Alaska Mariculture Alliance: Tracking The Fate of Farmed Kelp Dissolved Organic Carbon

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Project objectives:

1) To quantify rates of dissolved organic carbon (DOC) release by the farmed kelp *Alaria marginata* under controlled laboratory conditions.

2) To determine whether DOC release differs between kelp sourced from distinct Alaskan mariculture sites, reflecting site-specific local adaptation.

3) To evaluate how DOC production varies across ecologically relevant temperature and light regimes.

4) To use these empirical data to improve kelp farm carbon budget estimates and inform blue carbon and mariculture management in Alaska.

Project Update: Dissolved Organic Carbon (DOC) Release Measurements

Following the processing of DOC incubation water samples and normalization by tissue ash-free dry weight (AFDW), we successfully quantified mass-specific DOC production for *A. marginata* across temperature treatments, 6, 10 and 13°C, three light levels, 80, 120 and 160 µmol photons m^{-2} s^{-1}, and farm site, Kodiak (KOD) or Cordova (CDV). To our knowledge, these are the first DOC production measurements for this species. Using the 6-week incubation at ambient temperature treatment as our control, we characterized a baseline DOC production rate for the species, with mass-specific DOC release rates clustering tightly between 0.01 and 0.05 µmol C mg^{-1} hr^{-1}. Under ambient conditions, we identified a significant main effect of light (Fig. 1; Table 1; $F = 19.7$, $p = 0.002$), highlighting light availability as a primary, predictable driver of carbon exudation in unstressed kelp.

The ANOVA also revealed a significant interactive effect between mariculture site and light level ($F = 9.93$, $p = 0.010$). Biologically, this interaction demonstrates that the KOD and CDV populations do not react uniformly to changing light regimes. Specifically, the CDV population maintained highly consistent, low-level DOC release across all light treatments under ambient conditions (means ranging from 0.020 to 0.029 µmol C mg^{-1} hr^{-1}). In contrast, the KOD population's exudation fluctuated significantly depending on light availability, dropping to near zero (-0.004 µmol C mg^{-1} hr^{-1}) at 120 PAR before peaking at 0.047 µmol C mg^{-1} hr^{-1} at 160 PAR. This divergence suggests that site of

origin, in concert with light intensity, played a role in moderating DOC exudation, indicating that kelp populations adjust their metabolic carbon fluxes to best suit the specific optical and environmental conditions of their native habitats.

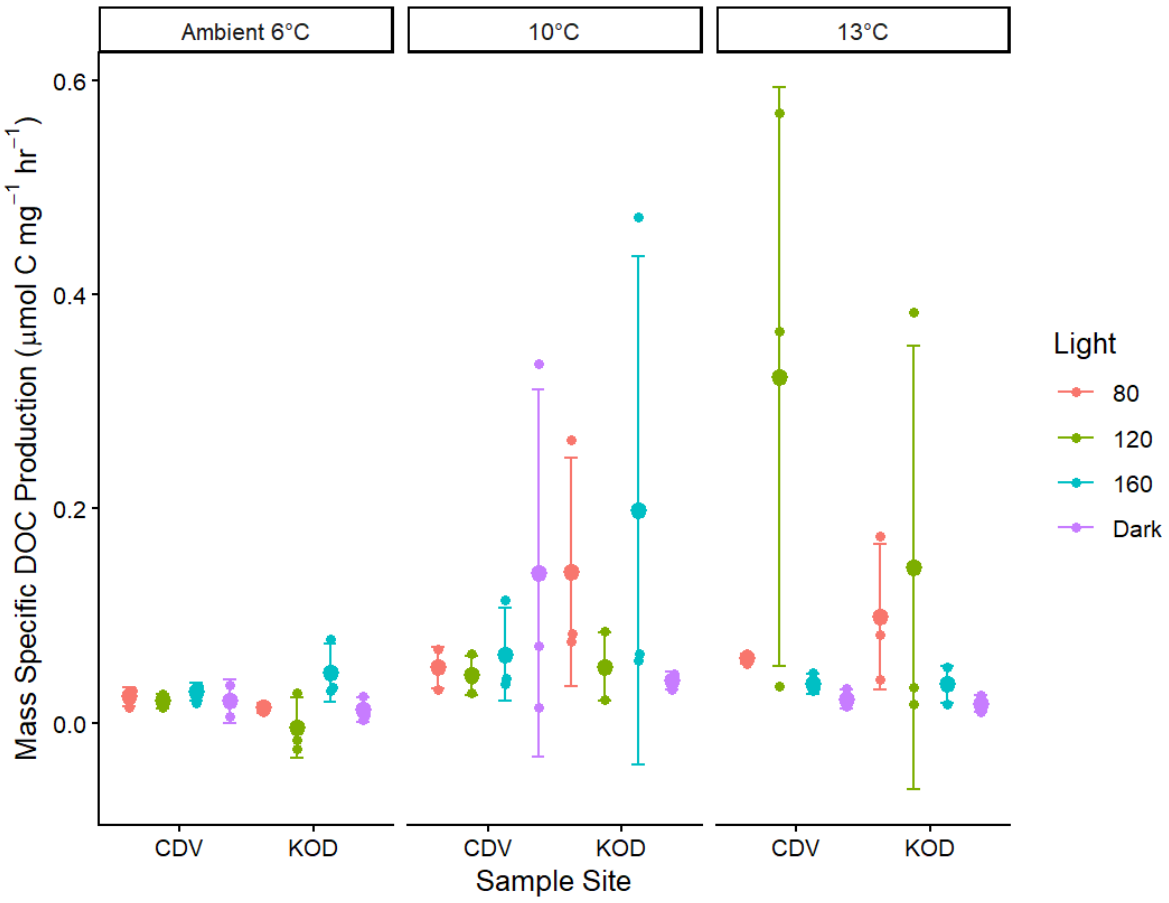


Figure 1 ***Mass-specific dissolved organic carbon (DOC) exudation rates of Alaria marginata across thermal and light regimes.*** *Mass-specific DOC production (µmol C mg⁻¹ hr⁻¹, normalized to tissue mass) measured in sporophytes sourced from Cordova (CDV) and Kodiak (KOD) mariculture sites. Faceted panels indicate responses across experimental temperature exposures (Ambient 6°C, 10°C, and 13°C). Colors indicate irradiance levels (80, 120, and 160 µmol photons m⁻² s⁻¹) alongside a dark control. Small points depict individual sample replicates; large points and error bars represent group means ± standard deviation (mean ± SD).*

While light availability and site-specific phenotypic variability moderated the significant physiological responses under ambient conditions, elevated thermal exposures (10°C and 13°C) altered these patterns and induced substantial, albeit highly variable, increases in DOC exudation. At the 13°C threshold, this stress response was most pronounced at the 120 PAR light level, where CDV DOC production spiked to a mean of 0.323 µmol C mg⁻¹ hr⁻¹ and KOD reached 0.145 µmol C mg⁻¹ hr⁻¹. However, the magnitude of this response was highly variable among biological replicates (standard deviations of 0.270 and 0.207, respectively). Because of this high individual variability, the ANOVA did not detect statistically significant main effects for site or light at the 10°C or 13°C. Rather than driving a uniform physiological shift, thermal stress appears to

compromise cell membrane integrity unpredictably, causing stressed individuals to release newly fixed carbon rather than investing it into tissue growth.

Table 1. Two-way analysis of variance (ANOVA) outputs evaluating the main and interactive effects of mariculture site (Kodiak vs. Cordova) and PAR on mass-specific dissolved organic carbon (DOC) release rates (μmol C mg^{-1} hr^{-1}) in *A. marginata*. Analyses were conducted independently across three temperature treatments: 10°C, 13°C, and a 6-week ambient control (n = 3 biological replicates per treatment group). Reported values include degrees of freedom numerator (DFn), degrees of freedom denominator (DFd), F-statistic (F), p-value (p), and bold text denote statistically significant effects (α = 0.05).

Source	Effect	DFn	DFd	F	p-value
Ambient	Site	1	2	2.82	0.235
Ambient	Light	3	6	19.7	**0.002**
Ambient	Site:Light	3	6	9.93	**0.01**
10C	Site	1	4	0.886	0.4
10C	Light	3	12	0.482	0.701
10C	Site:Light	3	12	1.11	0.383
13C	Site	1	4	0.371	0.575
13C	Light	1.04	4.17	4.34	0.102
13C	Site:Light	1.04	4.17	1.07	0.361

Comparison to Other Studies of Brown Algae

The empirical DOC exudation rates described here align well with established physiological ranges for healthy and stressed marine macroalgae. Under ambient, unstressed conditions, our calculated average exudation rates for *A. marginata* are comparable with baseline DOC release studies for other large brown macroalgae, which typically release between 1–10 μg C per gram of wet weight per hour depending on species and light availability (Abdullah & Fredriksen, 2004; Wada et al., 2007). Furthermore, the DOC spikes observed in our 13°C treatments mirror documented thermal stress responses in other kelp and macroalgae species, where elevated temperatures rapidly compromise cell membrane integrity and shift the organism from a state of carbon retention to heavy carbon exudation (Haas et al., 2010; Paine et al., 2021).

Broader Applications

The marine dissolved organic carbon (DOC) pool is comparable in size to atmospheric CO_2 and plays a vital role in global climate regulation. Integrating DOC exudation rates into broader marine Carbon Dioxide Removal (mCDR) frameworks fundamentally improves the evaluation of carbon sequestration capacity. Current mCDR models that omit DOC fluxes are inherently incomplete, as they rely heavily on standing stock particulate organic carbon (POC) or harvested biomass, thereby neglecting a substantial fraction of carbon exuded directly into the water column. By incorporating DOC production into mCDR estimates, modelers can account for this exported dissolved fraction, which may persist as recalcitrant DOC (RDOC) or be transported below the mixed layer for long-term ocean storage. Ultimately, evaluating DOC release provides the missing biogeochemical variable required to mechanistically uncouple transient carbon storage in harvested tissues from continuous dissolved carbon export, yielding a constrained, holistic evaluation of a kelp farm's true mCDR potential.

More specifically, these empirical DOC data can be directly integrated with published *A. marginata* farm field studies (e.g., Haag et al., 2026) to refine site-specific carbon cycling models. For example, by pairing our laboratory-derived mass-specific DOC rates with *in-situ* CO_2 flux measurements, continuous temperature profiles, wet-to-dry mass conversions, and seasonal blade growth estimates, a comprehensive mass-balance framework can be established for Alaskan kelp farms. Applying wet-to-dry conversions to empirical blade growth data allows total gross primary production to be calculated and partitioned into structural biomass versus dissolved exudate export. Furthermore, because field-based air-sea CO_2 flux measurements capture net atmospheric sinks across the growing season, overlaying these DOC exudation rates and farm temperature profiles provides the mechanistic resolution needed to resolve how much fixed carbon remains in harvested biomass, how much is exuded as DOC under ambient versus thermally stressed conditions, and how these internal fluxes reconcile with net atmospheric drawdown.

References

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