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学 位 論 文 内 容 の 要 旨/Dissertation Abstract

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Variability of macroalgal dissolved organic carbon dynamics: Insights for social-ecology beyond Blue Carbon
（大型藻類由来の溶存有機炭素動態の変動性：ブルーカーボンを超える社会生態学的洞察）

Globally, macroalgae are foundational to the social-ecological systems of many Indigenous Peoples (Sterling et al., 2017; Winter et al., 2020; Reid et al., 2022), inclusive of Ainu People in Ainu Mosir, where this study was conducted (Kawai et al., 2012; Kaminaga, 2018). Modern Indigenous science methodologies have also focused on improved understanding of macroalgae through systematic observation and analysis (Kobluk et al., 2021; Puniwai & Goin, 2021) and Indigenous scientists and stewards have stated interests in improved seaweed biogeochemistry knowledge (Kua ʻĀina Ulu ʻAuamo, 2021; Hahn et al., 2022; Spillias et al., 2022). However, data on the mechanisms of active exudation and passive leakage of macroalgal dissolved organic carbon (DOC) are sparse and contradictory (e.g., Weigel & Pfister, 2021; Paine et al., 2021) and the lability and traceability of macroalgal DOC is understudied (Wada et al., 2008; Gao et al., 2021). Multi-year, year-round, and multi-species studies are particularly lacking, resulting in high levels of uncertainty at multiple scales. These experiments aim to improve understanding of the variability of macroalgal DOC release, bioavailability, and fluorescence characteristics, with a particular focus on the effects of photosynthetically active radiation (PAR), seasonal variability related to growth stage, individual macroalgal tissue condition and stress exposure, and species variability through long-term studies. By developing and applying a decolonial research methodology from a diasporic Kanaka ʻŌiwi (Native Hawaiian) standpoint, these insights could allow macroalgal DOC to serve as a proxy for ecological health and be useful to Indigenous cultivation from Hawaiʻi to Ainu Mosir and beyond.

The primary subject is the prostrate annual kelp *Saccharina japonica* var. *religiosa* (order Laminariales) from Oshoro Bay, Ainu Mosir (Hokkaido). Individual biomass is at a minimum in winter, with growth up to two meters from spring to summer, followed by declines due to grazing, erosion, and senescence in autumn (Abe et al., 1985). Additional experiments were conducted on orders Fucales (*Sargassum thunbergii*, *Sargassum confusum*), Gelidiales (*Gelidium elegans*), Gigartinales (*Mazzaella japonica*, *Neodilsea yendoana*), Laminariales (*Costaria costata*), and Ulvales (*Ulva australis*, *Ulva linza*). Whole macroalgae were collected approximately bi-monthly from January 2020 to November 2023. In situ seawater was collected throughout the macroalgal ecosystem, as well as at reference points inside and beyond the bay. Tanks with macroalgae and control tanks with only reference seawater (3-L each) were incubated ex situ, subject to different PAR treatments (e.g., 200 and 400 or 200 and 1200 μmol photons PAR $m^{-2} \cdot s^{-1}$), and sampled at least daily. After incubation, the macroalgae were removed and dried to a constant weight. A 150-d bioavailability experiment then quantified the degradation rate of macroalgal DOC due to microbial activity, with the remaining portion considered to be recalcitrant. All seawater samples were filtered with pre-combusted 0.7 μm glass fiber filters and stored below −20 °C until analysis by a total organic carbon analyzer. Selected samples were analyzed by 3D fluorescence spectroscopy.

There were significant intra-annual differences (two-way ANOVA and Tukey HSD tests, $p < 0.05$) in mean kelp DOC release rates (mg C · g $DW^{-1} \cdot d^{-1}$) (± standard error between n kelp) with higher rates during the autumn "late decay" period (0.86 ± 0.13, $n = 27$) compared to the winter "early growth" period (0.17 ± 0.030, $n = 10$) and summer "early decay" period (0.35 ± 0.068, $n = 24$). Due to the high individual variability in DOC release rates in this and previous studies, methods recommendations

include 1) to verify linearity of DOC release and report least squares mean rates where appropriate, and 2) to quantify individual macroalgal "replicate" variability with coefficients of variation to facilitate comparisons between studies. Mean seasonal recalcitrant DOC (RDOC) % results were 3% ± 9% in the winter, 15% ± 2% in the spring, 14% ± 1% in the summer, and 22% ± 2% in the autumn. Fluorescence kinetics were variable but outperformed elevated RDOC concentrations in traceability. Mean results across seasons showed substantial degradation of protein-like "peak T", partial degradation of UV humic-like "peak A" (except when enhanced in autumn), enhancement of visible humic-like "peak C", and conservation of visible marine humic-like "peak M" by the end of the 150-d kelp DOC bioavailability experiments. Significant linear proportionality was established between fluorescence intensities and DOC concentrations, but were season-, sample time-, and fluorescence type-specific. When comparing red, green, and brown macroalgae, red macroalgae were the primary contributors of DOC and fluorescence in winter and summer, but green macroalgae were dominant in spring. Excluding results from bleaching and heatwave stress, the highest recalcitrant DOC proportionality was from *Sargassum* sp. (36–49%) in autumn and the highest recalcitrant DOC production rates were from *Ulva australis* (0.20 mg C · g DW^{-1} · d^{-1}) in spring. However, these differences were significantly outweighed by the typically order of magnitude enhancement effect of bleached tissue (for *Ulva australis* and *Mazzaella japonica*) and heatwave stress (for *Saccharina japonica* var. *religiosa* and *Neodilsea yendoana*) on DOC and fluorescence recalcitrance. In contrast, results from *Ulva australis* during the summer heatwave were several times lower than in spring.

These insights into the variability of macroalgal DOC release and bioavailability at the scales of seasons, species, and individual tissue conditions can help clarify the dynamics of macroalgal DOC in coastal ecosystems. In particular, studies addressing ecophysiological stress are essential to constraining macroalgal DOC and fluorescence contributions, yet certain species may be significantly more resilient or have contrasting responses to these stresses and must also be studied. Indigenous stewards and scientists may particularly benefit from incorporating these insights into their monitoring and management methodologies. Overall, most macroalgal species demonstrated low DOC recalcitrant proportionality (5–15%) relative to assumptions in global estimates (30%). More importantly, the variability at the scales of season, species, life history, and stress factors even within a single sampling site indicate the inherent difficulties in confidently monitoring, reporting, and verifying carbon sequestration contributions for the purpose of Blue Carbon credits.

Beyond the technical difficulties highlighted in the biogeochemical results of the preceding experiments, this dissertation also reviews the broader literature on technical and social challenges facing Blue Carbon as a climate change mitigation strategy. This review indicated that narrow ecosystem services accounting leads to perverse prioritization of carbon dioxide removal (CDR) over holistic social-ecological health, carbon offsets provide cover for the continuation of extractive corporate and colonial operations, industrial-scale interventions result in negative social-ecological disruptions, and even small-scale non-Indigenous projects exacerbate the loss of Indigenous coastal sovereignty. Therefore, funding and labor toward colonial Blue Carbon projects is ultimately counterproductive to holistic social-ecological vitality and should be re-directed toward the full-scale restoration of Indigenous aquaculture and coastal cultivation practices (within sovereign social-ecological systems). Moreover, since Blue Carbon and other ecosystem services should be considered a co-benefit of Indigenous stewardship and restoration, their funding should not be dictated by colonial monitoring, reporting, and verification requirements. Ultimately, existing and practical Indigenous alternatives to Blue Carbon and climate coloniality must be urgently prioritized to achieve a decarbonized and decolonized world.