Department of Ocean Technology, Policy, and Environment

Carbon dioxide removal via macroalgae mariculture and sinking in Japan’s EEZ: Macroalgae growth modeling and simulation

（日本のEEZにおける大型藻類の養殖と沈降による二酸化炭素除去：
マクロ藻類の成長モデリングとシミュレーション）

学籍番号: 47-226634　夏　増傑
指導教員:　　多部田　茂　教授

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Introduction

Introduction - Background

Definition

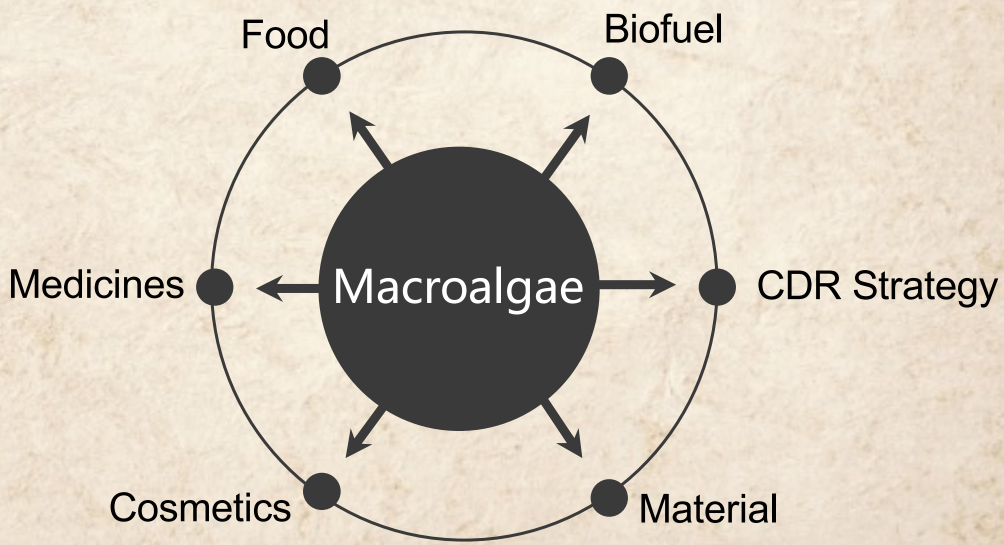
"Blue carbon" ecosystems such as mangroves, seagrass meadows, salt marshes and **kelp (macroalgae) forests** are extremely effective at taking up CO2 through photosynthesis and storing carbon in their soil and biomass. Thus, managing and restoring blue carbon ecosystems can increase the amount of carbon stored in coastal sediments.

Current Condition

- Anthropogenic emissions are rapidly increasing the atmospheric concentration of CO_2.

Importance

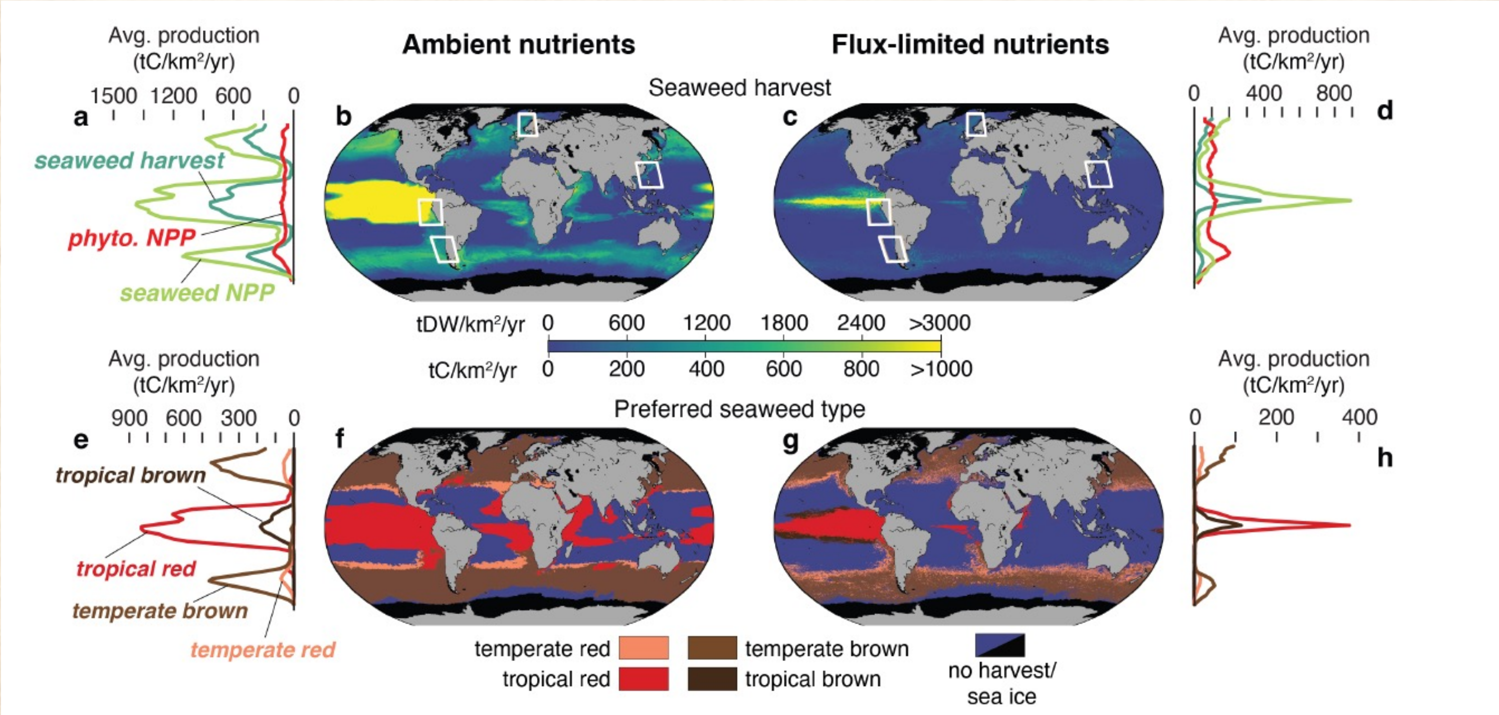
- Macroalgae are highly efficient carbon sequestrants with high C:N ratios, observed to have a Net Primary Production (NPP) rate of 91-522 ($gC\text{-}m^2yr^{-1}$).
- Wild seaweeds may sequester large amounts of carbon in the oceans through the export of organic matter (dissolved and particulate) to the deep ocean (>1000 m), where it is largely buried.



Introduction - Previous research

- Potential of global seaweed production and carbon sequestration (Arzeno-Soltero et al., 2023)

- The simulation has two scenarios:
  - Ambient nutrients
  - Flux-limited nutrients
- **Global MacroAlgae Cultivation Modelling System (G-MACMODS)** is developed.
  - only nitrate is the limiting nutrient
- The highest zonally-averaged annual harvest are found near the equator, followed by areas close to the North and South Poles.



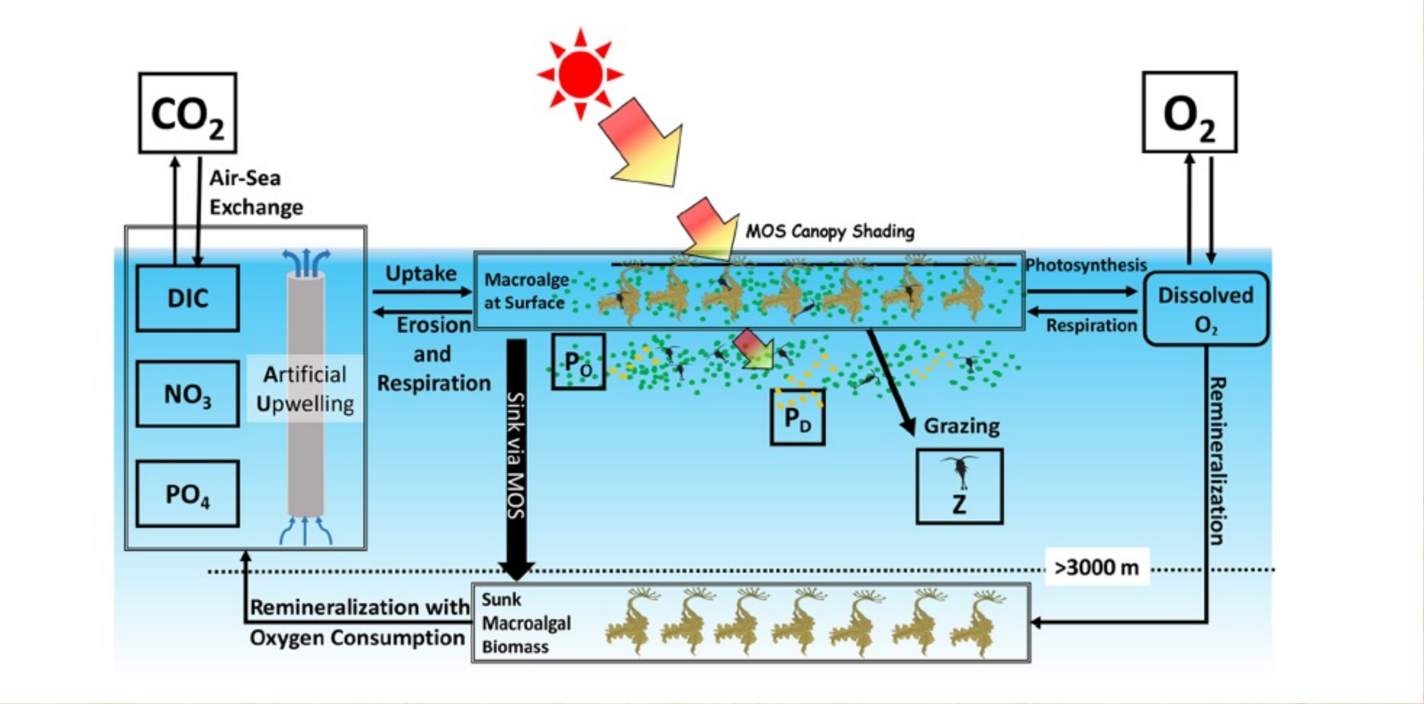
From Global MacroAlgae Cultivation Modelling System (G-MACMODS)

Reference： Arzeno-Soltero et al. (2023) : Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints

Introduction - Previous research

- Macroalgae open-ocean mariculture and sinking (MOS) (Wu et al., 2023)

- Global CDR potential under RCP 4.5 Scenario is simulated.
- The macroalgae model considers two types of limiting nutrients:
  - nitrate
  - phosphate
- The roles of remineralization and dissolved oxygen were also considered in estimating carbon sequestration.



Reference: Jiajun Wu, David P . Keller, and Andreas Oschlies Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study, Earth Syst. Dynam., 14, 185–221, 2023 https://doi.org/10.5194/esd-14-185-2023

Introduction - Research objectives

01 To estimate the potential of "macroalgae open-sea mariculture and sinking" as CDR method within **Japan's EEZ** area by using a macroalgae growth model.

02 To compare the effects of using **different nutrient uptake models** on macroalgal biomass yields and carbon sequestration to discuss their features.

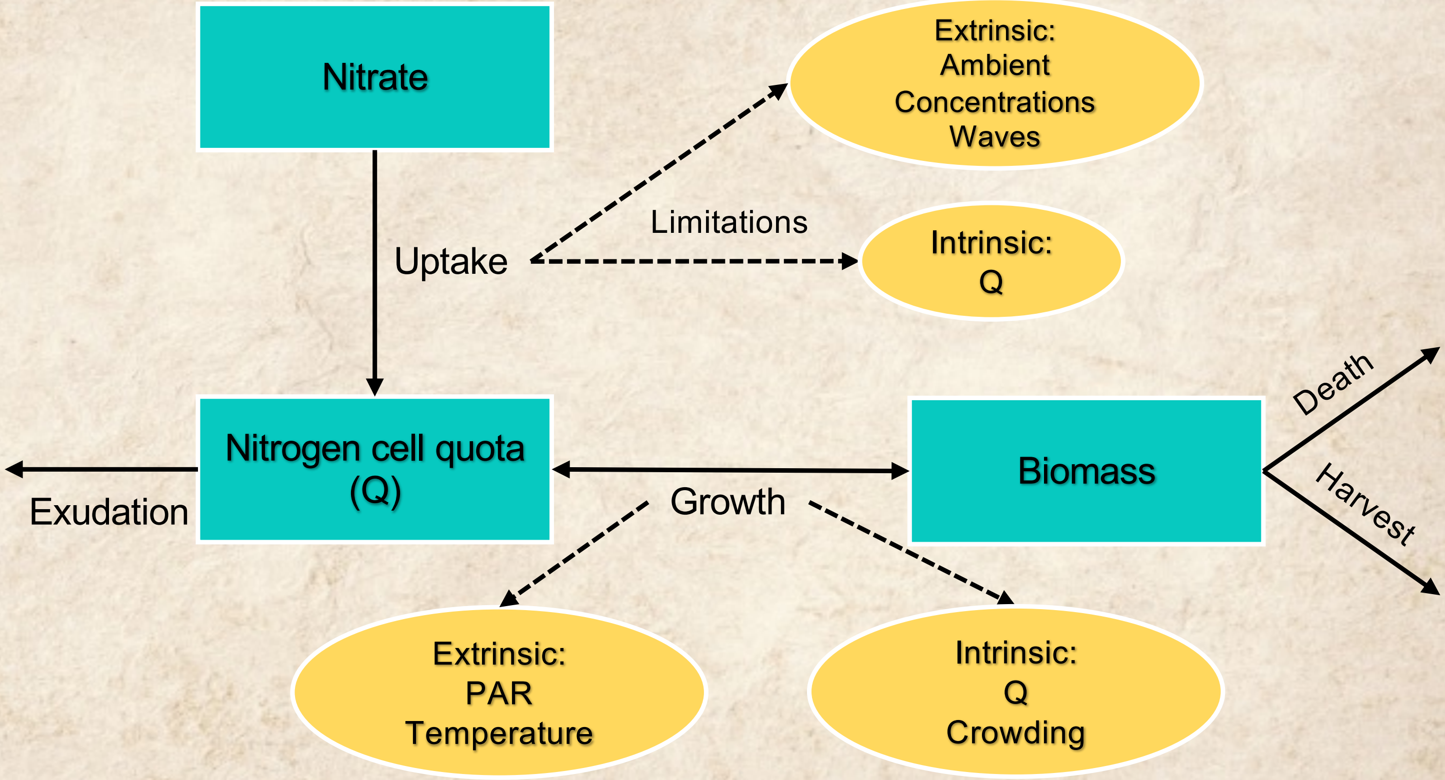
03 To discuss the effects of different limiting macronutrients (nitrogen and phosphorus) on the growth of macroalgae.

04 To find the impact of different harvesting strategies on macroalgae yields.

Materials and methods

Methods - Model overview

- The growth of macroalgae is influenced by 3 main factors:
  - Irradiation
  - Nutrients
  - Water temperature
- Nitrogen cell quotas are affected by external nitrate, which in turn affects biomass.
- Nitrogen uptake and biomass of macroalgae are affected by both intrinsic and extrinsic factors.



Reference: Isabella B. Arzeno-Soltero1,*, Christina Frieder2, Benjamin T. Saenz3, Matthew C. Long4,Julianne DeAngelo5, Steven J. Davis5,1, and Kristen A. Davis1,5,*, Biophysical potential and uncertainties of global seaweed farming, DOI: https://doi.org/10.31223/X52P8Z

Methods - Macroalgae Model

- **Model structure**

State variables:
Biomass (*B; g-DW/m²*) ,
Nitrogen cell quota (*Q; mg-N/g-DW*):

$$\frac{dB}{dt} = \mu B - d_M B$$

and

$$\frac{dQ}{dt} = V - \mu(Q - Q_{min}) - E(Q - Q_{min}) \quad Q \geq Q_{min}$$

$$\frac{dQ}{dt} = V \quad Q < Q_{min}$$

V: nitrogen uptake rate [μmol-N/(g-DW h)],
E: fractional exudation rate per day (1/day),
μ:growth rate per day (1/day),
d_M :mortality rate per day (1/day).

- **Growth**

The growth rate (μ) of macroalgae:

$$\mu = \mu_{max} g(Q) g(T) g(E)$$

μ_{max} (1/day) is the maximum growth rate of the seaweed.

➢ **The nitrogen cell quota limit:**

$$g(Q) = \frac{Q - Q_{min}}{Q}$$

➢ **The temperature limiting term:**

$$g(T) = \exp\left(-\beta_1 \left(T - T_{opt}\right)^2\right), T < T_{opt}$$

$$g(T) = \exp\left(-\beta_2 \left(T - T_{opt}\right)^2\right), T > T_{opt}$$

$$g(T) = 1, T = T_{opt}$$

T_{opt} :Optimal temperature range;
T :daily temperature.

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Methods - Macroalgae Model

- **The light limiting term:**

$$g(E) = f\frac{I-I_c}{I_s-I_c}\exp(-\frac{I-I_c}{I_s-I_c}+1)$$

I_s : daily averages of saturated irradiance (W/m^2);
I_c: daily averages of compensated irradiance (W/m^2);
f:is the percentage of daylight;
I:is the irradiance reaching a depth of 5m underwater.

The calculation of I is based on the surface incoming shortwave radiation (SIS):

$$I = I_{z=0}PARe^{-k_w\tilde{z}-k_c\int_0^{\tilde{z}} P\,dZ}$$

$I_{z=0}$: the downward shortwave radiation reaching the sea surface;

- **Nutrient Uptake**

Nitrogen uptake by seaweeds (V) depends on two main aspects: environmental factors and their own intrinsic factors:

$$V = V_{max}f_1(Q)f_2(|\vec{v}|, T_w, NO_3)$$

V_{max} : maximum rate of nitrogen uptake,
$f_1(Q)$: the dynamic nutrient cell quota,
$f_2(|\vec{v}|, T_w, NO_3)$: both kinetic and mass-transfer limitations on nitrogen uptake.

A linear nutrient cell quota was used:

$$f_1(Q) = \frac{Q_{max}-Q}{Q_{max}-Q_{min}}$$

Q_{min}:the minimum nitrogen content in the seaweed cell;
Q_{max}:the maximum nitrogen storage inside the seaweed cell;

Reference: Isabella B. Arzeno-Soltero1,*, Christina Frieder2, Benjamin T. Saenz3, Matthew C. Long4,Julianne DeAngelo5, Steven J. Davis5,1, and Kristen A. Davis1,5,*, Biophysical potential and uncertainties of global seaweed farming, DOI: https://doi.org/10.31223/X52P8Z

Methods - Macroalgae Model

- **Other models of nutrient uptake**

$$g(Q) \Rightarrow g(NP) \text{ and } g(N)$$

➤ **Model with phosphate limitation:**

$$g(N) = \frac{NO_3}{K_N + NO_3}$$

$$g(P) = \frac{PO_4}{K_P + PO_4}$$

$$g(NP) = Min\{g(N), g(P)\}$$

and

➤ **Model without nitrogen cell quota:**

$$g(N) = \frac{NO_3}{K_N + NO_3}$$

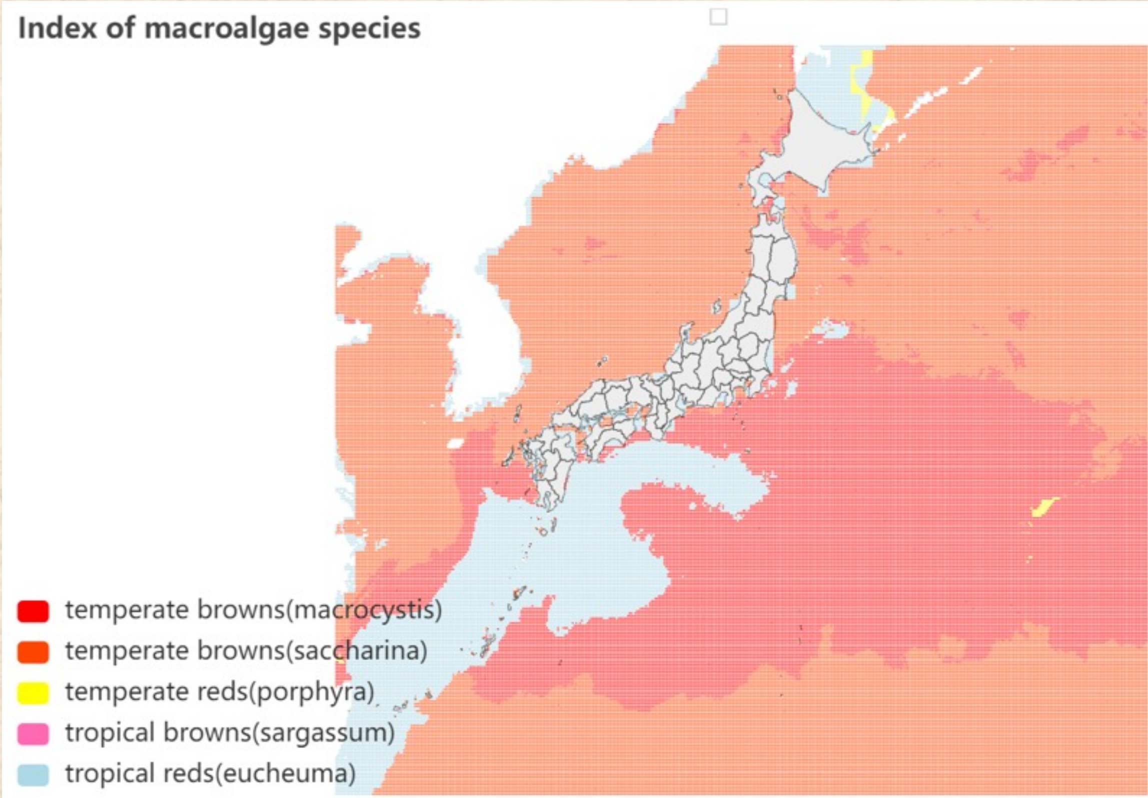
NO_3:External nitrate concentration
PO_4:External phosphate concentration
K_N :Half-saturation constant for nitrogen uptake
K_P :Half-saturation constant for phosphorus uptake

Reference： Jiajun Wu, David P . Keller, and Andreas Oschlies Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study, Earth Syst. Dynam., 14, 185–221, 2023 https://doi.org/10.5194/esd-14-185-2023

Methods - Macroalgae species

- The selection and distribution of macroalgae species are the same as G-MACMODS.

- Contained seaweed species that are among the top ten most cultivated seaweeds in the world by weight.
- Temperate brown seaweeds are the most widely distributed.
- Tropical red seaweeds are widely distributed in the south and some coastal areas.
- Tropical brown seaweeds were not used in the CDR method in the waters around Japan.



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Methods - Mass conversions

- We estimated the carbon sequestration capacity of macroalgae($\boldsymbol{C_{ma}}$, g-C/m^2/yr) from their carbon content.
- We assumed that macroalgae sink directly to the seafloor after harvesting, and ignored the effect of CO_2 overflow due to the shallow seawater and remineralization.
  - ➢ The final carbon sequestration capacity is very optimistic.

$$C_{ma} = Biomass \times R_{C:DW}$$

$R_{C:DW}$:Carbon content ratio of macroalgal biomass (g-DW/m^2).

Species	Carbon content($R_{C:DW}$)	Nitrogen content
Eucheuma	22.5% (±1.0)	0.71% (±0.31)
Sargassum	28.33%-30.53%	0.5%-1.5%
Porphyra	30%(±0.5)	0.63%-1.6%
Macrocystis	23.2%-30.5%	0.83%-2.96%
Saccharina	28% (±0.5)	2.67% (±0.08)

Methods - Harvest strategy

Harvest strategies for macroalgae in the baseline simulations were from previous research.

- 80% of the biomass was harvested if the biomass reached the target weight;
- 99% of the biomass was harvested if death >7 days or the final harvest period is reached.

Species	Target weight ($g\text{-}DW/m^2$)	Harvest cycle (day)
Eucheuma	800	45
Sargassum	400	45
Porphyra	80	150
Macrocystis	1350	220
Saccharina	1350	220

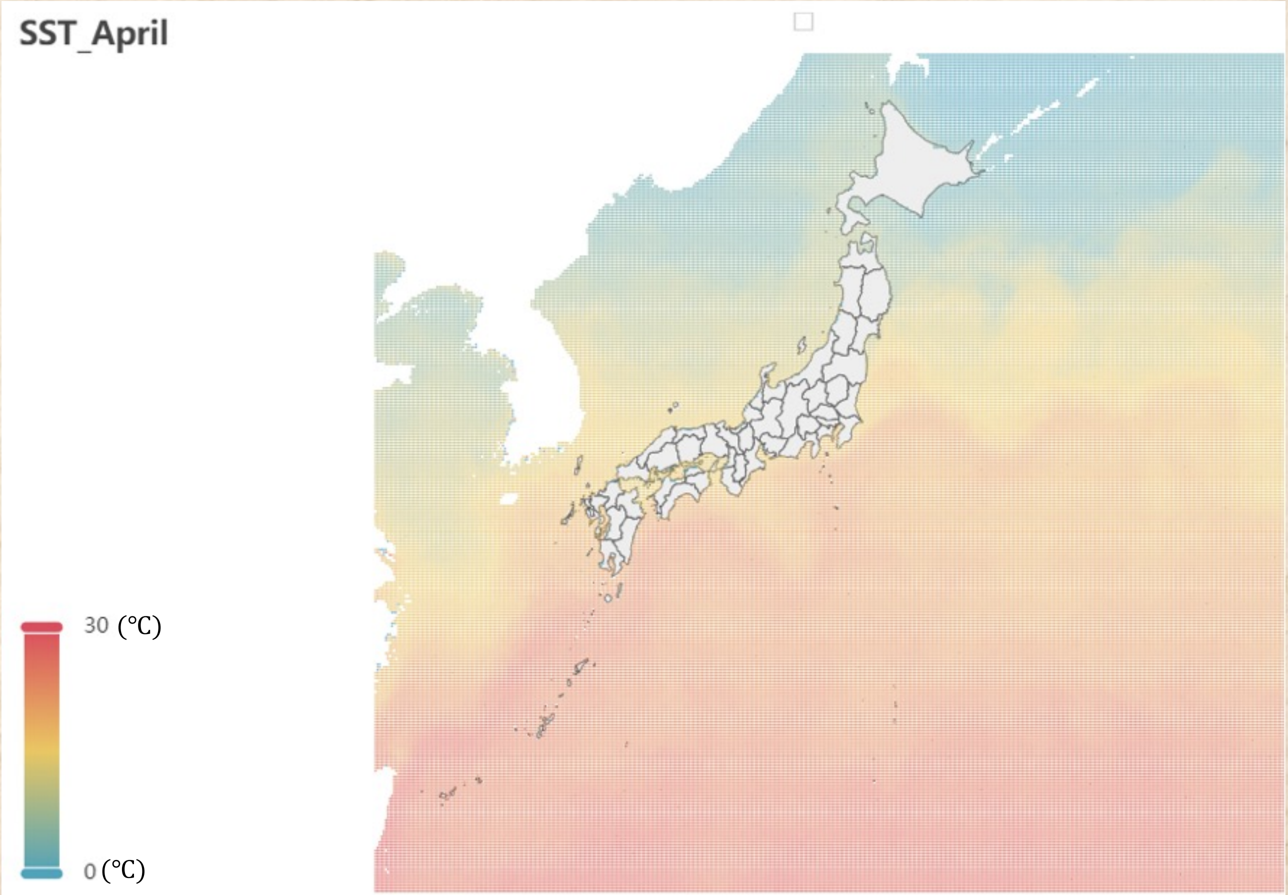
Reference： Isabella B. Arzeno-Soltero1,*, Christina Frieder2, Benjamin T. Saenz3, Matthew C. Long4,Julianne DeAngelo5, Steven J. Davis5,1, and Kristen A. Davis1,5,*, Biophysical potential and uncertainties of global seaweed farming, DOI: https://doi.org/10.31223/X52P8Z

Environmental data - Water temperature(℃)

- **Precision:** Daily average 1/12◦ spatial resolution data.

- **Condition:**

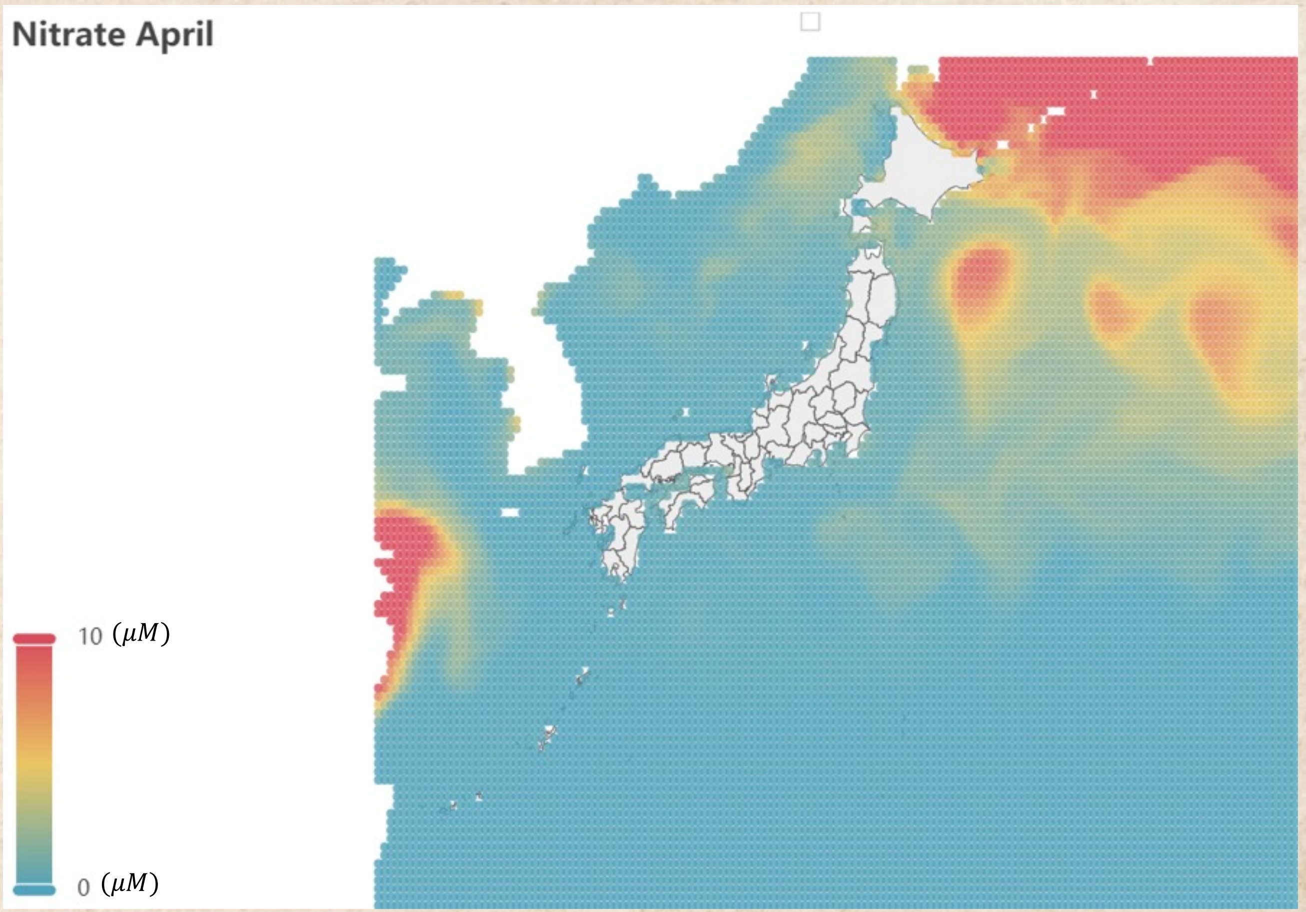
  - ➢ In the cold season, the water temperature spans a wide range.
  - ➢ Growth may be more difficult in the high water temperatures in the south.
  - ➢ Water temperature largely determines the distribution of macroalgae.



Source: Moderate Resolution Imaging Spectroradiometer (MODIS; R2018), obtained from the Ocean Productivity website.

Environmental data - Nitrate concentration(μM)

- **Precision:** Monthly average 1/4◦ spatial resolution data.
- **Condition:**
  - ➢ Winter is the most nutritious.
  - ➢ The further north, the richer the nutrients.

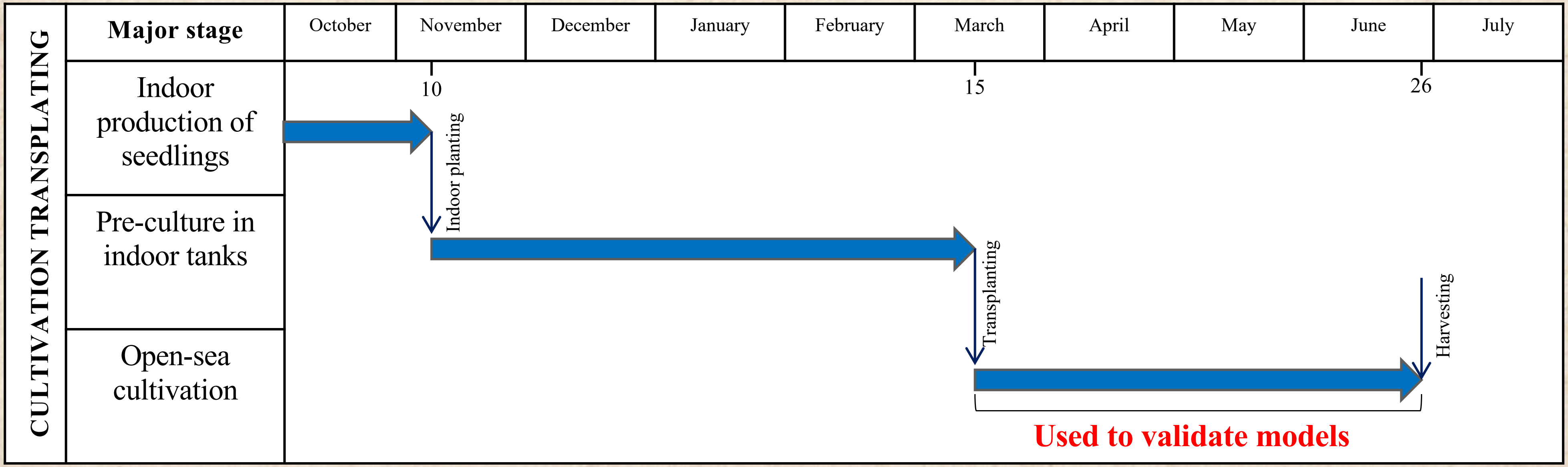


Source: High Resolution Biogeochemical Modeling Database for Biogeochemical Forecasting of the Global Oceans (obtained at CMEMS)

Model validation

Model validation - Actual experiment

- **Site:** Atlantic coast of northern Spain, Bay of Biscay (43°29′ N, 3°47′ W)
- **Cultivation facilities:** seven 20-meter culture ropes
- **Cultivation period (Experimental stage III):** March 15, 2006 - June 26, 2006



Reference: César Peteiro & Noemí Sánchez & Clara Dueñas-Liaño & Brezo Martínez, Open-sea cultivation by transplanting young fronds of the kelp Saccharina latissimi, J Appl Phycol (2014) 26:519–528 DOI 10.1007/s10811-013-0096-2

Model validation - Environmental data

- Comparison of environmental data recorded in the experiment and from the database.
  - ➢ Both nutrients were higher than those in the database.

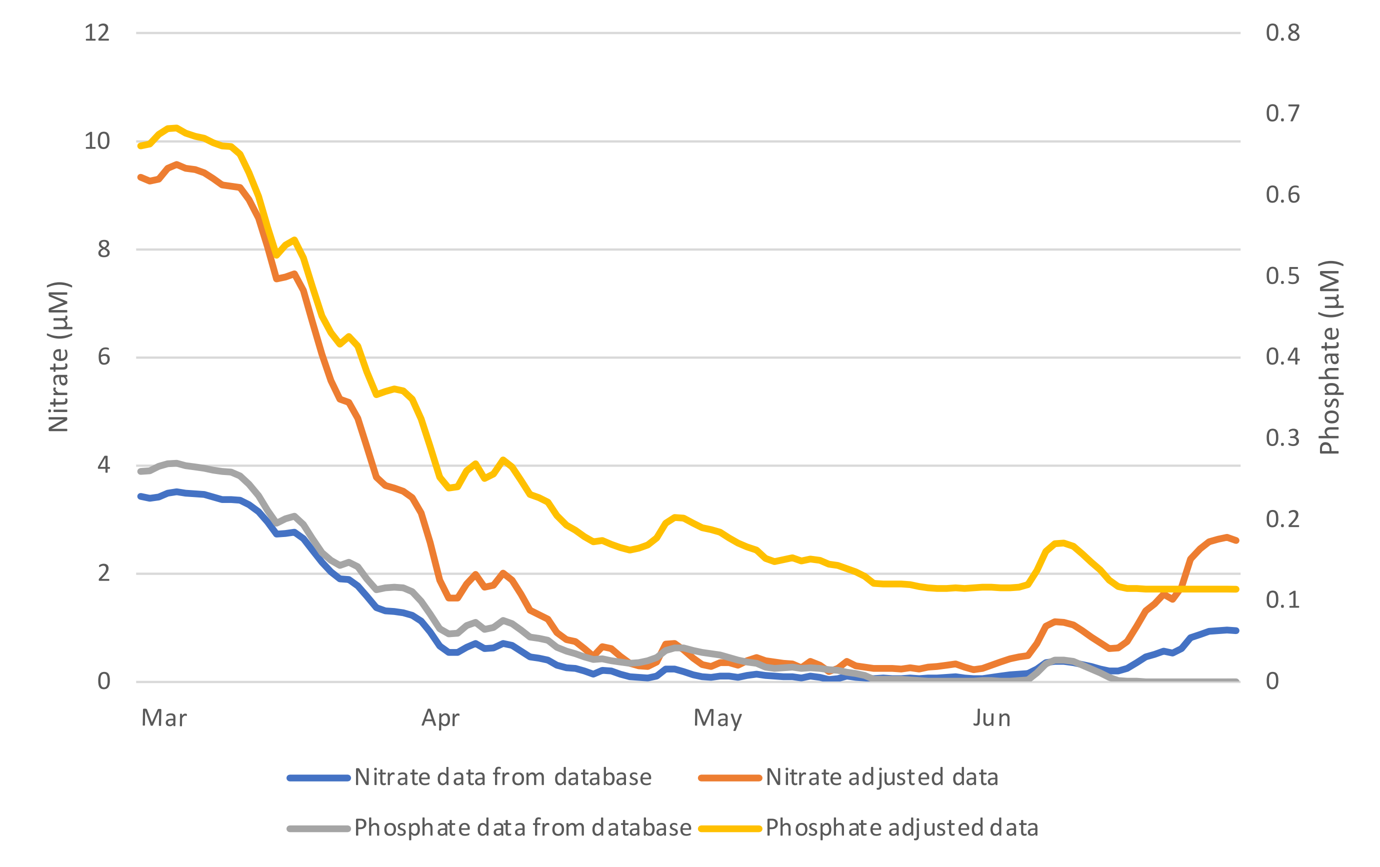
Parameters		Data recorded by the experiment	Data from database
Temperature (℃)		13.2±2.2 (11.1–16.2)	15.07±1.88 (12.29–18.9)
Underwater Irradiance (μmol photons m^{-2} s^{-1})		223±80 (0–746)	
Surface Incoming Shortwave Radiation flux (W m^{-2})			220.78±37.31(145.8–249.3)
Nutrients	Nitrate	4.9±4.2 (0.50–9.05)	0.56±0.72 (0.044–2.95)
	Phosphate	0.26±0.2 (0.09–0.43)	0.046±0.055 (0.0003-0.21)

Data expressed as mean ± standard deviation, minimum–maximum shown in parentheses
* 1 μmol photons m^{-2} s^{-1} ≈ 0.217 W m^{-2}

Reference: César Peteiro & Noemí Sánchez & Clara Dueñas-Liaño & Brezo Martínez, Open-sea cultivation by transplanting young fronds of the kelp Saccharina latissimi, J Appl Phycol (2014) 26:519–528 DOI 10.1007/s10811-013-0096-2

Model validation - Data adjustments

- Adjust the mean and standard deviation of the nutritional data to be equal to those recorded in the experiment.
  - ➢ Both nutrient concentrations increased.
  - ➢ Nitrate concentrations in May were close to pre-adjustment.



Model validation - Results

- **Simulation results using "nutrient data from databases"**

➢ **Biomass production in all three models was lower than the experimentally recorded values**

➢ **The value of the model with nitrogen cell quota is closest to the actual value.**

	Transplanting (15 March 2006) Fresh yield per length rope (kg fresh wt m^{-1} rope)	**Harvesting (26 June 2006)**	
		Fresh yield per length rope (kg fresh wt m^{-1} rope)	Fresh yield per hectare farm (t fresh wt ha^{-1} farm)
Experiment	2.1±0.2 (1.8-2.5)	7.8±1.1 (6.2-8.8)	45.6
Model with nitrogen cell quota	2.1	5.6	32.4
Model limited by N and P	2.1	2.47	14.386
Model without nitrogen cell quota	2.1	2.54	14.84

Data expressed as mean ± standard deviation, minimum–maximum are shown in parentheses with the exception of yield per hectare
* Sum of the fresh weight of all culture ropes in an area of 240 m^2

Model validation - Results

- **Simulation results using "adjusted nutrient data"**

➤ **The biomass yield of the model with nitrogen cell quotas far exceeded the experimentally recorded values.**

➤ **The yields of the two models without nitrogen cell quotas were very close to the actual values.**

	Transplanting (15 March 2006) Fresh yield per length rope (kg fresh wt m^{-1} rope)	**Harvesting (26 June 2006)**	
		Fresh yield per length rope (kg fresh wt m^{-1} rope)	Fresh yield per hectare farm (t fresh wt ha−1 farm)
Experiment	2.1±0.2 (1.8-2.5)	7.8±1.1 (6.2-8.8)	45.6
Model with nitrogen cell quota	2.1	14.655	85.49
Model limited by N and P	2.1	7.4	43.15
Model without nitrogen cell quota	2.1	7.4	43.15

Data expressed as mean ± standard deviation, minimum–maximum are shown in parentheses with the exception of yield per hectare
* Sum of the fresh weight of all culture ropes in an area of 240 m^2

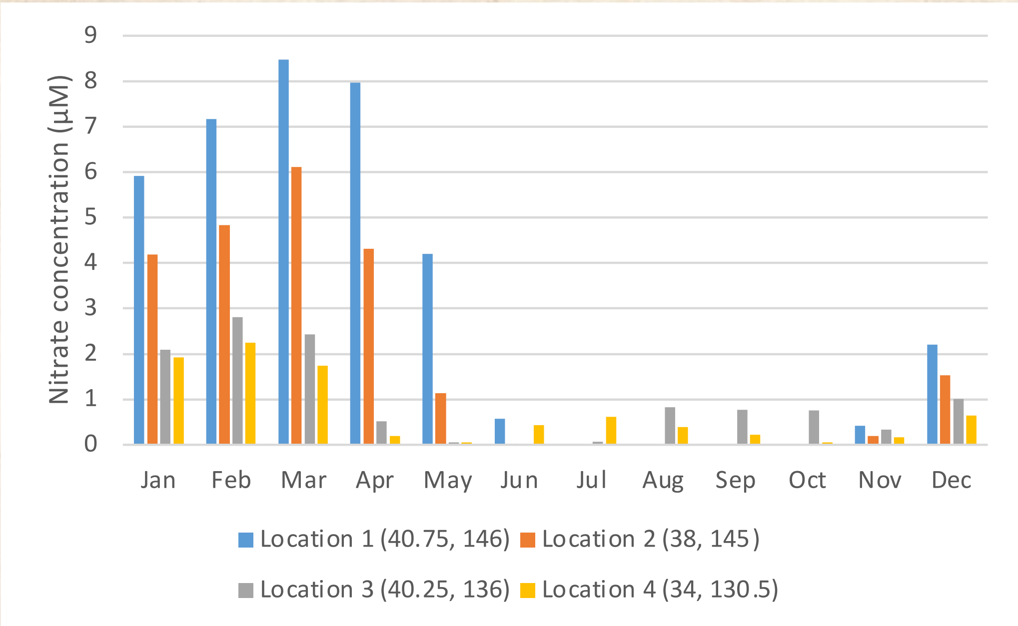
Simulation results

Simulation - Effects of nitrogen cell quota

- **Comparison to nitrogen cell quota model**

  To further discuss the effect of having or not having a nitrogen cell quota on macroalgal growth, we compare the biomass production of several grids with different nitrate concentrations.

$$g(Q) = \frac{Q - Q_{min}}{Q} \quad \text{and} \quad g(N) = \frac{NO_3}{K_N + NO_3}$$

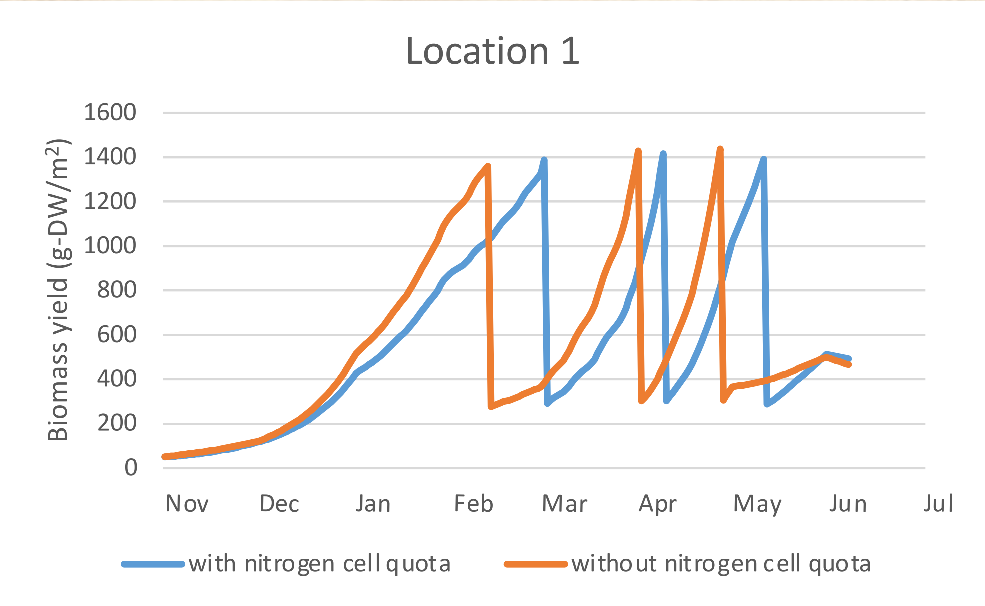


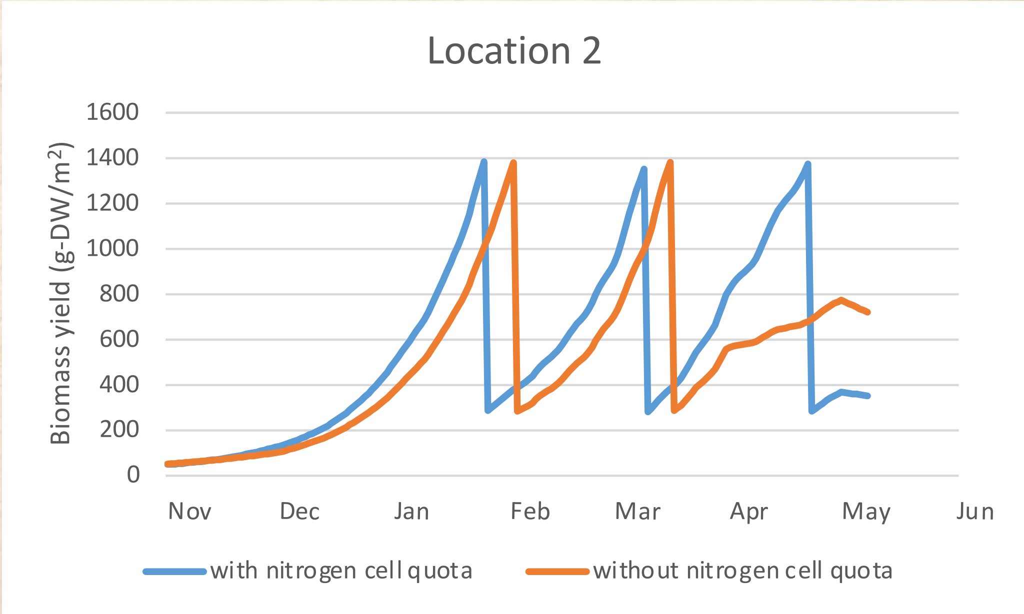
Results - Effects of nitrogen cell quota

After reaching the target weight[1350 (g-DW/m^2)], 80% of the biomass will be harvested.

- **Location 1:**
  - Both models were harvested 3 times and had similar yields with sufficient nutrients.
  - Growth was faster in the model without the nitrogen cell quota.

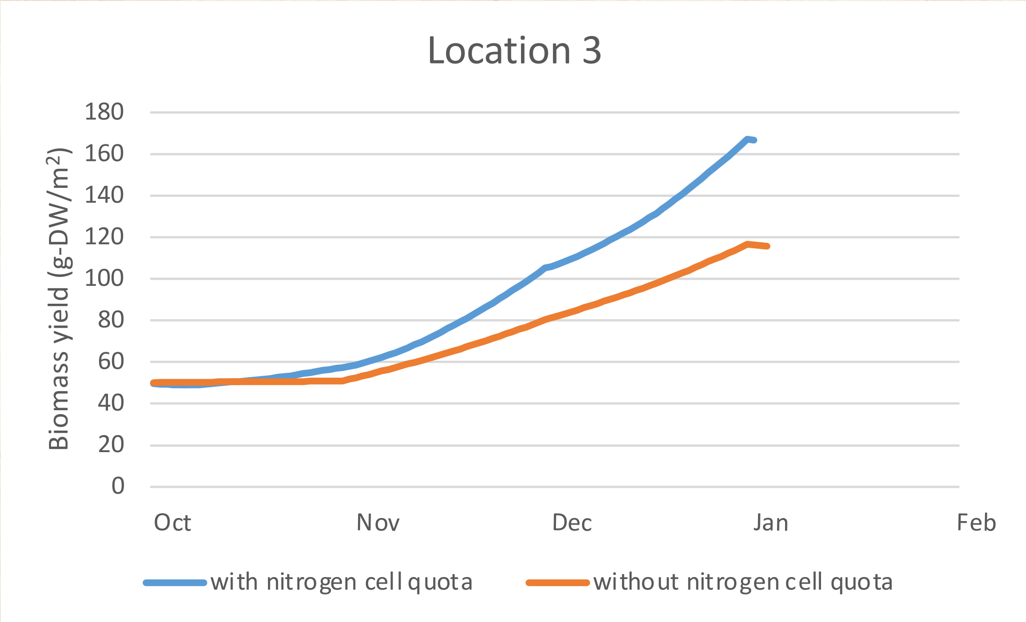
- **Location 2:**
  - The model with a nitrogen cell quota was harvested 3 times and the one without only 2 times, with the former growing faster.
  - The biomass production of the model without nitrogen cell quota decreased significantly with decreasing nutrient.

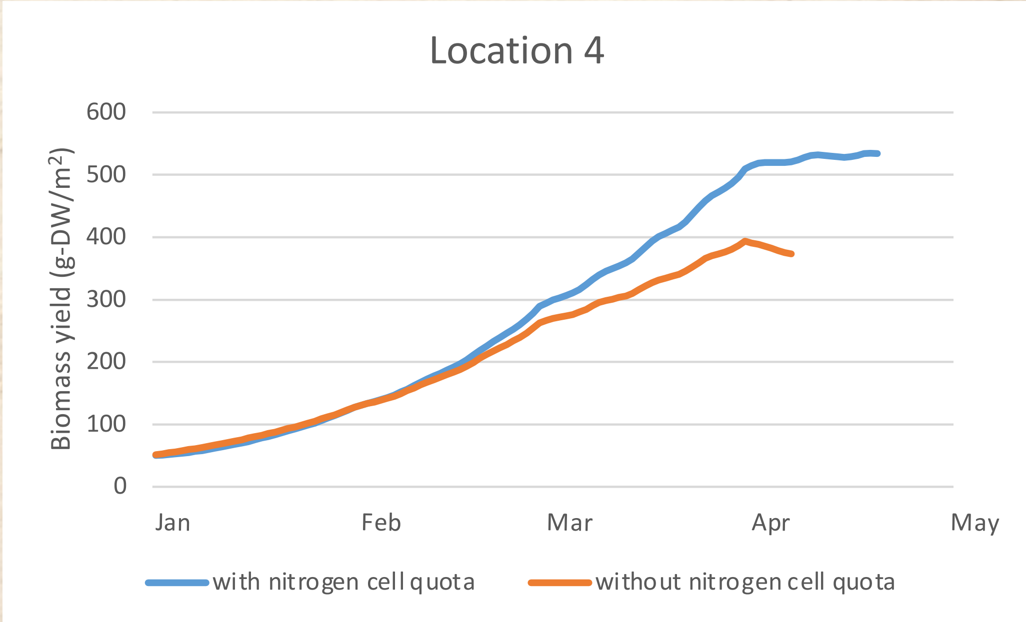




Results - Effects of nitrogen cell quota

- **Location 3 and Location 4:**
  - Biomass did not reach target weights at either site.
  - At lower nutrient concentrations, the model with nitrogen cell quotas grew faster and had higher biomass production.



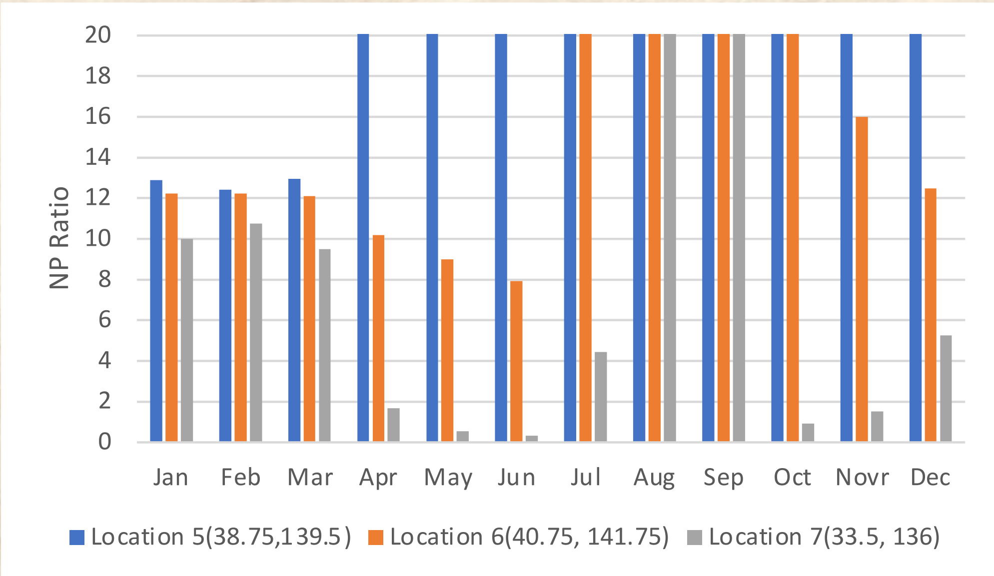


Simulation - Influences of phosphorus limitation

● **Growth in areas with different NP ratios**

Saccharina K_N : 2(μM) K_P : 0.1(μM) → **Optimal N:P ratio: 20**

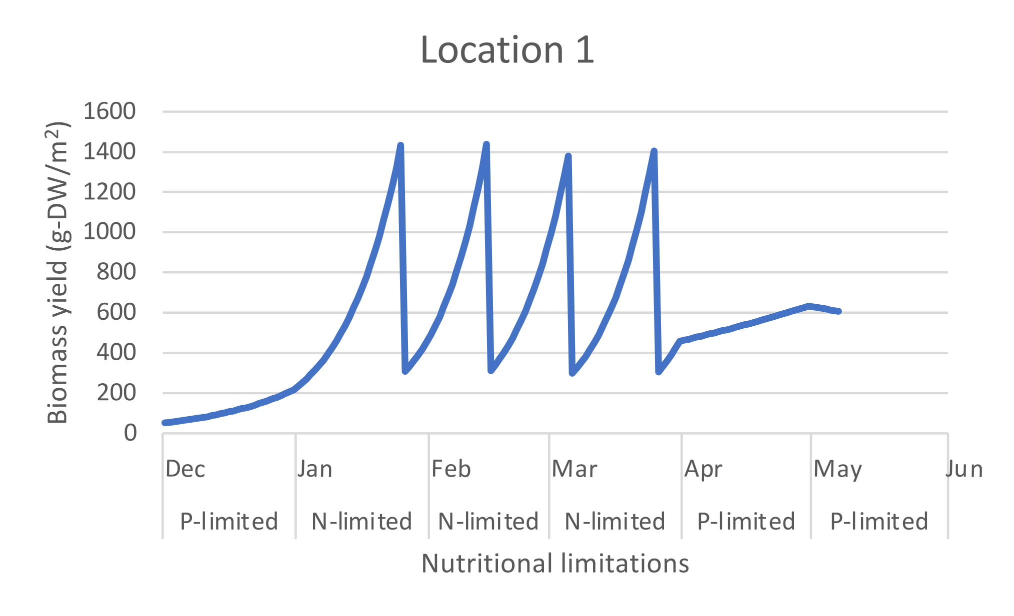
- Location 5: where have low NP ratios in the cold season and high NP ratios in the warm season;
- Location 6: where are similar to the first site, but with a lag in the increase of NP ratios;
- Location 7: where only briefly have high NP ratios in the summer.

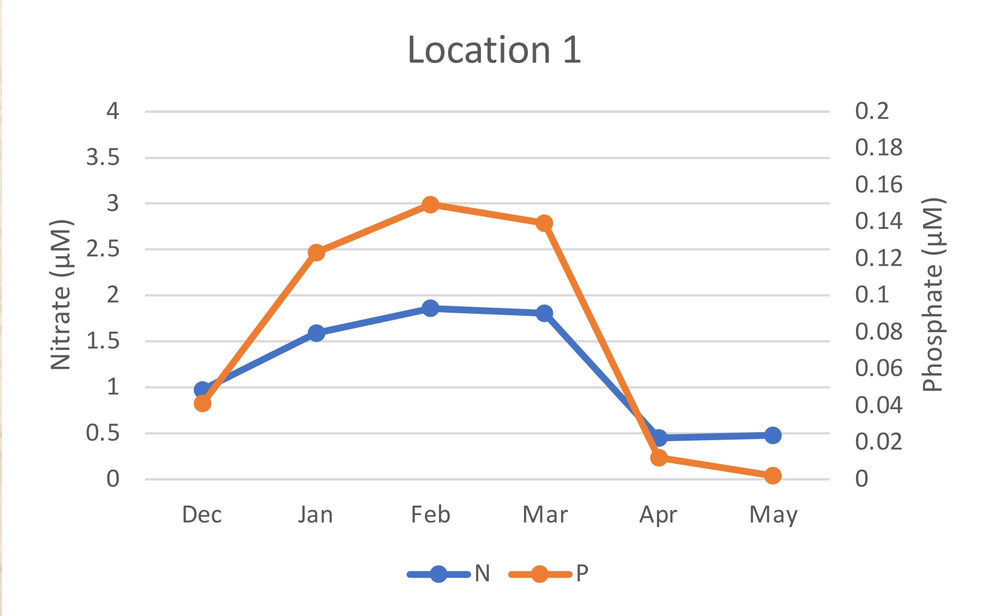


Results - Influences of phosphorus limitation

Biomass of macroalgae (Keeping other conditions optimal):

- Because of the increase in NP ratio, the growth of macroalgae in Site 1 began to slow down in April.
- Macroalgae are limited by phosphorus in the late stages of growth and grow very slowly, but it was limited by nitrogen during the rapid growth phase.
- The N:P < 20 from January to March, and macroalgae were limited by nitrogen.
- The N:P > 20 starting from April and the growth of macroalgae is limited by phosphorus.

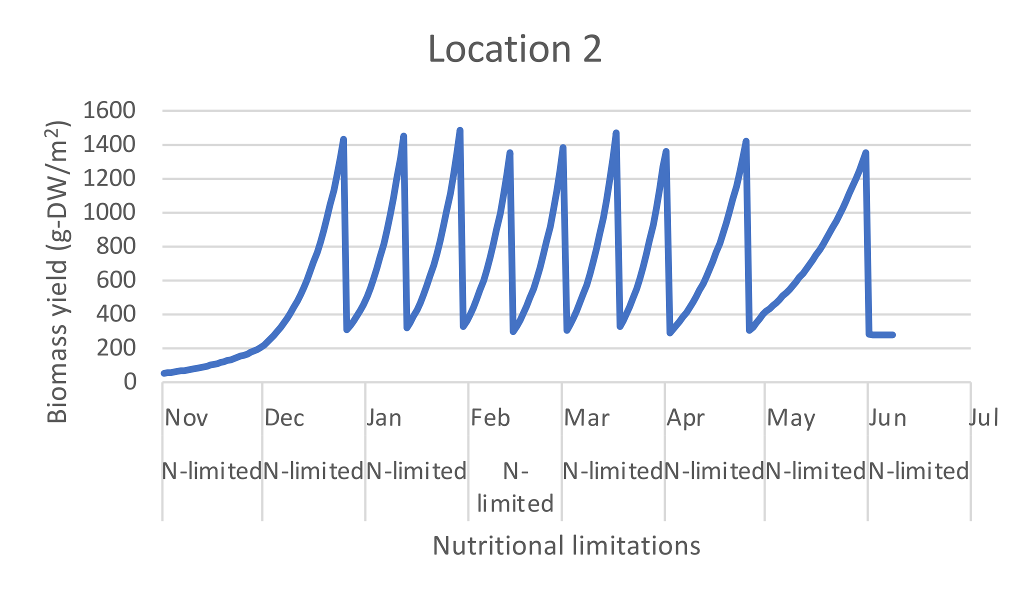


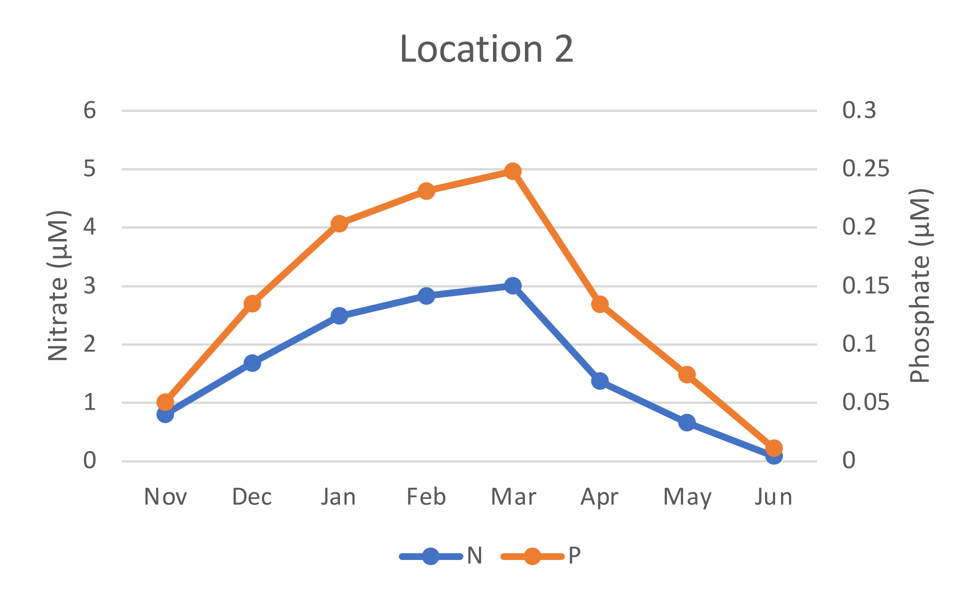


Results - Influences of phosphorus limitation

Biomass of macroalgae (Keeping other conditions optimal):

- Although the decrease in NP ratio was not obvious in June, both nutrients dropped to very low levels at the same time, resulting in limited growth of macroalgae.
- Macroalgae in the rapid growth phase are nitrogen limited.
- The NP ratio during the growth period is all below 20 and is limited by nitrogen.

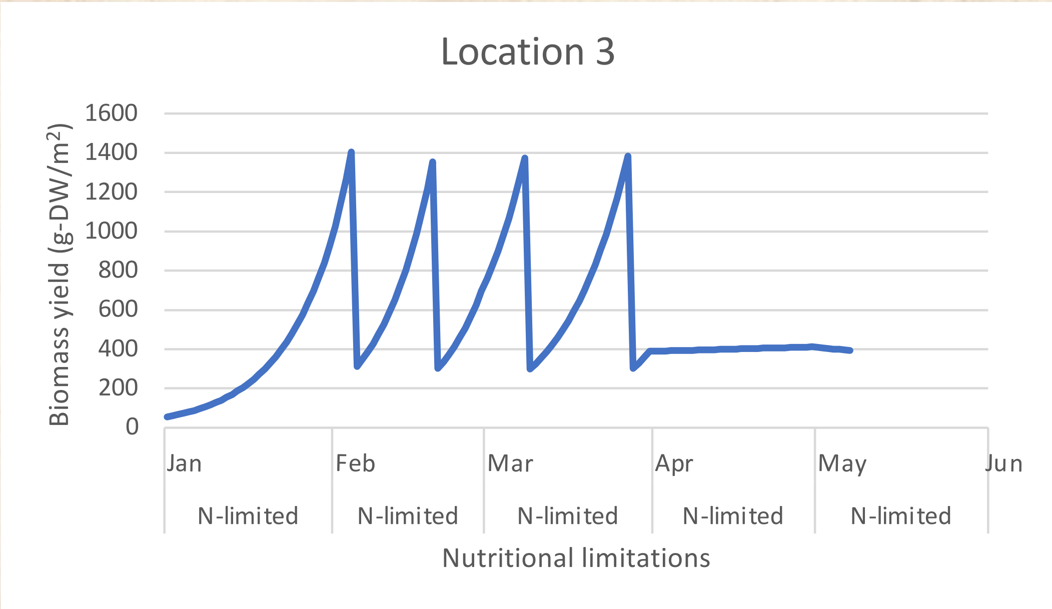


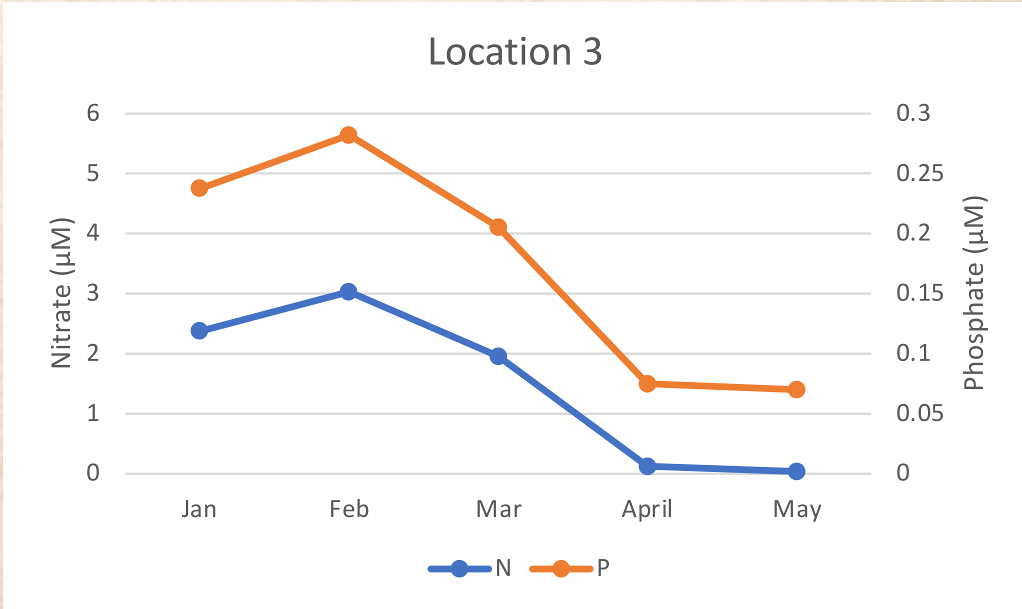


Results - Influences of phosphorus limitation

Biomass of macroalgae (Keeping other conditions optimal):

- In April, because the nitrate concentration dropped significantly, the NP ratio also dropped to a very low value, so the growth of macroalgae also slowed down.





Simulation - Define optimal yield

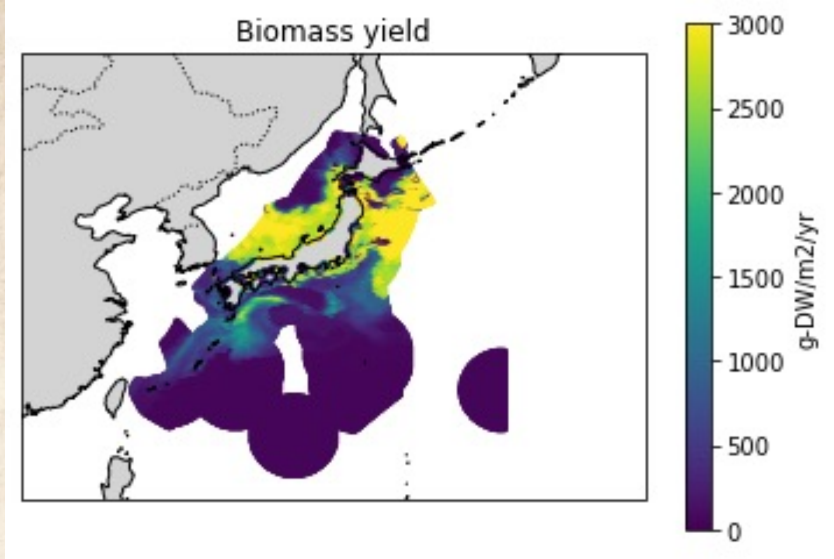
- To find the grid with the best yield, we use the common number of harvests per year for each macroalgae based on the literature and set an optimal yields for each macroalgae in combination with the target weights in the "Harvest Strategy".

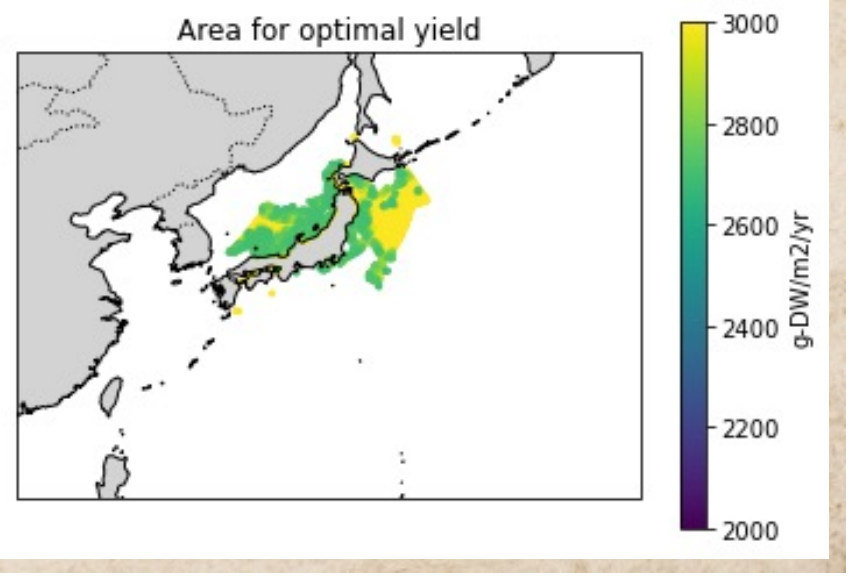
Species	Number of harvests (per year)	Optimal yield (g-DW/m^2/yr)
Eucheuma	8	3200
Sargassum	8	6400
Porphyra	6	480
Macrocystis	2	2700
Saccharina	2	2700

Results - Biomass yield

- **Yield by model with nitrogen cell quota**
  - 12% of the grids achieved optimal yields.
  - Compared to the other two models, the model with nitrogen cell quota is relatively optimistic.
  - Models with nitrogen cell quotas have lower requirements for external nitrate concentrations.
  - Grids with final annual production greater than 500 (g-DW/m^2/yr) accounted for about 33.5% of the total.
  - Macroalgae production was highest in the north-central (east coast) and south-central (west coast) regions of the entire EEZ.

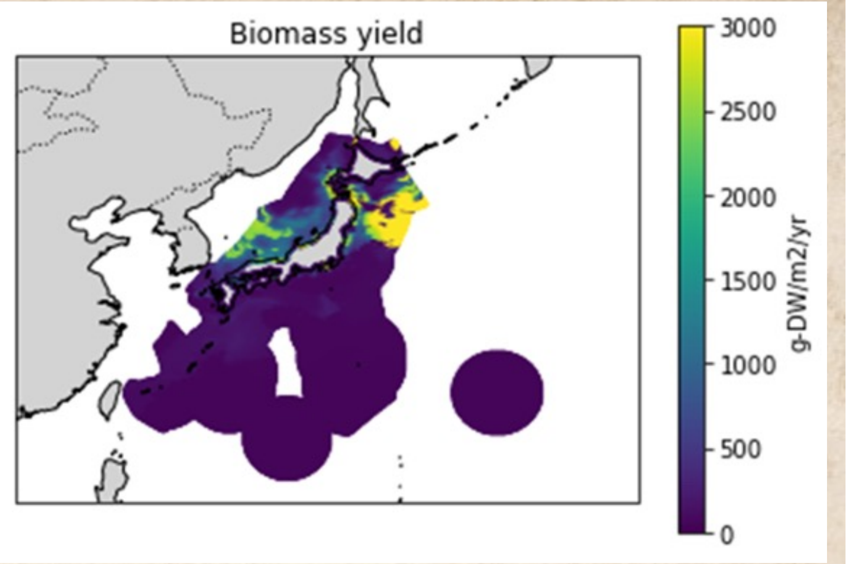
Parameter	**Genus**	**Minimum and Maximum values**	**Average Values**
Biomass (g-DW/m^2/yr) Macroalgal biomass yields	*Eucheuma (Tropical red)*	81.85-31550	727.85
	Sargassum (Tropical brown)	No distribution	0
	Porphyra (Temperate red)	210.54-217.8	201.78
	Macrocystis (Temperate brown)	46.6-5186.2	553.39
	Saccharina (Temperate brown)	46.6-9134.31	1032.28

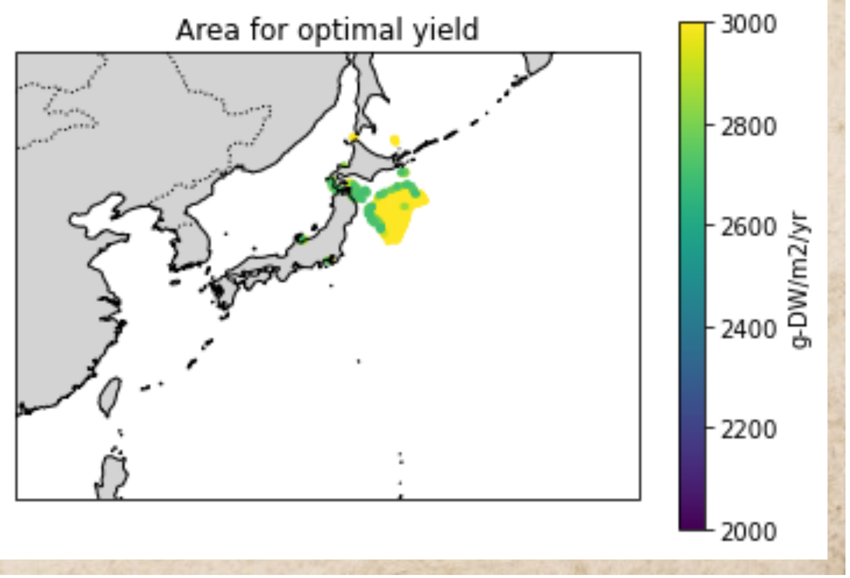




Results - Biomass yield

- **Yield by N limitation model without Nitrogen cell quota**
  - 3.4% of the grids achieved optimal yields, and are concentrated in the northeastern part of the EEZ.
  - Biomass production was much lower compared to the model with nitrogen cell quota.
  - Grids with final annual production greater than 500 (g-DW/m^2/yr) accounted for about 14.5% of the total.



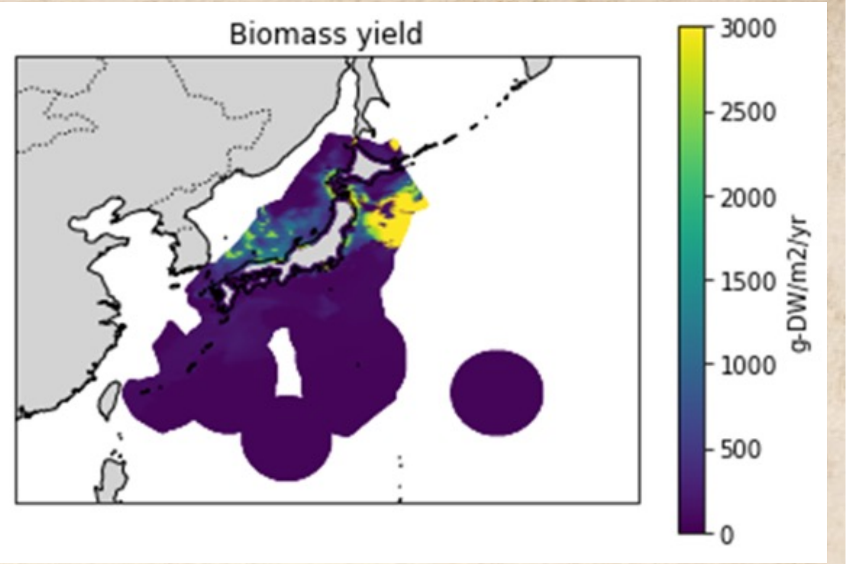


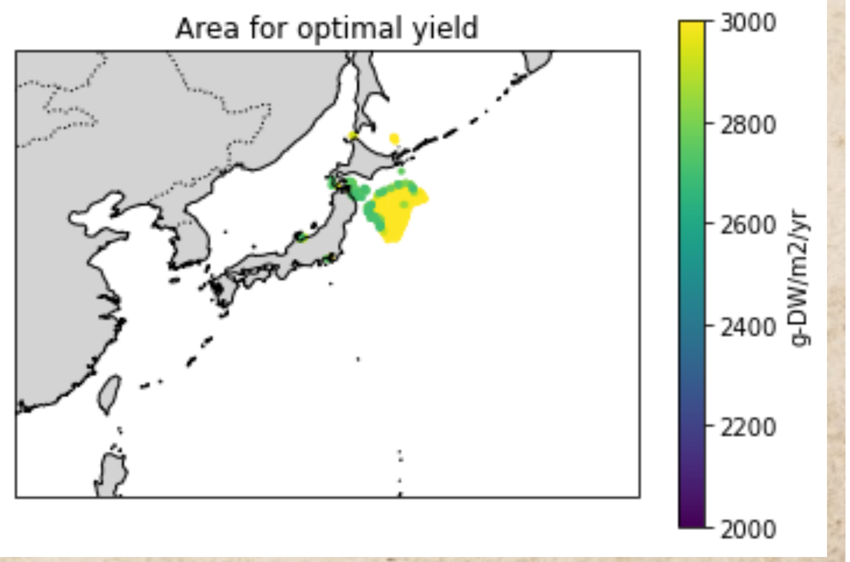
Parameter	Genus	Minimum and Maximum values	Average Values
Biomass (g-DW / m^2/yr) Macroalgal biomass yields	*Eucheuma (Tropical red)*	81.77-2982.35	152.43
	Sargassum (Tropical brown)	No distribution	0
	Porphyra (Temperate red)	9.8-154.86	88.6
	Macrocystis (Temperate brown)	46.6-418.1	59.6
	Saccharina (Temperate brown)	46.6-7300.196	573.61

Results - Biomass yield

- **Yield by N and P limitation model**
  - 3.2% of the grids achieved optimal yields, also concentrated in the northeastern part of the EEZ.
  - After introducing phosphorus limitation, macroalgae production was slightly reduced.
  - Models with N and P limitation have strictest requirements for external nitrate concentrations.
  - Grids with final annual production greater than 500 (g-DW/m^2/yr) accounted for about 13.4% of the total.

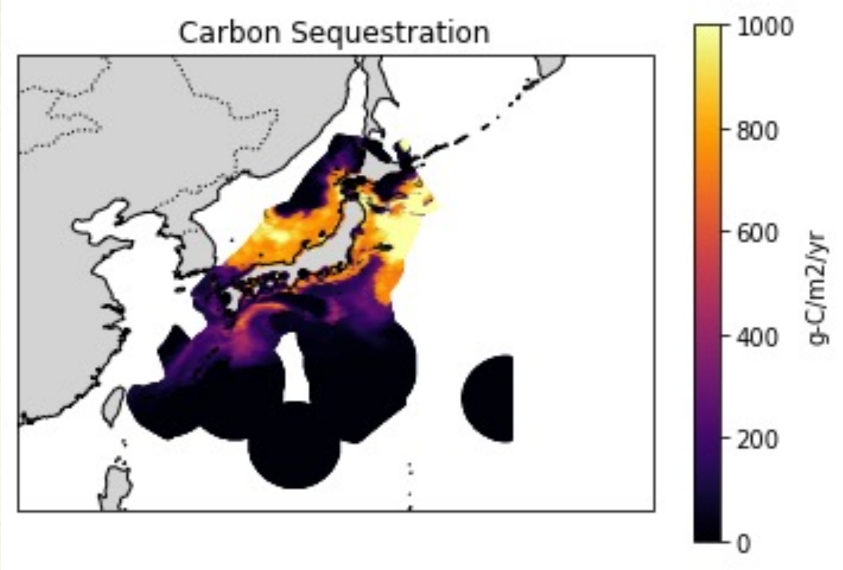
Parameter	Genus	Minimum and Maximum values	Average Values
Biomass (g-DW/m^2/yr) Macroalgal biomass yields	*Eucheuma (Tropical red)*	81.77-1616.387	143
	Sargassum (Tropical brown)	No distribution	0
	Porphyra (Temperate red)	9.8-154.86	88.6
	Macrocystis (Temperate brown)	46.6-418.1	59.4
	Saccharina (Temperate brown)	46.6-7266.186	530.1





Results - Carbon Sequestration

- The northeastern region of the EEZ has the most potential, followed by the western sea area.
- 18% of grids sequestering more than 500(g-C/m^2/yr) by model with nitrogen cell quota
- Carbon sequestration in the northeastern part of the Japanese EEZ is optimistic compared to the results of global simulations in previous research.
- Tropical red and temperate brown seaweeds are the main contributors to carbon sequestration.



Parameter	**Genus**	**Minimum and Maximum values**	**Average Values**
C_{seq} (g-C/m^2/yr) Carbon sequestration by macroalgae	*Eucheuma (Tropical red)*	21.69-8360.75	192.88
	Sargassum (Tropical brown)	No distribution	0
	Porphyra (Temperate red)	63.16-65.33	60.533
	Macrocystis (Temperate brown)	13.05-1452.13	154.95
	Saccharina (Temperate brown)	13.05-255.61	289.04

Discussion on harvesting scenarios

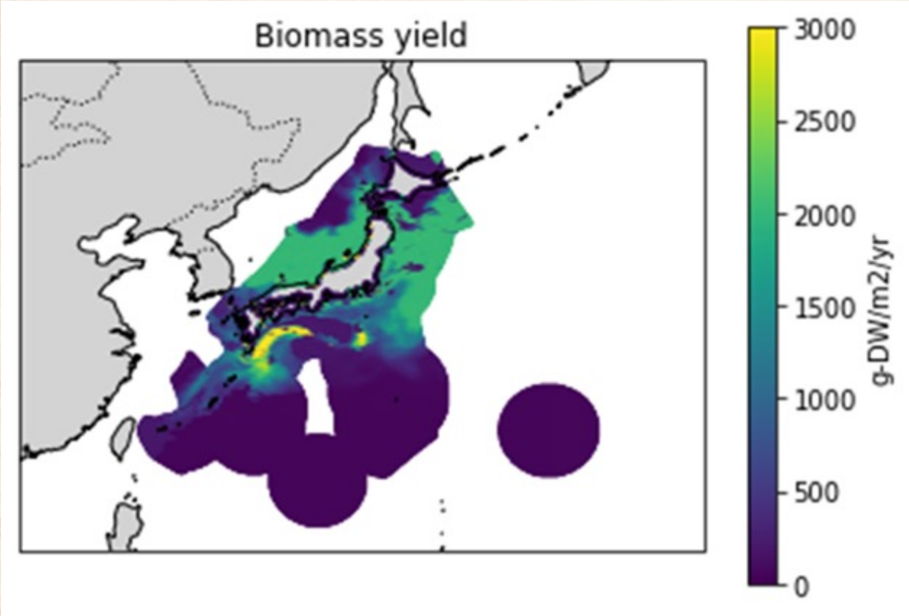
Discussion on harvesting scenarios - Harvest strategy

- **New target weight: maximum biomass density: B_{cap} (g-DW/m^2)**
  - Seaweeds are harvested only if their biomass reaches the maximum biomass density B_{cap} or when mortality exceeds growth by 7 days.
  - When the biomass of macroalgae meets the above conditions, the macroalgae stopped growing and waited for sinking.

Parameter	Species	Target weight (g-DW/m^2)
B_{cap} $(g - DW\ /m^2)$ Maximum biomass density	*Eucheuma*	2963
	Sargassum	800
	Porphyra	200
	Macrocystis	1985
	Saccharina	1985

Discussion on harvesting scenarios - Results

- **Biomass yield of macroalgae**
  - The single harvest strategy heavily influences the final yield.
  - The different number of harvests may also have an effect on cost, which may be one of the directions for future research.



Parameter	Genus	Minimum and Maximum values	Average Values
Biomass (g-DW / m^2/yr) Macroalgal biomass yields	*Eucheuma (Tropical red)*	186.413-3117.248	853.59
	Sargassum (Tropical brown)	No distribution	0
	Porphyra (Temperate red)	170.69-207.62	195.76
	Macrocystis (Temperate brown)	46.6-2096.4	533.28
	Saccharina (Temperate brown)	46.6-2122.1	560.3

Conclusion and Future work

Conclusion

- Carbon sequestration in the northeastern part of the Japanese EEZ is optimistic compared to the results of global simulations in previous studies. And tropical red and temperate brown seaweeds are the main contributors to carbon sequestration.

- The use of sinking macroalgae as a CDR method is showing potential, especially in the northeastern part of the EEZ. However, not all of Japan's EEZ is suitable for this method of carbon sequestration, such as some southern regions.

- By validating the model using two different sets of nutrient data we found that the growth model of macroalgae is sensitive to external nutrient concentrations, so more accurate nutrient data is more helpful to improve the correctness of yield simulation and model validation.

- The introduction of phosphate may lead to lower yields in some areas. The growth of macroalgae is limited by P when the NP ratio in seawater is greater than the optimal NP ratio that we assumed by the half-saturation constant, and by N when it is less than that.

- The model with the nitrogen cell quota is relatively optimistic compared to the nutrient uptake models without nitrogen cell quota in that it has a relatively low external nutrient requirement, so yields will be higher in areas where nutrient concentrations are not very high.

- Multiple harvesting strategies can increase the final biomass yields of macroalgae, but for some grids, the cost of multiple harvesting and emissions from transportation may be another topic of discussion.

Future work

● Studies on the growth performance of different species of macroalgae with different nutrients at different concentrations are of importance.

● The design of seaweed farms and their impacts cannot be ignored for example, the impacts of farms on macroalgae nutrient uptake can be explored by considering the hydrodynamic modeling of the farms.

● Harvesting strategies and sinking strategies have a huge impact on the final carbon sequestration, and we need to consider more of the environmental impacts of this CDR approach.

As the global greenhouse effect continues, it is impractical to achieve carbon neutrality through the cultivation of macroalgae, but their potential for carbon sequestration cannot be ignored, so more efforts are needed to achieve this goal.