Development of a Dynamic Energy Budget Model for *Pyropia dentata* Cultivation in Korean Coastal Waters

Anonymous Author(s)

Abstract

We developed a Dynamic Energy Budget (DEB) model for *Pyropia dentata* cultivation in Korea, explicitly accounting for contrasting farming environments. The model integrates temperature, light, nutrients, wave exposure, and intertidal emersion to simulate reserve dynamics and structural growth, and was calibrated and validated across two sites (Imha, pole-type; Eoran, floating) and three cultivars. Performance evaluation indicates that the model reproduces observed biomass dynamics across all six site–cultivar scenarios, with R^2 values between 0.8822 and 0.9924 and RMSE values between 0.3219 and 3.2816. Sensitivity analysis using one-at-a-time perturbations shows that growth rate and thermal tolerance parameters are consistently dominant drivers, while desiccation-related parameters are particularly influential at the intertidal site. These results demonstrate that site-specific exposure processes are essential for modeling pole-type cultivation and provide a mechanistic basis for growth prediction and management under variable coastal conditions.

1 Introduction

Global seaweed aquaculture has expanded rapidly in recent decades and now contributes substantially to food supply, coastal livelihoods, and biogeochemical services such as carbon sequestration. The Food and Agriculture Organization reports continued growth in farmed seaweed production and emphasizes its role in nutrition, industrial bioproducts, and climate mitigation strategies. [FAO, 2022] These trends motivate the development of mechanistic growth models that can support sustainable cultivation planning under changing environmental conditions.

Korea is a leading producer of laver (genus *Pyropia* and *Porphyra*), and the sector has significant national economic value. Recent reports highlight both the scale of production and the need for improved management tools to stabilize yield across variable environments. [FAO, 2022, Ministry of Oceans and Fisheries, 2022] Cultivation practices in Korea include intertidal pole-type systems with periodic exposure and coastal floating systems that remain largely submerged. These contrasting settings impose distinct thermal, light, and hydrodynamic regimes that can drive site-specific growth responses.

Dynamic Energy Budget (DEB) theory provides a general framework to describe how organisms assimilate and allocate energy for maintenance, growth, and reproduction. [Kooijman, 2010a,b] DEB-based models are attractive for aquaculture because they link growth to environmental drivers through physiologically meaningful parameters. Prior macroalgal applications include DEB formulations for *Pyropia yezoensis* and other taxa such as *Saccharina latissima* and *Ulva lactuca*, as well as broader macroalgae modeling frameworks. [Tac et al., 2025, Broch and Slagstad, 2012, Lavaud, 2013, Hadley et al., 2014, Arzeno-Soltero et al., n.d.] However, existing models have focused on floating or fully submerged cultivation and do not capture the exposure dynamics of pole-type systems.

Pyropia dentata is a commercially valuable species in Korea with multiple cultivars exhibiting distinct growth traits. [Han et al., 2021] Despite its importance, no DEB model has been developed specifically for *P. dentata*, and no model has been validated across both pole-type and floating cul-
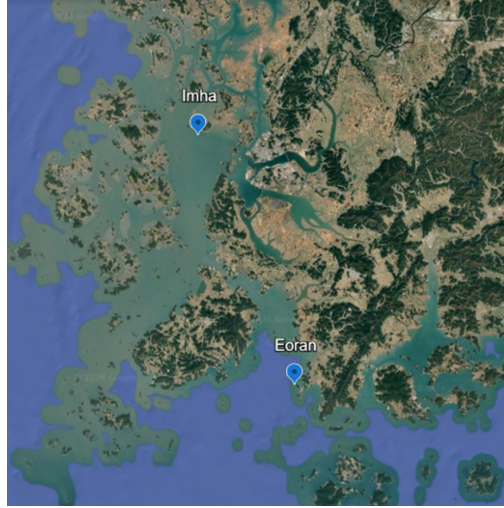
Figure 1: Location of the study sites in Haenam County, South Korea. Imha represents a tidal-flat pole-type system, and Eoran represents a coastal floating system.

tivation systems. [National Institute of Fisheries Science, 2018] The objectives of this study are to (1) develop a DEB model tailored to *P. dentata* that incorporates site-specific environmental forcing, including intertidal exposure effects, (2) calibrate and validate the model simultaneously across two sites (Imha and Eoran) and three cultivars, and (3) quantify parameter sensitivities to identify dominant drivers of biomass accumulation. By addressing these gaps, the study provides a mechanistic tool for growth prediction and management in contrasting Korean cultivation environments.

2 Materials and Methods

2.1 Study sites and environmental data

The study considered two cultivation systems in Haenam County, Korea (Figure 1). The Imha site (34°49'48"N, 126°14'31"E) represents an intertidal pole-type system with periodic emersion, whereas the Eoran site (34°21'33"N, 126°27'42"E) represents a coastal floating system that remains largely submerged. Environmental forcing data were compiled for the 2018–2019 cultivation season and summarized in Table 1. Hourly meteorological variables (air temperature, wind speed, and solar radiation) were obtained from the ASOS station records, tidal height and salinity were obtained from the Korea Hydrographic and Oceanographic Agency, and water temperature data were obtained from the National Institute of Fisheries Science. [Korea Meteorological Administration, 2026, Korea Hydrographic and Oceanographic Agency, 2026, National Institute of Fisheries Science, 2026] Salinity statistics were derived from the Jindo tide station records and applied to both sites for the study period. Nutrient observations (NO$_3$-N and DIP as P) and growth measurements were derived from the *P. dentata* cultivar dataset. [Han et al., 2021]

All forcing series were aligned to a fixed hourly index spanning 2018-09-01 to 2019-02-28. Weather and water temperature data were resampled to hourly means and linearly interpolated; missing values were forward/back-filled to preserve continuity. Sparse nutrient observations were interpolated to hourly resolution with a hold extrapolation policy outside the sampling window. Exposure fraction for the intertidal site was computed from minute-resolution tide data by identifying low-tide times (one per half-day) on a smoothed tide series, then calculating the fraction of each hour that overlapped a ±1 h window centered on low tide. This exposure fraction was used to reduce light- and nutrient-driven assimilation during emersion.

2.2 DEB model formulation

A hybrid DEB model was developed to describe reserve dynamics and structural growth of *Pyropia dentata*. The state variables are structural biomass proxy M_V (cm^2-equivalent area), and reserve densities for carbon, nitrogen, and phosphorus (m_{EC}, m_{EN}, m_{EP}). Temperature effects are repre-

Table 1: Environmental conditions during the 2018–2019 cultivation period.

Parameter	Unit	Imha (Pole-type)		Eoran (Floating)	
		Mean±SD	Range	Mean±SD	Range
Temperature	°C	15.26±5.08	9.24–25.10	12.88±6.76	5.14–25.44
Salinity	PSU	32.26±0.60	0.20–38.20	32.26±0.60	0.20–38.20
Solar rad.	W m^{-2}	111.47±197.37	0.00–894.44	111.47±197.37	0.00–894.44
Nitrogen (NO$_3$-N)	μM	2.39±0.91	0.36–3.00	4.35±2.73	2.57–11.57
Phosphorus (DIP-P)	μM	1.38±0.54	0.32–1.74	1.24±0.24	0.74–1.39
Tidal range	m	2.33±1.24	0.00–4.56	-	-
Exposure time	h	3.25±1.47	0.00–5.03	-	-

sented with an Arrhenius function with lower and upper tolerance limits:

$$
f_T(T) = \frac{\exp\left(\frac{T_A}{T_{\text{ref}}} - \frac{T_A}{T}\right)}{\left(1 + \exp\left(\frac{T_{AL}}{T} - \frac{T_{AL}}{T_L}\right)\right)\left(1 + \exp\left(\frac{T_{AH}}{T_H} - \frac{T_{AH}}{T}\right)\right)},
\tag{1}
$$

where T is water temperature in Kelvin and T_A, T_L, T_H, T_{AL}, and T_{AH} are Arrhenius parameters.

Solar radiation (MJ m^{-2} per period) was converted to photosynthetically active radiation (PAR) using fixed conversion factors and the sampling period Δt (s). The carbon assimilation rate follows a saturating light response:

$$
P = P_{\max}\left(1 - \exp\left(-\alpha I/P_{\max}\right)\right), \qquad P_{\max} = P_{\max}^{\text{ref}} f_T(T),
\tag{2}
$$

with a CO$_2$ limitation factor $f_{CO_2} = \frac{CO_2}{CO_2 + K_c}$ and an emersion reduction $f_{\text{em}} = 1 - \gamma\,\text{exposure}$ (clamped to [0,1]). The carbon assimilation flux is

$$
\dot{j}_C = \eta_C\, P\, f_{CO_2}\, f_{\text{em}}\, M_V,
\tag{3}
$$

where η_C is an assimilation efficiency coefficient.

Nitrogen and phosphorus assimilation were modeled with Michaelis–Menten uptake modulated by temperature and emersion:

$$
\dot{j}_N = V_{\max,N} f_T(T)\frac{N}{N + K_N} \cdot \phi_N \cdot M_V \cdot (1 - \text{exposure})^{p_e},
\tag{4}
$$

$$
\dot{j}_P = V_{\max,P} f_T(T)\frac{P}{P + K_P} \cdot \phi_P \cdot M_V \cdot (1 - \text{exposure})^{p_e},
\tag{5}
$$

where N and P are dissolved nutrient concentrations (converted to model units), ϕ_N and ϕ_P are cultivar-specific scaling factors, and p_e is the emersion nutrient power.

Reserve dynamics are expressed per unit structural mass:

$$
\frac{dm_{EC}}{dt} = \frac{\dot{j}_C - \dot{j}_{ECM}}{M_V}, \quad \frac{dm_{EN}}{dt} = \frac{\dot{j}_N - \dot{j}_{ENM}}{M_V}, \quad \frac{dm_{EP}}{dt} = \frac{\dot{j}_P - \dot{j}_{EPM}}{M_V},
\tag{6}
$$

where maintenance fluxes $\dot{j}_{ECM}$, $\dot{j}_{ENM}$, and $\dot{j}_{EPM}$ are proportional to M_V. A quota limitation factor was defined as the minimum of normalized C, N, and P reserves:

$$
q = \min\left(\frac{m_{EC} - C_{\min}}{C_{\max} - C_{\min}},\ \frac{m_{EN} - N_{\min}}{N_{\max} - N_{\min}},\ \frac{m_{EP} - P_{\min}}{P_{\max} - P_{\min}}\right),
\tag{7}
$$

clamped to the interval [0,1].

Structural growth was modeled as

$$
\frac{dM_V}{dt} = v_{\text{eff}}\, q\, M_V - L_{\text{shade}} - L_{\text{wave}} - L_{\text{des}},
\tag{8}
$$

where $v_{\text{eff}} = v_{\text{effective}} f_T(T)\exp(-k_v\,\text{exposure})$. Shading loss is $L_{\text{shade}} = k_{\text{shade}}\max(0, M_V - K)$, with carrying capacity K. Wave loss is proportional to significant wave height H_s computed

from wind speed and local fetch/depth, $L_{\text{wave}} = k_{\text{wave}} w_{\exp} H_s M_V$. Desiccation loss was applied only to the intertidal site and scaled with exposure and weather forcing:

$$L_{\text{des}} = r_{\text{des}} \, \text{exposure}^{p_{\text{des}}} M_V \left(1 + s_{\text{w}}(0.1I + 0.05U)\right), \tag{9}$$

where I is solar radiation (MJ m^{-2} per period) and U is wind speed (m s^{-1}).

Biomass output was computed as $B = k_A M_V$, and thallus length and width were derived from the modeled area assuming a fixed shape factor and width-to-length ratio. Initial conditions (L_0, W_0) were set from the first observation in each site-cultivar series.

2.3 Numerical integration

The model was integrated with a fourth-order Runge–Kutta scheme at hourly time steps ($\Delta t = 1$ h), matching the temporal resolution of the forcing series. This ensured consistent coupling between environmental inputs and physiological responses.

2.4 Parameter calibration and validation

Calibration used the growth observations for three cultivars (Supoom 1, Supoom 2, and Yuldo) at Imha and Eoran. [Han et al., 2021] For each cultivar, the parameter set was tuned jointly across the two sites. Observed biomass was estimated from measured length and width using a constant areal density (0.004 g cm^{-2}) and a shape factor (0.65). The objective function minimized the root mean square error (RMSE) between observed and simulated biomass aggregated across both sites:

$$J(\theta) = \sum_{s \in \{\text{Imha,Eoran}\}} \text{RMSE} \left(B_s^{\text{obs}}(t), B_s^{\text{sim}}(t; \theta)\right). \tag{10}$$

A site-specific scaling coefficient k_A was estimated by least squares from predicted M_V and observed biomass for each site, and was constrained to [0.05, 10].

Parameter search used Optuna with a TPE sampler (60 trials, seed 42) when available; otherwise, a two-stage adaptive search (uniform random sampling followed by local perturbation) was applied. Tuned parameters included the common growth rate $v_{\text{effective}}$, cultivar-specific nutrient assimilation factors (ϕ_N, ϕ_P), emersion and desiccation parameters (k_v, r_{des}, p_{des}, p_e, and weather scaling), and site-specific wave exposure coefficients. The search bounds followed the ranges defined in the model code. Model performance was evaluated with RMSE and R^2 for each of the six site-cultivar scenarios.

2.5 Sensitivity analysis

One-at-a-time (OAT) sensitivity analysis was conducted using the calibrated parameter sets for each cultivar and site. Non-temperature parameters were perturbed by ±10%, while temperature parameters (T_A, T_L, T_H, T_{AL}, T_{AH}) were perturbed by ±1 K. Sensitivity was quantified using the normalized change in final biomass:

$$S = \frac{B_+ - B_-}{0.2 \, B_0}, \tag{11}$$

where B_0 is baseline final biomass and B_+ and B_- are the perturbed outputs. Results were summarized by the top-ranked parameters for each site and cultivar.

3 Results

3.1 Model performance

Model performance metrics are summarized in Table 2. Across the six site–cultivar scenarios, RMSE ranged from 0.3219 to 3.2816 and R^2 ranged from 0.8822 to 0.9924. For all three cultivars, the floating Eoran site showed lower RMSE (0.3219–0.7450) than the intertidal Imha site (0.8228–3.2816). The fitted site-specific biomass scaling coefficient k_A varied from 0.0611 (Supoom1, Imha) to 0.9347 (Supoom2, Eoran), reflecting differences in biomass conversion between cultivation systems. The validation periods were 2018-10-19 to 2018-11-07 for Eoran and 2018-11-21 to 2019-01-06 for Imha, matching the observation windows used for calibration.

Table 2: Best-model performance after parameter tuning.

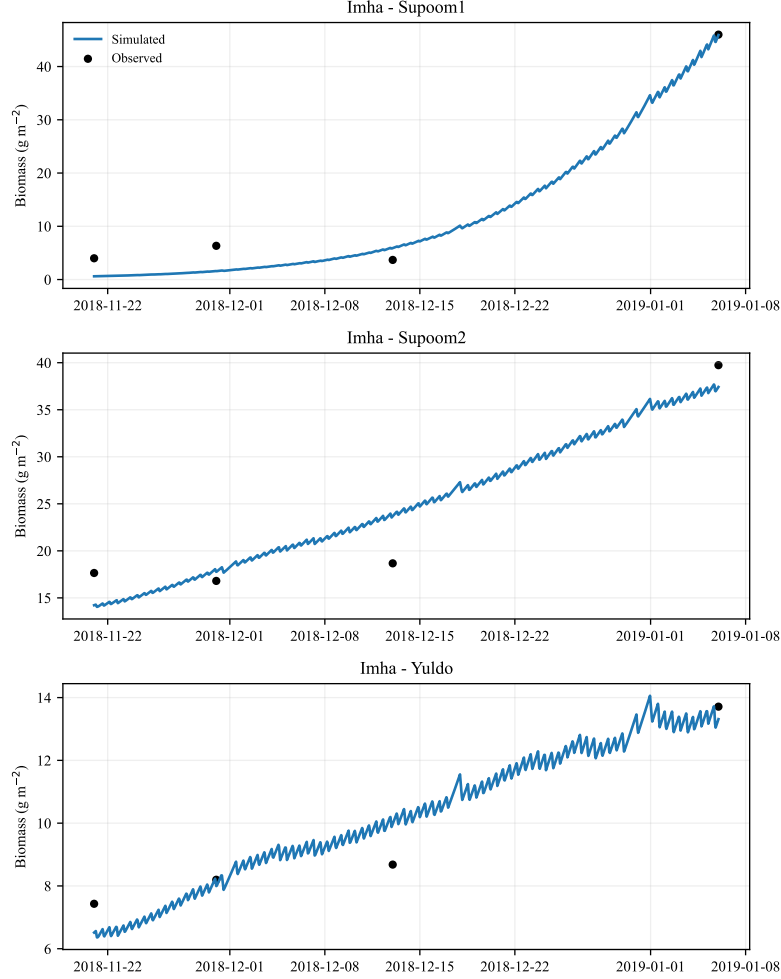| Cultivar	Location	Mode	n	RMSE	R^2	k_A	Period
Supoom1	Eoran	floating	3	0.5263	0.9924	0.4443	2018-10-19–2018-11-07
Supoom1	Imha	fixed	4	3.1239	0.9696	0.0611	2018-11-21–2019-01-06
Supoom2	Eoran	floating	3	0.7450	0.8849	0.9347	2018-10-19–2018-11-07
Supoom2	Imha	fixed	4	3.2816	0.8822	0.3223	2018-11-21–2019-01-06
Yuldo	Eoran	floating	3	0.3219	0.9885	0.6709	2018-10-19–2018-11-07
Yuldo	Imha	fixed	4	0.8228	0.8889	0.3507	2018-11-21–2019-01-06

Figure 2: Observed (symbols) and simulated (lines) biomass for three cultivars at the Imha site.

3.2 Growth predictions

Figures 2 and 3 compare observed and simulated biomass for the three cultivars at each site. The model reproduced the overall temporal trajectories for all cultivars, capturing the timing and magnitude of the observed growth increases within the sampling windows. Site-specific differences were evident: growth at the floating Eoran site exhibited smoother trajectories and consistently lower error metrics, whereas the intertidal Imha site showed larger deviations at some observation points. Figure 4 highlights the contrast between cultivation systems, with differences in growth rates and final biomass linked to the distinct exposure regimes.
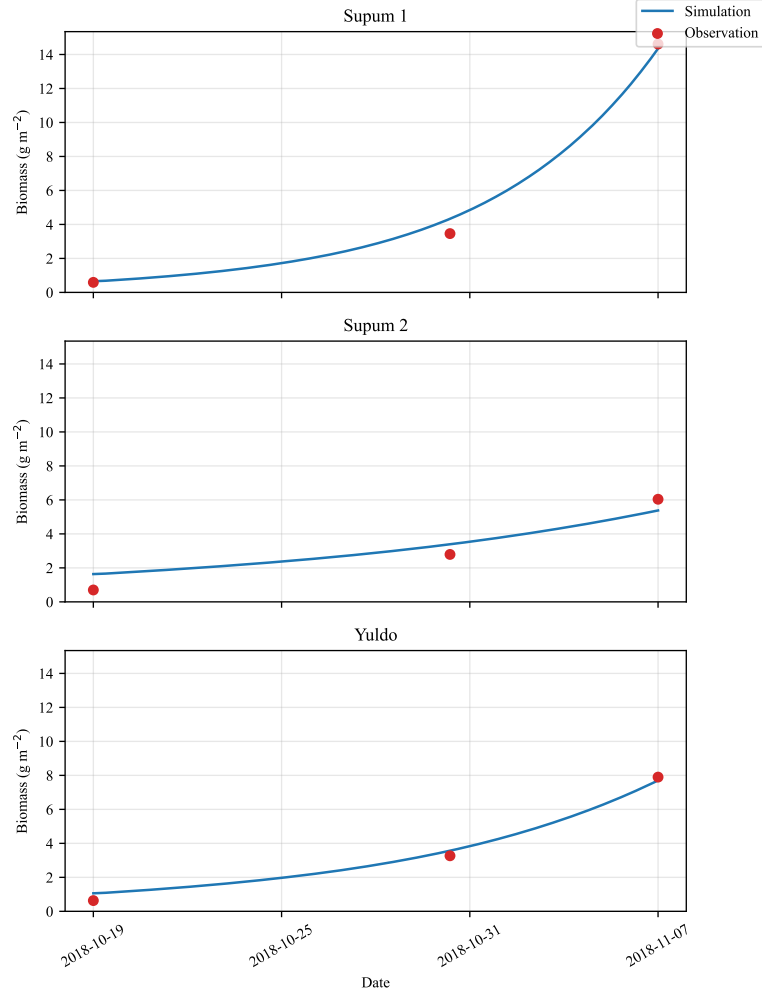
Figure 3: Observed (symbols) and simulated (lines) biomass for three cultivars at the Eoran site.

3.3 Sensitivity analysis

Sensitivity results for the Imha and Eoran sites are shown in Figures 5 and 6. The dominant drivers were consistent across cultivars: the effective growth rate $v_{\text{effective}}$ and temperature tolerance parameters (particularly T_H, and to a lesser extent T_L) produced the largest absolute sensitivities. At the intertidal Imha site, desiccation rate (r_{des}) was among the top three parameters for all cultivars, indicating strong dependence on exposure-related losses. At the floating Eoran site, desiccation effects were comparatively small, and temperature-related parameters ranked highest. These patterns indicate that exposure-driven losses dominated sensitivity in the pole-type system, whereas thermal response controlled sensitivity in the floating system.

4 Discussion and Conclusions

4.1 Model contributions and performance

This study presents the first DEB model tailored to *Pyropia dentata* and the first to explicitly incorporate intertidal emersion dynamics for pole-type cultivation in Korea. The model was calibrated and evaluated across two sites and three cultivars, demonstrating robust performance in six scenarios. The consistently high R^2 values (0.8822–0.9924) indicate that the model captures observed biomass variability, while the larger RMSE values at the Imha site highlight the greater complexity of intertidal conditions.
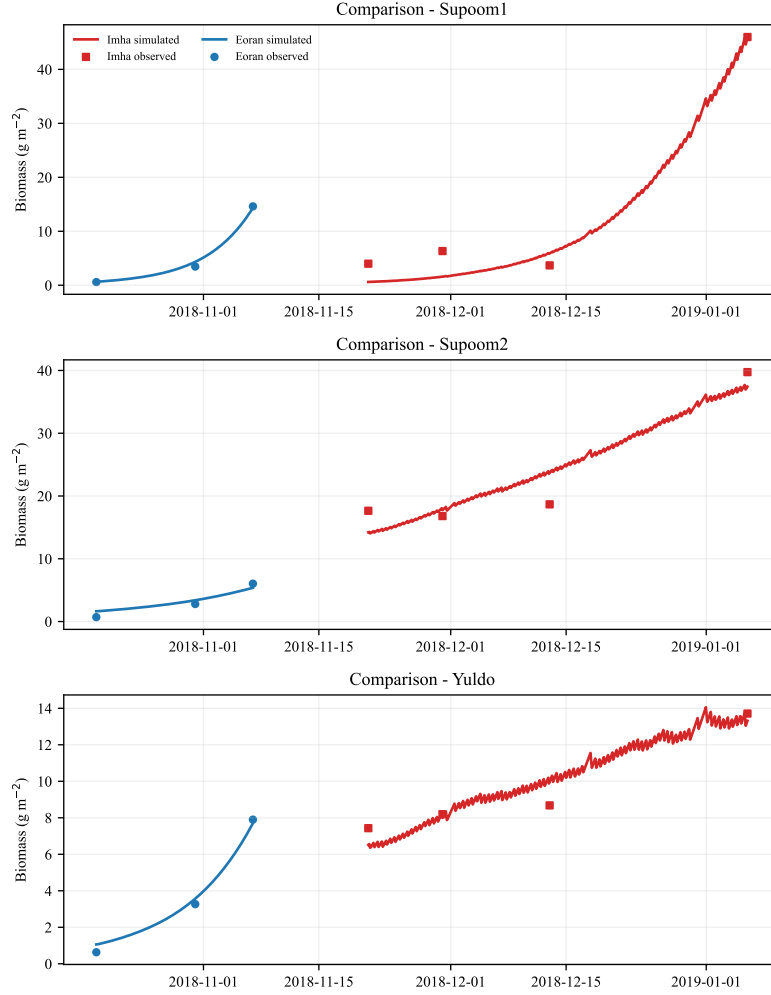
6

Figure 4: Comparison of growth patterns between Imha (pole-type) and Eoran (floating) cultivation systems.

4.2 Cultivation system differences

Growth dynamics differed between the floating and pole-type systems. The floating Eoran site showed smoother trajectories and lower prediction errors, consistent with more stable submergence and reduced exposure stress. In contrast, the intertidal Imha site required explicit loss terms for wave action and desiccation, reflecting the combined effects of emersion and weather forcing. These results emphasize that site-specific processes, particularly exposure and desiccation, are critical for modeling pole-type cultivation and cannot be inferred directly from floating-system models. [National Institute of Fisheries Science, 2018]

Sensitivity analysis further supports these system-level differences. At Imha, desiccation parameters ranked among the most influential drivers across cultivars, whereas at Eoran, temperature-related parameters dominated. This indicates that management strategies for pole-type systems should prioritize mitigating exposure-related stress, while floating systems are more sensitive to thermal variability. The consistent importance of the effective growth rate and thermal tolerance parameters across sites underscores the central role of temperature response in *P. dentata* growth.

4.3 Limitations

Several limitations should be acknowledged. First, the model does not include explicit competition with phytoplankton for dissolved nutrients, which can affect nutrient availability in coastal waters. [Hein et al., 1995] Second, nutrient observations were sparse and required interpolation and extrapo-
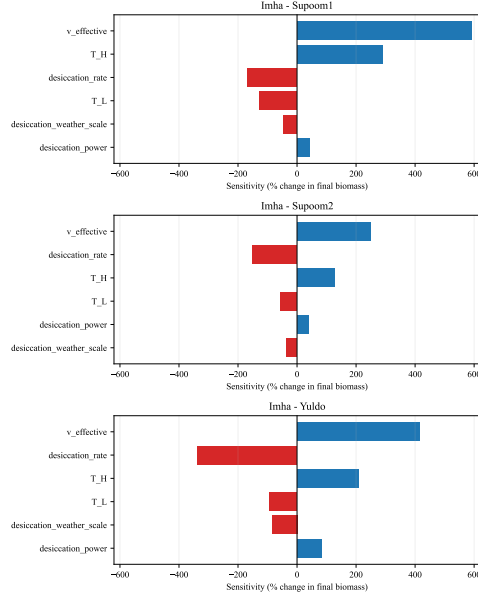
Figure 5: Sensitivity analysis for the Imha site. Bars show the effect of parameter perturbations on final biomass.
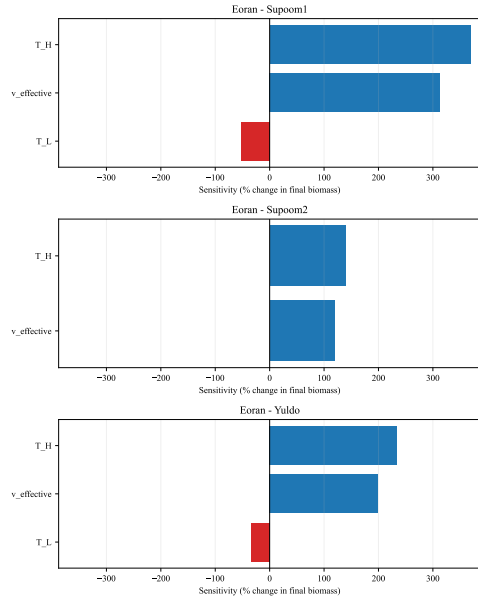

Figure 6: Sensitivity analysis for the Eoran site. Bars show the effect of parameter perturbations on final biomass.

lation, which may introduce uncertainty in the forcing inputs. Third, calibration and validation were limited to a single growing season, so interannual variability and extreme events are not captured. Finally, the model focuses on biomass dynamics and does not explicitly represent reproductive allocation or tissue composition changes.

4.4 Future directions

Future work should incorporate multi-species competition and improved nutrient dynamics, including phytoplankton interactions and higher-frequency nutrient monitoring. Extending the model to climate change scenarios would enable assessment of cultivation resilience under warming and altered hydrodynamic regimes. Additional datasets across years and sites would allow stronger validation and enable refinement of cultivar-specific parameters. Integration of the model with farm

management decision tools could further enhance its practical value for optimizing cultivation timing and site selection.

4.5 Conclusions

The proposed DEB model provides a mechanistic framework for predicting *P. dentata* biomass across contrasting Korean cultivation systems. By calibrating and validating across two sites and three cultivars, the model demonstrates robust performance beyond single-site or single-cultivar studies. Sensitivity analysis reveals site-dependent dominant drivers, highlighting the importance of exposure-related losses in intertidal systems and thermal response in floating systems. These findings support the model's utility for aquaculture planning and provide a foundation for future extensions to climate and management applications.

References

Isabella B. Arzeno-Soltero et al. Biophysical potential and uncertainties of global seaweed farming, n.d. Manuscript submitted to *Nature Geoscience*; PDF in docs/.

Ole Jacob Broch and Dag Slagstad. Modelling seasonal growth and composition of the kelp *Saccharina latissima*. *Journal of Applied Phycology*, 24(4):759–776, 2012. doi: 10.1007/s10811-011-9695-y.

FAO. The state of world fisheries and aquaculture 2022. Technical Report 1408750-EN, Food and Agriculture Organization of the United Nations, 2022.

Scott Hadley, Karen Wild-Allen, Craig Johnson, and Catriona Macleod. Modeling macroalgae growth and nutrient dynamics for integrated multi-trophic aquaculture. *Journal of Applied Phycology*, 2014. doi: 10.1007/s10811-014-0370-y.

M. K. Han, D. S. Jeong, C. W. Kim, and S. J. Choi. Study on characteristic of *Pyropia dentata* three cultivars in haenam aquafarm, jellanam-do. *Journal of Practical Agriculture & Fisheries Research*, 23(2):43–50, 2021. In Korean with English abstract; PDF in docs/.

Mette Hein, Morten Foldager Pedersen, and Kaj Sand-Jensen. Size-dependent nitrogen uptake in micro- and macroalgae. *Marine Ecology Progress Series*, 118:247–253, 1995.

S. A. L. M. Kooijman. *Dynamic Energy Budget Theory for Metabolic Organisation*. Cambridge University Press, 3rd edition, 2010a. doi: 10.1017/CBO9780511805400.

S. A. L. M. Kooijman. Summary of concepts of dynamic energy budget theory for metabolic organisation, 2010b. PDF in docs/.

Korea Hydrographic and Oceanographic Agency. Tidal observation data - jindo station. `https://www.khoa.go.kr/oceandata/service/reference/distribution.do`, 2026. Accessed January 2026.

Korea Meteorological Administration. Automated synoptic observing system (asos) data. `https://data.kma.go.kr/data/grnd/selectAsosRltmList.do`, 2026. Accessed January 2026.

R. Lavaud. A dynamic energy budget model for the macroalga *Ulva lactuca*, 2013. PDF in docs/.

Ministry of Oceans and Fisheries. Korea's fisheries production in 2022 decreased by 6.0% and production value by 0.4% from the previous year, February 2022. Press release (English translation of MOF 2022-02-24).

National Institute of Fisheries Science. Porphyra cultivation standard manual. Technical report, National Institute of Fisheries Science, December 2018. In Korean. PDF in docs/.

National Institute of Fisheries Science. Ocean data in grid framework. `https://www.nifs.go.kr/risa/main.risa`, 2026. Accessed January 2026.

D. H. Tac, S. E. Park, and J. Y. Lee. Estimation of growth and carrying capacity of *Porphyra* spp. under aquaculture conditions on the southern coast of korea using dynamic energy budget (deb), 2025. PDF in docs/.

AI Co-Scientist Challenge Korea Paper Checklist

1. **Claims**

   Question: Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope?

   Answer: [Yes]

   Justification: The abstract and Introduction state the DEB model contribution, sites/cultivars, and validation scope, which match the Results and Discussion.

   Guidelines:

   - The answer NA means that the abstract and introduction do not include the claims made in the paper.
   - The abstract and/or introduction should clearly state the claims made, including the contributions made in the paper and important assumptions and limitations. A No or NA answer to this question will not be perceived well by the reviewers.
   - The claims made should match theoretical and experimental results, and reflect how much the results can be expected to generalize to other settings.
   - It is fine to include aspirational goals as motivation as long as it is clear that these goals are not attained by the paper.

2. **Limitations**

   Question: Does the paper discuss the limitations of the work performed by the authors?

   Answer: [Yes]

   Justification: Limitations are described in the Discussion (e.g., nutrient competition, temporal resolution, and single-season constraints).

   Guidelines:

   - The answer NA means that the paper has no limitation while the answer No means that the paper has limitations, but those are not discussed in the paper.
   - The authors are encouraged to create a separate "Limitations" section in their paper.
   - The paper should point out any strong assumptions and how robust the results are to violations of these assumptions (e.g., independence assumptions, noiseless settings, model well-specification, asymptotic approximations only holding locally). The authors should reflect on how these assumptions might be violated in practice and what the implications would be.
   - The authors should reflect on the scope of the claims made, e.g., if the approach was only tested on a few datasets or with a few runs. In general, empirical results often depend on implicit assumptions, which should be articulated.
   - The authors should reflect on the factors that influence the performance of the approach. For example, a facial recognition algorithm may perform poorly when image resolution is low or images are taken in low lighting. Or a speech-to-text system might not be used reliably to provide closed captions for online lectures because it fails to handle technical jargon.
   - The authors should discuss the computational efficiency of the proposed algorithms and how they scale with dataset size.
   - If applicable, the authors should discuss possible limitations of their approach to address problems of privacy and fairness.
   - While the authors might fear that complete honesty about limitations might be used by reviewers as grounds for rejection, a worse outcome might be that reviewers discover limitations that aren't acknowledged in the paper. The authors should use their best judgment and recognize that individual actions in favor of transparency play an important role in developing norms that preserve the integrity of the community. Reviewers will be specifically instructed to not penalize honesty concerning limitations.

3. **Theory Assumptions and Proofs**

   Question: For each theoretical result, does the paper provide the full set of assumptions and a complete (and correct) proof?

Answer: [N/A]

Justification: The paper does not present formal theorems or proofs.

Guidelines:

- The answer NA means that the paper does not include theoretical results.
- All the theorems, formulas, and proofs in the paper should be numbered and cross-referenced.
- All assumptions should be clearly stated or referenced in the statement of any theorems.
- The proofs can either appear in the main paper or the supplemental material, but if they appear in the supplemental material, the authors are encouraged to provide a short proof sketch to provide intuition.
- Inversely, any informal proof provided in the core of the paper should be complemented by formal proofs provided in appendix or supplemental material.
- Theorems and Lemmas that the proof relies upon should be properly referenced.

4. **Experimental Result Reproducibility**

   Question: Does the paper fully disclose all the information needed to reproduce the main experimental results of the paper to the extent that it affects the main claims and/or conclusions of the paper (regardless of whether the code and data are provided or not)?

   Answer: [Yes]

   Justification: Methods specify equations, parameters, data sources, and evaluation metrics sufficient to reproduce the reported results.

   Guidelines:

   - The answer NA means that the paper does not include experiments.
   - If the paper includes experiments, a No answer to this question will not be perceived well by the reviewers: Making the paper reproducible is important, regardless of whether the code and data are provided or not.
   - If the contribution is a dataset and/or model, the authors should describe the steps taken to make their results reproducible or verifiable.
   - Depending on the contribution, reproducibility can be accomplished in various ways. For example, if the contribution is a novel architecture, describing the architecture fully might suffice, or if the contribution is a specific model and empirical evaluation, it may be necessary to either make it possible for others to replicate the model with the same dataset, or provide access to the model. In general. releasing code and data is often one good way to accomplish this, but reproducibility can also be provided via detailed instructions for how to replicate the results, access to a hosted model (e.g., in the case of a large language model), releasing of a model checkpoint, or other means that are appropriate to the research performed.
   - While AI Co-Scientist Challenge Korea does not require releasing code, the conference does require all submissions to provide some reasonable avenue for reproducibility, which may depend on the nature of the contribution. For example
     (a) If the contribution is primarily a new algorithm, the paper should make it clear how to reproduce that algorithm.
     (b) If the contribution is primarily a new model architecture, the paper should describe the architecture clearly and fully.
     (c) If the contribution is a new model (e.g., a large language model), then there should either be a way to access this model for reproducing the results or a way to reproduce the model (e.g., with an open-source dataset or instructions for how to construct the dataset).
     (d) We recognize that reproducibility may be tricky in some cases, in which case authors are welcome to describe the particular way they provide for reproducibility. In the case of closed-source models, it may be that access to the model is limited in some way (e.g., to registered users), but it should be possible for other researchers to have some path to reproducing or verifying the results.

5. **Open access to data and code**

Question: Does the paper provide open access to the data and code, with sufficient instructions to faithfully reproduce the main experimental results, as described in supplemental material?

Answer: [No]

Justification: The paper cites public data sources, but does not release a consolidated dataset or code repository.

Guidelines:

- The answer NA means that paper does not include experiments requiring code.
- Please see the NeurIPS code and data submission guidelines (`https://nips.cc/public/guides/CodeSubmissionPolicy`) for more details.
- While we encourage the release of code and data, we understand that this might not be possible, so "No" is an acceptable answer. Papers cannot be rejected simply for not including code, unless this is central to the contribution (e.g., for a new open-source benchmark).
- The instructions should contain the exact command and environment needed to run to reproduce the results. See the NeurIPS code and data submission guidelines (`https://nips.cc/public/guides/CodeSubmissionPolicy`) for more details.
- The authors should provide instructions on data access and preparation, including how to access the raw data, preprocessed data, intermediate data, and generated data, etc.
- The authors should provide scripts to reproduce all experimental results for the new proposed method and baselines. If only a subset of experiments are reproducible, they should state which ones are omitted from the script and why.
- At submission time, to preserve anonymity, the authors should release anonymized versions (if applicable).
- Providing as much information as possible in supplemental material (appended to the paper) is recommended, but including URLs to data and code is permitted.

6. **Experimental Setting/Details**

Question: Does the paper specify all the training and test details (e.g., data splits, hyperparameters, how they were chosen, type of optimizer, etc.) necessary to understand the results?

Answer: [Yes]

Justification: Methods describe calibration approach, forcing data, parameterization, and evaluation setup for all site–cultivar scenarios.

Guidelines:

- The answer NA means that the paper does not include experiments.
- The experimental setting should be presented in the core of the paper to a level of detail that is necessary to appreciate the results and make sense of them.
- The full details can be provided either with the code, in appendix, or as supplemental material.

7. **Experiment Statistical Significance**

Question: Does the paper report error bars suitably and correctly defined or other appropriate information about the statistical significance of the experiments?

Answer: [No]

Justification: Results report performance metrics (RMSE, MAE, R^2, Bias) but do not include error bars or statistical tests.

Guidelines:

- The answer NA means that the paper does not include experiments.
- The authors should answer "Yes" if the results are accompanied by error bars, confidence intervals, or statistical significance tests, at least for the experiments that support the main claims of the paper.

- The factors of variability that the error bars are capturing should be clearly stated (for example, train/test split, initialization, random drawing of some parameter, or overall run with given experimental conditions).
- The method for calculating the error bars should be explained (closed form formula, call to a library function, bootstrap, etc.)
- The assumptions made should be given (e.g., Normally distributed errors).
- It should be clear whether the error bar is the standard deviation or the standard error of the mean.
- It is OK to report 1-sigma error bars, but one should state it. The authors should preferably report a 2-sigma error bar than state that they have a 96% CI, if the hypothesis of Normality of errors is not verified.
- For asymmetric distributions, the authors should be careful not to show in tables or figures symmetric error bars that would yield results that are out of range (e.g. negative error rates).
- If error bars are reported in tables or plots, The authors should explain in the text how they were calculated and reference the corresponding figures or tables in the text.

8. **Experiments Compute Resources**

Question: For each experiment, does the paper provide sufficient information on the computer resources (type of compute workers, memory, time of execution) needed to reproduce the experiments?

Answer: [No]

Justification: Compute resources and runtimes are not reported in the manuscript.

Guidelines:

- The answer NA means that the paper does not include experiments.
- The paper should indicate the type of compute workers CPU or GPU, internal cluster, or cloud provider, including relevant memory and storage.
- The paper should provide the amount of compute required for each of the individual experimental runs as well as estimate the total compute.
- The paper should disclose whether the full research project required more compute than the experiments reported in the paper (e.g., preliminary or failed experiments that didn't make it into the paper).

9. **Code Of Ethics**

Question: Does the research conducted in the paper conform, in every respect, with the NeurIPS Code of Ethics https://nips.cc/public/EthicsGuidelines?

Answer: [Yes]

Justification: The study uses observational environmental data and does not involve human subjects.

Guidelines:

- The answer NA means that the authors have not reviewed the NeurIPS Code of Ethics.
- If the authors answer No, they should explain the special circumstances that require a deviation from the Code of Ethics.
- The authors should make sure to preserve anonymity (e.g., if there is a special consideration due to laws or regulations in their jurisdiction).

10. **Broader Impacts**

Question: Does the paper discuss both potential positive societal impacts and negative societal impacts of the work performed?

Answer: [No]

Justification: The Discussion focuses on positive aquaculture applications; potential negative impacts are not explicitly discussed.

Guidelines:

- The answer NA means that there is no societal impact of the work performed.

- If the authors answer NA or No, they should explain why their work has no societal impact or why the paper does not address societal impact.
- Examples of negative societal impacts include potential malicious or unintended uses (e.g., disinformation, generating fake profiles, surveillance), fairness considerations (e.g., deployment of technologies that could make decisions that unfairly impact specific groups), privacy considerations, and security considerations.
- The conference expects that many papers will be foundational research and not tied to particular applications, let alone deployments. However, if there is a direct path to any negative applications, the authors should point it out. For example, it is legitimate to point out that an improvement in the quality of generative models could be used to generate deepfakes for disinformation. On the other hand, it is not needed to point out that a generic algorithm for optimizing neural networks could enable people to train models that generate Deepfakes faster.
- The authors should consider possible harms that could arise when the technology is being used as intended and functioning correctly, harms that could arise when the technology is being used as intended but gives incorrect results, and harms following from (intentional or unintentional) misuse of the technology.
- If there are negative societal impacts, the authors could also discuss possible mitigation strategies (e.g., gated release of models, providing defenses in addition to attacks, mechanisms for monitoring misuse, mechanisms to monitor how a system learns from feedback over time, improving the efficiency and accessibility of ML).

11. **Safeguards**

Question: Does the paper describe safeguards that have been put in place for responsible release of data or models that have a high risk for misuse (e.g., pretrained language models, image generators, or scraped datasets)?

Answer: [N/A]

Justification: The work does not release high-risk models or datasets.

Guidelines:

- The answer NA means that the paper poses no such risks.
- Released models that have a high risk for misuse or dual-use should be released with necessary safeguards to allow for controlled use of the model, for example by requiring that users adhere to usage guidelines or restrictions to access the model or implementing safety filters.
- Datasets that have been scraped from the Internet could pose safety risks. The authors should describe how they avoided releasing unsafe images.
- We recognize that providing effective safeguards is challenging, and many papers do not require this, but we encourage authors to take this into account and make a best faith effort.

12. **Licenses for existing assets**

Question: Are the creators or original owners of assets (e.g., code, data, models), used in the paper, properly credited and are the license and terms of use explicitly mentioned and properly respected?

Answer: [No]

Justification: Data sources are cited, but explicit license terms are not stated in the manuscript.

Guidelines:

- The answer NA means that the paper does not use existing assets.
- The authors should cite the original paper that produced the code package or dataset.
- The authors should state which version of the asset is used and, if possible, include a URL.
- The name of the license (e.g., CC-BY 4.0) should be included for each asset.
- For scraped data from a particular source (e.g., website), the copyright and terms of service of that source should be provided.

- If assets are released, the license, copyright information, and terms of use in the package should be provided. For popular datasets, `paperswithcode.com/datasets` has curated licenses for some datasets. Their licensing guide can help determine the license of a dataset.
- For existing datasets that are re-packaged, both the original license and the license of the derived asset (if it has changed) should be provided.
- If this information is not available online, the authors are encouraged to reach out to the asset's creators.

13. **New Assets**

    Question: Are new assets introduced in the paper well documented and is the documentation provided alongside the assets?

    Answer: [N/A]

    Justification: No new datasets or code assets are released with the paper.

    Guidelines:
    - The answer NA means that the paper does not release new assets.
    - Researchers should communicate the details of the dataset/code/model as part of their submissions via structured templates. This includes details about training, license, limitations, etc.
    - The paper should discuss whether and how consent was obtained from people whose asset is used.
    - At submission time, remember to anonymize your assets (if applicable). You can either create an anonymized URL or include an anonymized zip file.

14. **Crowdsourcing and Research with Human Subjects**

    Question: For crowdsourcing experiments and research with human subjects, does the paper include the full text of instructions given to participants and screenshots, if applicable, as well as details about compensation (if any)?

    Answer: [N/A]

    Justification: No crowdsourcing or human-subject research was conducted.

    Guidelines:
    - The answer NA means that the paper does not involve crowdsourcing nor research with human subjects.
    - Including this information in the supplemental material is fine, but if the main contribution of the paper involves human subjects, then as much detail as possible should be included in the main paper.
    - According to the NeurIPS Code of Ethics, workers involved in data collection, curation, or other labor should be paid at least the minimum wage in the country of the data collector.

15. **Institutional Review Board (IRB) Approvals or Equivalent for Research with Human Subjects**

    Question: Does the paper describe potential risks incurred by study participants, whether such risks were disclosed to the subjects, and whether Institutional Review Board (IRB) approvals (or an equivalent approval/review based on the requirements of your country or institution) were obtained?

    Answer: [N/A]

    Justification: The study does not involve human subjects.

    Guidelines:
    - The answer NA means that the paper does not involve crowdsourcing nor research with human subjects.
    - Depending on the country in which research is conducted, IRB approval (or equivalent) may be required for any human subjects research. If you obtained IRB approval, you should clearly state this in the paper.

- We recognize that the procedures for this may vary significantly between institutions and locations, and we expect authors to adhere to the NeurIPS Code of Ethics and the guidelines for their institution.
- For initial submissions, do not include any information that would break anonymity (if applicable), such as the institution conducting the review.