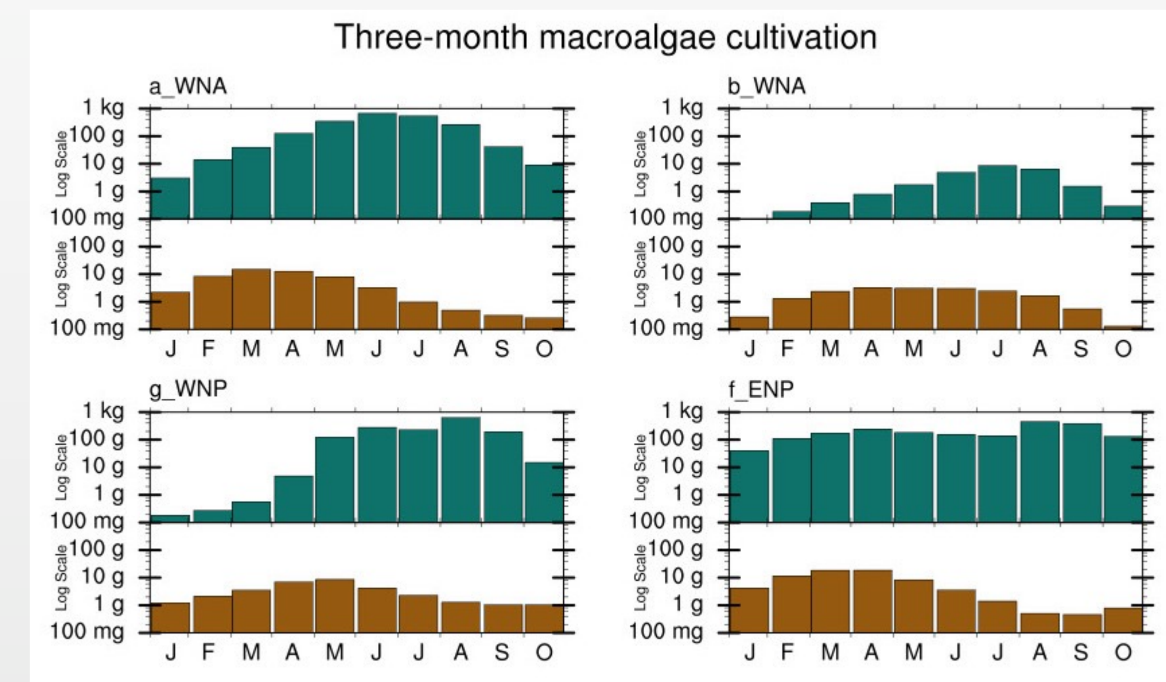


Figure 5: Ulva and Sugar Kelp biomass at four productive sites for three months.

Discussion and Conclusion

The optimal locations for Ulva and Sugar Kelp cultivations commonly reside in subarctic regions where nutrients remain abundant, and suitable temperature ranges prevail. However, the preferred seasons for cultivations differ, with Ulva thriving in summer and Sugar Kelp in spring. **This underscores the need to establish distinct cultivation strategies for each species**.

Two primary uncertainties persist regarding biomass simulations: (1) the inherent variability of environmental conditions and (2) the functions of controlling factors reliant on insolation, temperature, and nitrate concentrations. Moreover, the current setup assumes uniform biomass concentrations across broad regions. Yet, **the interaction between the external environments and growth, influenced by Lagrangian floating movements, remains unexplored.** Addressing these questions is imperative for deeper insights in future research endeavors.

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