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Marine carbon dioxide removal and macroalgae aquaculture: Opportunities for marine energy

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INTRODUCTION

Marine energy is an emerging technology with many benefits for niche markets, remote communities, and environmental benefits. The opportunity for marine energy to provide power for marine carbon dioxide removal (mCDR) and macroalgae cultivation in particular has been identified [1] and is explored in this work, with an emphasis on United States (U.S.) kelp farms.

The generic process of turning kelp into products is shown in Figure 1, and traces the flow of energy and carbon dioxide (CO_2) throughout the process.

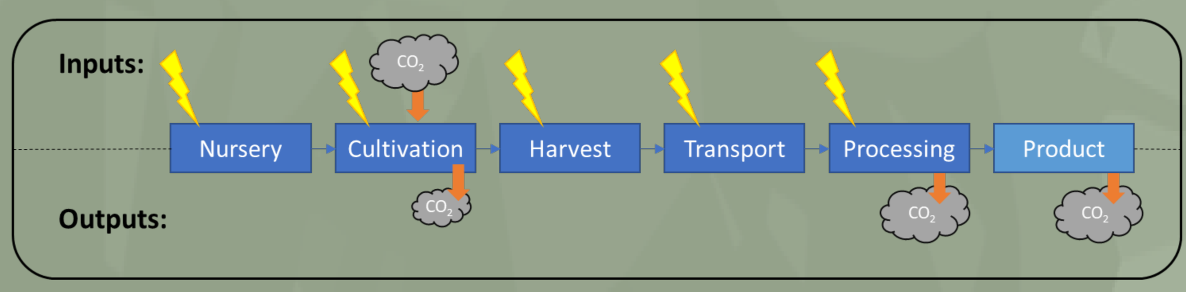


Figure 1. Generic macroalgae to product pathway.

APPROACH

This project takes a multi-pronged approach to explore opportunities for marine energy.

- We assessed marine energy power availability at permitted and pending U.S. kelp farm sites [2], using data from Marine Energy Atlas [3].
- We reviewed life cycle analyses (LCAs) for macroalgae products for their carbon capture and sequestration potential [4].
- We conducted case studies on substituting marine energy for traditional sources in LCAs to assess the potential to alter or improve environmental outcomes.

RESULTS

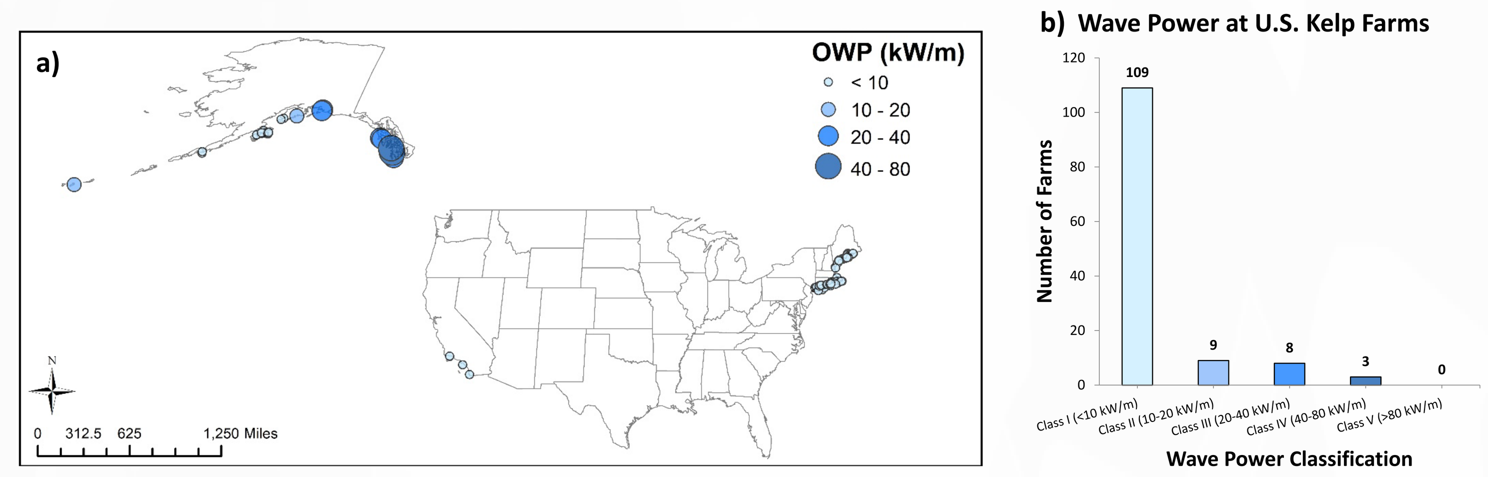


Figure 2. Wave power potential at kelp farms (n=129). a) Spatial distribution of farms by omnidirectional wave power (OWP, kW/m, data from Marine Energy Atlas [3]); b) Number of farms in each wave power class [5], where Class III is of primary interest for exploitation.

- *155 kelp farms across the U.S. were permitted or pending permits as of July 2021*
- *Several farms have significant marine energy resource potential (Figure 2, Figure 3)*
- *In general, farms in Alaska have potential for wave, and farms on the East Coast have potential for tidal (Figure 4)*

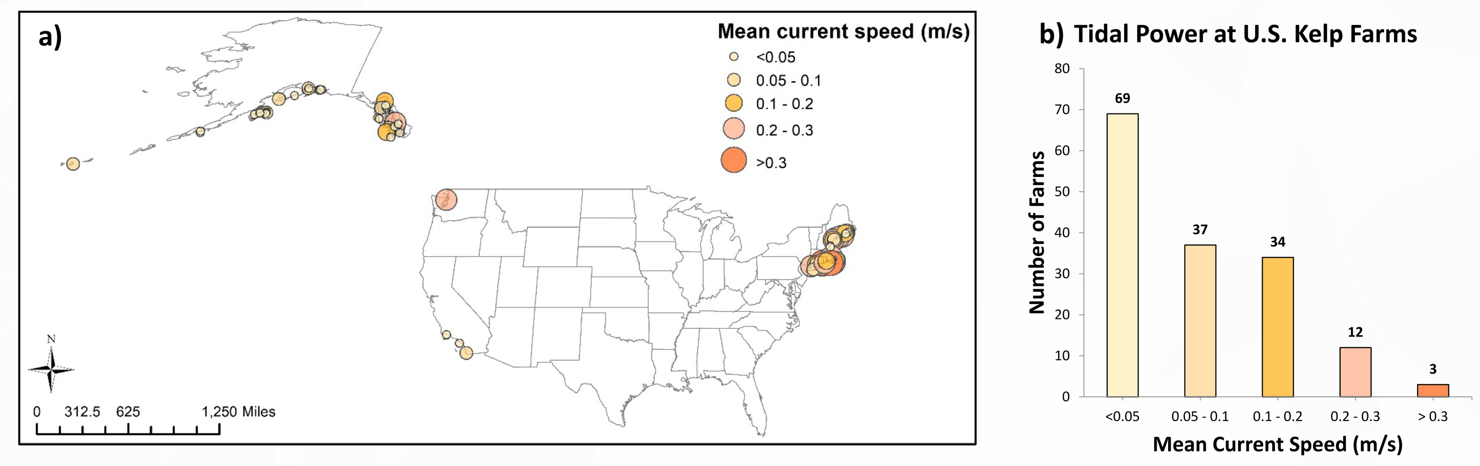


Figure 3. Tidal current potential at kelp farms (n=155). a) Spatial distribution of farms by mean current speed (m/s, data from Marine Energy Atlas [3]); b) Distribution of current speeds across farms.

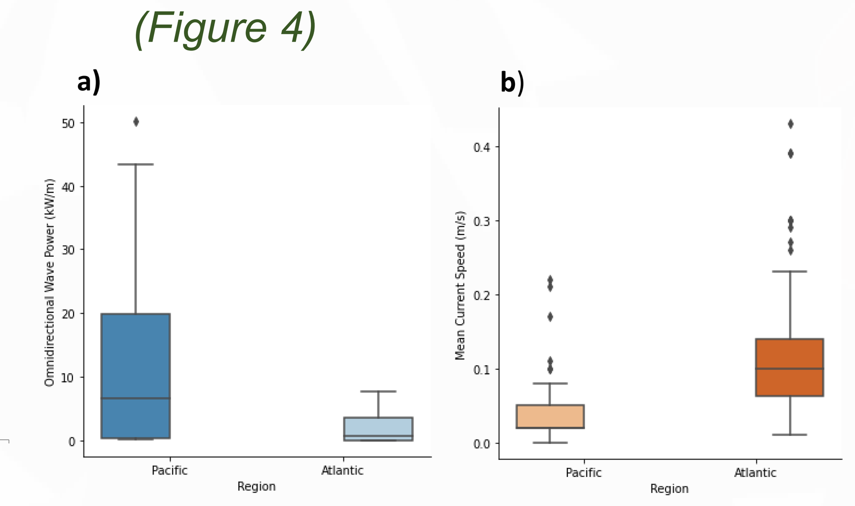


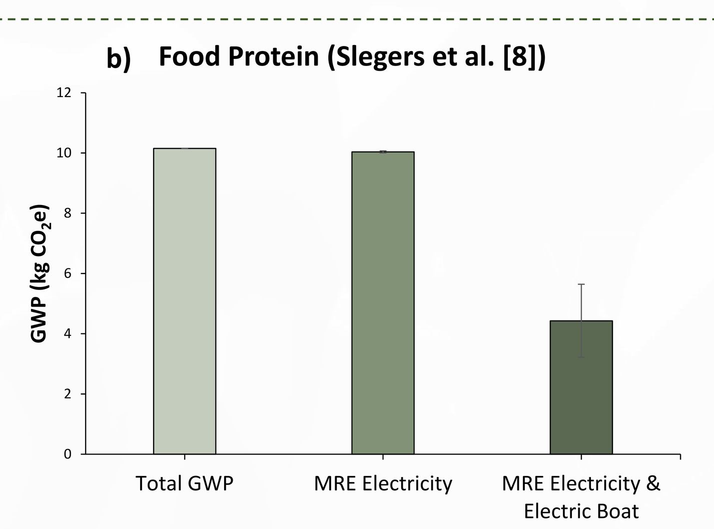
Figure 4. Comparison of a) wave and b) tidal power availability between the U.S. Pacific and Atlantic coast kelp farm sites.

A preliminary ranking of kelp products by carbon capture and sequestration potential was developed (Table 1).

Table 1. Possible macroalgae products or uses and descriptions. Preliminary categorization of carbon capture and permanence based on review of 39 life cycle analyses.

Product	CO_2 Capture	Permanence
Multispecies farms, Habitat	High	*Medium / unknown* – a portion of macroalgal detritus will export carbon to the deep-sea sediments (geologic time scales), but not all. This is an area of active research.
Materials	Medium	*High / variable* – building materials, textiles and packaging (landfilled) have a life span of decades, which could qualify as permanent. Biodegradable packaging, depending on disposal practices, could have more variability in permanence.
Fertilizer	Medium / variable	*High* – biochar has been shown to increase soil carbon, with a portion shown to be sequestered long term (decades to thousands of years).
Bioenergy with carbon capture and storage	Medium	*High* – carbon captured can be stored similar to direct air capture technologies on geologic time scales.
Protein	Medium	*Low* – food is consumed and carbon is returned to the system in days to months.
Biofuel	Medium	*Low* – fuel is produced and consumed on the order of months to years.
Extracts	Unknown / variable	*Unknown* – depends on the shelf life of the application and final destination of the carbon contained in these products.

- *Three LCAs were selected as case studies to assess the potential for marine energy*
- *Marine energy could reduce emissions with investments in electrifying production processes (Figure 5)*



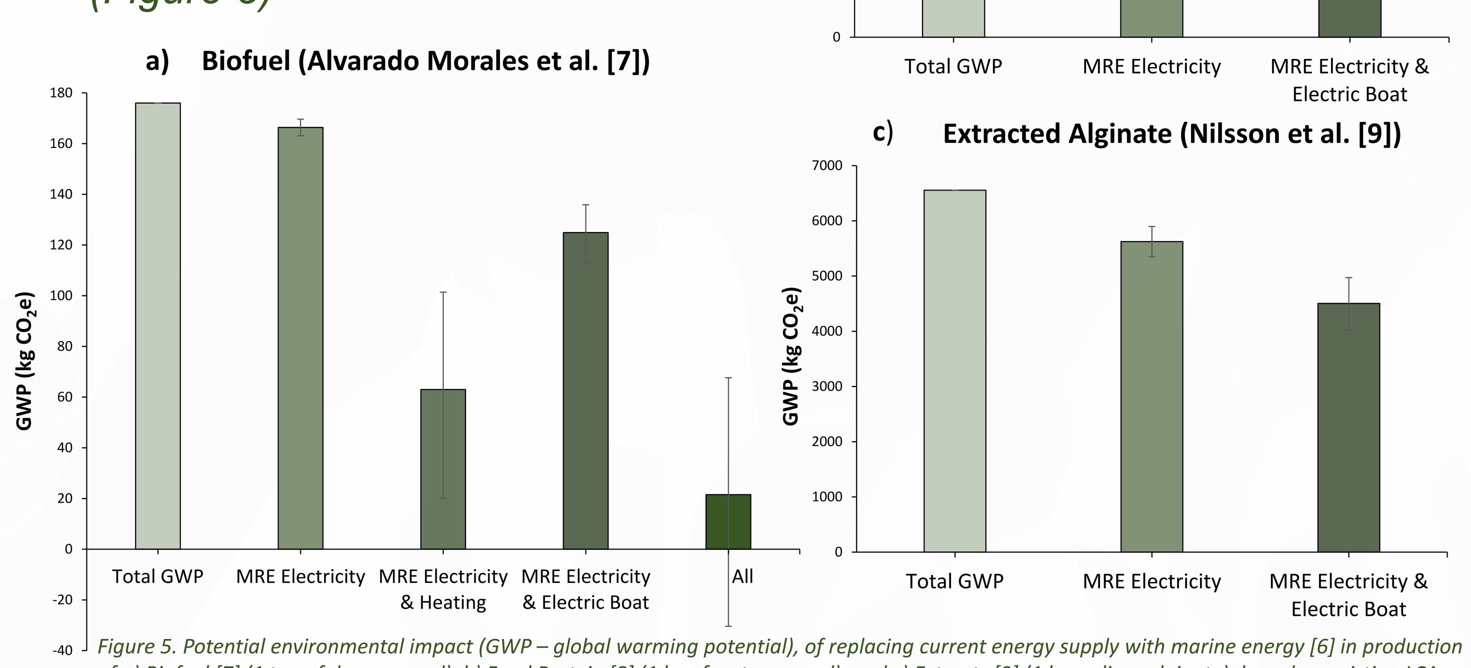


Figure 5. Potential environmental impact (GWP – global warming potential), of replacing current energy supply with marine energy [6] in production of a) Biofuel [7] (1 ton of dry seaweed), b) Food Protein [8] (1 kg of wet seaweed), and c) Extracts [9] (1 kg sodium alginate), based on existing LCAs.

CONCLUSIONS

- Sufficient marine energy resources exist at a few current and planned kelp farm sites in the U.S., though the practicality of utilization has not been demonstrated.
- Marine energy can improve environmental performance of macroalgae products – though further case studies are needed to look at site specificity, limitations in current assumptions, and procedural details.
- LCAs are a widely used method for assessing environmental impacts of products, but fall short in assessing the permanence and value of carbon capture in kelp products. A literature review is underway to explore other assessment possibilities and develop recommendations for standardization.

ACKNOWLEDGEMENT

This work has been supported by the U.S. Department of Energy's Water Power Technology Office with Seedling funds in FY21 and FY22.

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