

Kelponomics: The State of North American Kelp Mariculture

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Abstract

The kelp sector is growing in Canada, the USA, and Mexico. In part, this expansion is due to the enthusiasm around the sector's promise for environmental, social, economic, and climate benefits. However, these Blue Economy goals may not be inherently realized by Indigenous Nations and coastal communities where kelp industries operate. To investigate the status of the kelp-economy in North America, we compiled a database of 267 kelp-related organizations from across North America and gave each a score from 1–4 for community participation as a proxy for community-derived benefit. We then looked at broader political, economic, social, technological, legal, and environmental (PESTLE) factors at the state/province level to evaluate which enabled community participation. Finally, we used a cluster analysis to group states/provinces into broader regions based on their PESTLE variables. We found that factors that influence community participation included state-level political legislation (local adoption of UNDRIP), regional economic support/planning, public support of seaweed aquaculture, initial permitting investment, and environmental trends reflected in wild kelp abundance. Of the regions evaluated, British Columbia (a cluster in itself) had the strongest enabling conditions (highest PESTLE scores) and had higher participation than other clusters. Overall, we recommend that if the North American kelp-economy aims to meet the social-environmental goals of the Blue Economy, additional effort should be directed by state/provincial powers towards enabling greater community participation, particularly of Indigenous Nations, in areas engaged with the seaweed economy. Further, we discuss how seaweed-specific legislation, species reporting, authentic collaboration, and inter-industry connections may progress these goals.

2 Introduction

Interest in seaweed industries is expanding in Canada, the United States of America, and Mexico (FAO 2024). Globally, seaweed aquaculture swelled from 10 million to 36 million tonnes between 2000 and 2022, an average annual growth rate of 5.8% (FAO 2024). The vast majority of seaweed (macroalgae) is produced in Asia (~ 97%), with North America (NA; Canada, USA, Mexico) contributing less than 1% to global markets (FAO 2024). However, seaweed production in this region is currently being emphasized given its potential for local employment, bioremediation, habitat production, and climate change mitigation, leading to a increased interest in investment and commercial enterprises within the “Phyconomy” (a contraction of the words phycology and agronomy describing seaweed crop production; Critchley et al., 2024). Here, we analyzed this growth in the NA Phyconomy, with particular focus on enabling benefits for local communities.

Canada and Mexico [and prior to the 2025 Trump administration, the USA] are members of the High Level Panel for a Sustainable Ocean Economy, which explicitly prioritises seaweed aquaculture (High Level Panel for a Sustainable Ocean Economy 2023). Moreover, the United Nations General Assembly launched a Global Seaweed Initiative in September 2025, aiming “to accelerate the safe, sustainable, and inclusive development of the global seaweed sector” (UN Trade and Development 2025). Seaweed industries can indeed lead to socioeconomic benefits such as increased social cohesion, income, and

employment, especially for women (Hamad and Islam 2022; Spillias et al. 2023; Sultana et al. 2023; Mwaijande and Rashidi 2025). On the other hand, rapid seaweed development can have trade-offs for communities such as financial dependency, population displacement, and overproduction (Steenbergen et al. 2017; Spillias et al. 2023; Meng 2025).

Although aquaculture is the most prominent seaweed industry type globally (FAO 2024), seaweed-based businesses and initiatives are not limited to cultivation, particularly in NA (Gutzmann and Cisneros-Montemayor 2026). In 2023, Food and Agriculture Organization (FAO) data reveals that landings from wild seaweed harvest in NA totaled at least 14,000 tonnes live weight, compared with only ~ 730 tonnes live weight of farmed seaweed production (FAO 2025). Seaweed industries like aquaculture and wild harvest can advance 12 of the 17 Sustainable Development Goals, including those aimed at food security, gender equality, and clean water (Khan et al. 2024). Seaweed businesses thus fit within the concept of a Blue Economy, which explicitly calls for centering social equity in addition to environmental sustainability in both new and emerging ocean sectors (Cisneros-Montemayor et al. 2022).

To move towards the goal of a Blue Economy, we suggest that the complementary practise of Regenerative Development and Design is used to guide ocean sectors as it requires that businesses, local communities, and the environment all benefit from project development. This practise starts with analyzing potential, or “the gap between what something is and what it could be” (Regenesis Institute for Regenerative Practice 2019). Hence, despite the fact that NA has a high potential for Blue Economic operationalization and implementation socially and ecologically (Cisneros-Montemayor et al. 2021; Wuwung et al. 2022), studies on the social impacts and benefits of seaweed industry in NA are underdeveloped (Spillias et al. 2023).

In NA, nearly 50% of previously documented ($n = 40/84$) seaweed organizations target kelp species (seaweed species in the order Laminariales). However, 68% of 266 companies’ data do not include the species used (Hermans 2024). This gap is important given the prominence of wild harvest in NA seaweed production. Kelps are ecologically critical, forming undersea forests along much of NA’s coastline where Canada and the USA have an estimated 609,000 km² of kelp habitat combined (Eger et al. 2024b). Indeed, throughout human evolution, kelps have helped to shape NA with evidence that kelp forests allowed humans to travel the coast before glacial retreat (Erlandson et al. 2007), and nutrients from macroalgae supporting human brain evolution through dietary supplements (Cornish et al. 2017). Moreover, kelps have held cultural importance to Indigenous Peoples for generations (Turner and Bell 1973; Turner 2000; Erlandson et al. 2007; Dillehay et al. 2008; Hale Hendlin et al. 2024; Gutzmann et al. 2025). Diverse human-kelp relationships continue today, and thus a spectrum of kelp relationships and uses is important to consider for wholistic governance of a NA kelp economy (Gutzmann and Cisneros-Montemayor 2026). For example, kelp monitoring and restoration are required for a regenerative kelp-economy, although long-term financing remains a challenge at present (Eger et al. 2022, 2024c). Further, for connecting to global markets, downstream market actors who develop and sell kelp applications and products as well as processing facilities, are critical to consider from a supply chain perspective. In this way, the Phyconomy is expanded from aquaculture and/or harvest to include downstream applications

of biomass as well as research and stewardship organizations (Hermans 2024; note that within this work we focus on a kelp specific subset of the Phyconomy in NA and use aquaculture and farming interchangeably. To maintain this distinction, we use “kelp-economy” to describe this kelp focused economic development in NA).

The interest in a kelp-economy highlights the need for NA not only to determine pathways to entering global seaweed markets, but also to invest in guardrails for local equity and community-derived benefits. Globally, ocean based economic expansion has and continues to lead to violations of human rights to a healthy ocean, food, livelihood, health, and security (Bennett et al. 2023; The Ocean Defenders Project 2025). Hence, although the seaweed industry has championed social, environmental, and cultural benefits for coastal communities, these may not be inherently realized (The Nature Conservancy 2021; Spillias et al. 2023). For instance, licencing and permitting, public support, market size, and technological investment are larger hurdles to kelp industries than environmental factors like warming waters in the global North (Koch et al. 2026). Further, Indigenous economic sovereignty is highlighted as a necessity in resource sectors due to past and present colonial systems (Boron and Markey 2020; Atleo and Boron 2023; Jobin 2023; Atleo 2024) where sector actors (including states/provinces and the private sector) must increase the recognition and protection of specific Indigenous rights to the ocean (Bennett et al. 2023; The Ocean Defenders Project 2025).

Despite the clear interest in expanding the kelp-economy in NA, the current political, economic, social, technological, legal, and environmental (PESTLE) factors that enable or constrain community-derived benefits have not been specifically explored for the sector. If the NA kelp-economy is to meet its regenerative potential and benefit coastal communities per Blue Economic initiatives, it is critical to assess current community decision-making sovereignty as the sector expands because power distribution to local communities is a precursor for an equitable, co-managed resource sector (Carlsson and Berkes 2005; Hamilton-Smith 2005). In NA, this assessment must specifically include the level of engagement and leadership of Indigenous peoples given the extent of their marine and coastal territories across the Pacific Northwest. This research addresses this need by presenting a preliminary, novel investigation into the distribution of Indigenous/community participation in NA kelp-economy by addressing the questions of:

- 1) What is the current state of the kelp-economy in NA; specifically, how many actors are there, what are their main objectives, and where are they located?
- 2) What are the regional PESTLE profiles which may enable community-derived benefits at the organization level, and are these variables associated with current community participation?
- 3) Do regional PESTLE profiles cluster into larger regional units that can be used to direct focus to increase local benefits?

We reiterate that this work is for the contemporary, commercial kelp-economy and does not represent cultural and traditional relationships that Indigenous peoples and communities have had for generations.

Additionally, while there are different definitions of equity, here we consider it in the context of decision-making power at the organizational level (participation in the kelp-economy) as a proxy for community-based benefit.

3 Methods

Herein we detail how we addressed each of the above research questions, beginning with database development and mapping (question 1); political, economic, social, technological, legal, and environmental (PESTLE) analysis (question 2); and finally, a cluster analysis (question 3).

3.1 Data on NA Kelp Economy (question 1)

First, we compiled a kelp economy database for NA from an existing global Phyconomy database by Hermans (2024). As of December 2024, the global database included more than 1400 entries updated by Hermans and through public submission. We manually verified existing NA entries in the database and added new ones found using LinkedIn, Google searches, as well as via the websites and word-of-mouth of organizations which were already named in the Hermans Phyconomy Database (e.g., documented collaborators). Using publicly available information, we detailed company/organization information, kelp species utilized, and date of establishment (see Supplementary Materials for details). We also recorded organization type as non-profit, for-profit private, Guardians (Indigenous resource and stewardship organizations), and knowledge hubs (kelp-specific research or management related conglomerates/networks; note that we did not include individual academic groups/labs whose portfolios included some kelp work as, to avoid double counting, we assumed significant players were represented by the larger knowledge hubs). We stopped adding organizations to our database in December 2025.

We categorized up to three organization objectives as either: agriculture; bioplastics; consulting; food product; kelp aquaculture; kelp propagation; nutraceuticals, biostimulants, or other chemically derived applications); processing (wholesale); regulation/governance/policy; research, blue carbon; research, ecology or biology including monitoring; research, genetics/biobanking; research, social or economic factors; restoration; skincare; spatial planning; stewardship, or; wild kelp harvest. Secondly, we further grouped what we determined to be each organizations' primary objective into categories for 'mariculture' activities (representing the spectrum of harvest, farming, seed propagation, and restoration), 'research and management', 'Indigenous stewardship or governance bodies', and kelp 'products or applications' (e.g., food products, skincare, biostimulants, etc.).

To address Indigenous engagement in organizations, we developed a participation scale based on Boron and Markey (2020) which details a framework of participation in resource decision-making that describes the distribution of decision-making power. The framework goes from the power being entirely in colonial systems (i.e., consultation), to those entirely within Indigenous control (i.e., autonomous governance), transitioning through stages of collaboration and co-governance (Boron and Markey 2020). We gave each organization in our kelp-economy database a score from 1–4 for Indigenous participation

inferred from the information given by each organization's website(s). A score of 1 indicated that the organization made no mention of Indigenous participation and/or no evidence of any consultation on public facing materials. A score of 2 was given when the organization demonstrated a low-level commitment to Indigenous participation within their project/company such as a land acknowledgement or an indication of consultation (consultation was defined per Boron and Markey 2020). A score of 3 was given when an organization had some level of formal collaboration, co-management or co-ownership. Finally, a score of 4 indicated that the organization was owned (in majority or entirely) by an Indigenous Nation(s).

Indigeneity is recognized differently in Mexico due to its distinct colonial history and majority mestizo population throughout the country, so the method was slightly modified to make this comparable to the other countries in NA. Except for a small number of specific regions (most of which are not within significant kelp ecosystems), local community participation is a more appropriate comparison for engagement by private firms with more equitable practices and distribution of benefits. In this case, a score of 1 indicated no mention of the company giving back to local communities, a 2 for some sort of interest statement or indication of hiring local peoples, a 3 for community project(s) or funding initiative(s), and 4 for co-ownership.

3.2 Regional Profiles (question 2)

Following a preliminary screen of our database, we selected regions with a higher number active of actors in each region (≥ 3 organizations) for PESTLE analysis. Thus, for Alaska, Baja California, British Columbia, California, Connecticut, Maine, New Brunswick, Newfoundland, Nova Scotia, Oregon, Prince Edward Island, Quebec, Sinaloa, and Washington we conducted an information search to determine categorical scores for each PESTLE category in each region as follows. As we explain below, a higher score was associated with conditions we hypothesized would better enablers of Indigenous/community participation in a kelp-economy.

Political (P) scores were derived from state or province-level commitments to Indigenous rights consistent with the United Nations Declaration on the Rights of Indigenous People (UNDRIP). Here we utilized a scale from 1–4 where a score of 1 indicated not enough information, 2 indicated that UNDRIP was not legislated in the region, 3 indicated UNDRIP was legislated at the federal or provincial (or state) level, and 4 indicated that UNDRIP was legislated at **both** federal and provincial levels.

The economic (Econ) score is out of 6 corresponding to various levels of economic plans associated with each of the jurisdictions. A score of 1 constituted not enough information; 2 indicated that there were no relevant plans; 3 indicated some sort of state/province-level aquaculture plan that was inclusive of kelp/seaweed; 4 indicated the presence of some sort of state/province-level Indigenous/community-focused economic plan; 5 indicated a plan that linked kelp economic development with Indigenous/community-focused economic development but with no proof of commitment, and finally; 6 indicated a plan that linked kelp and Indigenous/community-focused economic development with proof of commitment (e.g., funding specified, programs associated with). For these purposes, we considered

an 'Indigenous economic plan' to be any state or province level government document which aimed to support Indigenous economic development within the region, and we acknowledge that many Nations and Tribes have their own economic plans distinct from the plans we considered in this context.

Social (S) PESTLE scores were determined from documentation of public support for kelp/seaweed mariculture. Three studies notably covered multiple regions, these being Flaherty et al. (2019), Kotowicz et al. (2024), and Tenorio-Rodríguez et al. (2025), in which social support for a seaweed sector was expressed explicitly through surveys or inferred (by us) through public willingness to eat kelp/seaweed products. Where possible, we averaged the findings of these overarching surveys with regional specific studies (e.g., Getchis et al. 2020; Guan et al. 2022; Colombo et al. 2024; Xue 2025). Each region was assigned a score of 1 for not enough information, 2 for $\leq 25\%$ support, 3 for 26–50% support, 4 for 51–75% support, and a 5 for $> 75\%$ support.

Technology (T) scores represented the relative level of investment required to acquire permits for kelp farming, specifically. While technological investment differs across objectives and by operation, for consistency in and across regions we selected an objective (farming) which consistently required permitting in all regions. Moreover, we assumed that because downstream applications of kelp would be facilitated in regions with greater kelp production, this mariculture investment may function as a proxy for downstream investment. We note that the case-by-case cost for equipment and any individual studies required by each permitting body are highly variable and additional to those we present. T scores were broken down into categories from 1–5, where 1 indicated not enough information, 2 potentially prohibitive conditions, 3 a high level of initial investment ($> \$5000$ USD), 4 a moderate initial investment (> 1000 and $< \$5000$ USD), and 5 a comparatively low level of initial investment ($< \$1000$ USD).

Legal (L) scores were a representation of the number of permits required to begin mariculture operations on a scale of 1–6. Like the T scores, we assumed that kelp farming would be a proxy for downstream uses of kelp for consistency across regions. A score of 1 indicated not enough information, 2 indicated that kelp aquaculture was not permitted, 3 indicated > 10 permits or regulations were required, 4 indicated 7–9 permits or regulations, 5 indicated 4–6 permits or regulations, and 6 indicated 1–3 permits or regulations. Where a harmonized review process was used, we considered the authorizations within the harmonization to be represented by a single permit. We acknowledge that L scores do not reflect nuance in permitting processes; for instance, a convoluted, slower system could require fewer permits but be more of a barrier than a streamlined, faster process with a larger number of permits.

Environmental (Env) scores were based off Krumhansl et al. (2016), which was the most recent global assessment of kelp abundance at the time of writing. Krumhansl et al. (2016) showed positive change for the North American Pacific Fjordland (British Columbia), the Gulf of Alaska and the Southern California Bight, no change for Oregon, Washington and Vancouver Island, and negative change for North-Central California, Southern New England, the Gulf of Maine, and along the Atlantic coast of Nova Scotia. While slight increases in kelp were found in the Gulf of St. Lawrence, Newfoundland, and Labrador, data were sparse. A score of 1 indicated no information, 2 an annual declining trend of $> 2\%$, 3

a declining trend < 2%, 4 for stable populations, 5 for increasing trend < 2%, and a 6 for an increasing trend > 2%.

4.4.3 (R Core Team, 2025) was used for all data analysis and data were ordinal in nature. Kruskal-Wallis tests were used to look for a difference in participation scores across objective categories with a Conover-Iman test for pairwise comparison (R package 'conover.test' (Dinno 2024). Ordered chi squared tests (R package "coin" (Hothorn et al. 2023)) were used to look for associations between each PESTLE category and participation. Association strength between each PESTLE category and participation was checked with Goodman and Kruskal's gamma (R package "DescTools" (Signorell et al. 2025)).

Mapping of organizations was done through ARCGIS Pro 3.5. The organizations were displayed according to the city indicated as their headquarters. Each organization was given regional PESTLE scores (described below), alongside the organization type, adjusted scale of participation, and its primary objective category. Symbology was then added to the points to illustrate the adjusted participation scale, with unique icons per score (1–4).

3.3 Geopolitical Cluster Analysis (question 3)

The "eclust" function with 1000 iterations (R package "factoextra" (Kassambara and Mundt 2020)) was used to cluster regions (n = 14 states/provinces) based on their PESTLE scores' k-means. The number of clusters (5) was determined by evaluating of scree and silhouette plots (see Supplementary Material). Kruskal-Wallis and Conover-Iman tests were used to look for significant differences in Indigenous/community participation between clusters. Clusters were made at the state/province level to avoid complications due to pseudoreplication and unequal sample sizes at the organization level.

4 Results

4.1 Current State of the NA Kelp Phyconomy (question 1)

We added 118 kelp-specific actors to the original Phyconomy database (Hermans 2024) for a total of 267 active organizations in NA. Overall, we found 159 kelp-economy actors in the USA, 101 in Canada, and 7 in Mexico (Fig. 1). While only about 57% organizations publicized their date of establishment (n = 153), we found that generally the NA kelp-economy has been increasing exponentially since the early 2000's (Fig. 2). British Columbia and California saw the greatest increase in kelp-sector actors with 75 and 42 organizations active by 2025 respectively, followed by Washington and Alaska with 38 and 25. Only 87 (~ 33%) of organizations specifically identified which species of kelp they worked with, where the most common species listed were *Saccharina latissima* (n = 36 instances of documentation), *Nereocystis luetkeana* (n = 25 instances), *Macrocystis spp.* (n = 23 instances). Note that organizations may work with more than one species of kelp.

4.2 Regional Profiles (question 2)

Subsetting our NA data to the regions more active in the kelp-economy (≥ 3 organizations) resulted in a subsample of 248 actors (Alaska, British Columbia, Baja California, California, Connecticut, Maine, New Brunswick, Newfoundland, Nova Scotia, Oregon, Prince Edward Island, Quebec, Sinaloa, and Washington). Of the 248, we classified 25% ($n = 62$) as Guardians (Indigenous Nations, Nations' resource and stewardship offices, Guardian programs), 5% ($n = 13$) as knowledge hubs (research or management focused conglomerates), 13% ($n = 33$) non-profits, and 56% ($n = 140$) private sector entities. Out of the 248 organizations, 49% ($n = 121$) had a participation score of 1, 3% ($n = 8$) received a score of 2, 19% ($n = 48$) a score of 3, and 29% ($n = 71$) a score of 4 (Fig. 3). Mean participation scores were significantly different ($p < 2.2e-16$) between objective categories across all 248 organizations. Pairwise tests revealed significant differences between the mean participation scores of Indigenous stewardship/governance organizations and all other groups, as well as between mariculture- and kelp product-focused organizations, mariculture and research/management organizations, and product-focused organizations and research/management organizations ($p < 0.00$ for all). The mean participation score of Indigenous stewardship organizations was 4, mariculture was 1.7, kelp-products was 1.1, and research/management-based organizations was 2.3.

Companies with high participation scores are focused on BC and Washington, encapsulating most of the Pacific Northwest through to Alaska. This area does not extend through Oregon and California. Within the Pacific Northwest is a high concentration of Indigenous Guardian networks, centered between Alaska, British Columbia and Washington's Puget Sound. Furthermore, this region sees the largest cluster of direct-kelp activities such as farming, harvest, and restoration, with companies averaging higher participation scores than East Coast companies. The East Coast lacks Indigenous participation outside of Guardian networks and it has a higher proportion of its companies dealing with farming than other categories (maps are presented in the Supplementary Material).

Ordered chi-square analysis of PESTLE score results (Table 1) found that political, economic, social, technological, and environmental categories were significantly ($p < 0.00$) and positively associated with organization-level community participation, supporting our initial hypotheses. Political and economic scores had the greatest association at ~ 0.44 . Social, technological, and environmental categories all had moderate gammas of $= 0.34, 0.37$, and 0.32 , respectively. Legal scores were non-significant ($p = 0.5$) and had the weakest association (~ 0.05) (for additional detail on scores, see the supplementary material). Legal scores had no impact on overall cluster groupings (i.e., the same clusters formed with or without the inclusion of L scores) but were retained in the final clusters as they slightly improved model fit.

Table 1: PESTLE Scores by region evaluated. 1 scores (grey) indicate data deficient. Higher scores represent criteria hypothesized to support greater Indigenous/community participation in the NA kelp-economy.

	Political	Economic	Social	Technological	Legal	Environmental	
Region	1-4	1-6	1-5	1-5	1-6	1-6	Cluster
Alaska (AK)	3	6	2	3	3	5	5
Baja California (BCN)	2	3	4	4	6	5	1
British Columbia (BC)	4	6	4	4	5	6	4
California (CA)	2	6	3	2	3	4	5
Connecticut (CT)	2	3	2	4	3	2	3
Maine (ME)	3	6	3	3	4	2	5
New Brunswick (NB)	3	4	3	5	6	6	2
Newfoundland (NL)	3	4	3	4	6	6	2
Nova Scotia (NA)	3	5	3	5	6	3	2
Oregon (OR)	2	2	2	2	2	4	3
Prince Edward Island (PEI)	3	2	3	5	6	6	2
Quebec (QC)	3	4	2	5	4	6	2
Sinaloa (SIN)	2	2	4	4	6	1	1
Washington (WA)	3	6	3	4	3	4	5

4.3 Regional Clusters (question 3)

The PESTLE cluster analysis resulted in 5 groupings (Table 1; Fig. 3; Fig. 4). Cluster one (SIN, BCN) was defined by proportionally high (> 0.75) S and L, moderate T, but low Econ, Env, and P. Looking at the organizations within Cluster 1, the number is comparatively low with a focus on product applications. Cluster 2 (NB, NL, PEI, NS, QC) had high (> 0.75) L and T scores, and moderate P, Econ, S, Env scores. The organizations in Cluster 2 were relatively evenly distributed across objectives but few overall. Cluster 3 (CT, OR) had comparatively low (< 0.25) scores for all PESTLE categories, with a focus on research and mariculture across a small kelp-sector in this region. Cluster 4 (BC) was defined by high (> 0.75) P, Econ, S, L, and Env scores but a moderate T score. The organizations within cluster 4 revealed a focus on Indigenous governance/stewardship and mariculture, including aquaculture, restoration, propagation, and harvest. Finally, cluster 5 (CA, ME, WA, and AK) was defined by a high Econ score (> 0.75) but low-moderate (< 0.50) scores for the remaining categories. Looking at the organizations within this grouping, the cluster 5 region prioritizes mariculture activities, followed by stewardship and research.

Mean participation varied between clusters (cluster 1, n = 7, mean = 1.57, sd = 0.98; cluster 2, n = 25, mean = 1.72, sd = 1.31; cluster 3, n = 12, mean = 1.75, sd = 0.97; cluster 4, n = 75, mean = 2.83, sd = 1.29; cluster 5, n = 129, mean = 2.14, sd = 1.28). We found that the mean participation score of cluster 4 was significantly different from clusters 2 and 5 ($p < 0.00$; Fig. 5). There was no significant difference detected between cluster 4 and clusters 1 or 3, likely due to small sample sizes in the latter groups.

5 Discussion

A better understanding of both the extent of the current seaweed economy and the current participation of local communities is necessary to reach (or course correct for) a kelp-economy that meets the equity, environmental, and economic goals of a Blue Economy. This work presents a novel investigation into the state of the kelp-economy across Canada, the USA, and Mexico. We documented a total of 267 active kelp-related organizations in North America (Fig. 1, Fig. 2). We then subset our data to focus on regions more active in the kelp-economy (i.e., contained ≥ 3 organizations) resulting in 248 organizations across 14 states/provinces, namely: Alaska, British Columbia, Baja California, California, Connecticut, Maine, New Brunswick, Newfoundland, Nova Scotia, Oregon, Prince Edward Island, Quebec, Sinaloa, and Washington. The majority (56%) of these 248 organizations were for-profit, private sector companies. Simultaneously, 49% do not appear to have any local community participation (i.e., a participation score of 1 by our ranking). Most regions had relatively fewer product-focused organizations (Supplementary Fig. 1, Fig. 4), which corroborates the observation that kelp-product markets are lacking in North America (Kotowicz et al. 2024; Koch et al. 2026, Tamburello et al. *in press*), especially compared to Asia (World Bank 2023). However, we acknowledge that this work did not follow supply chains between states/provinces where cross-border sales may supplement the demand for kelp product/applications in each region.

Using participation as a proxy for community-derived benefit (Fig. 5) our results show that if the North American kelp-economy aims to meet the social-environmental goals of the Blue Economy, additional effort should be directed by state/provincial powers towards enabling greater community participation, particularly of Indigenous Nations, in areas engaged with the seaweed economy. We found that PESTLE factors influenced community participation, specifically state-level political legislation (e.g., local adoption of UNDRIP), regional economic support/planning, social (public) support of seaweed aquaculture, technological capacity (e.g., initial permitting investment), and environmental trends reflected in wild kelp abundance. The legal status of UNDRIP as well as specific regional economic planning had the largest influence on participation, while the number of permits was not statistically significant. These PESTLE variables were used to cluster the 14 states/provinces into 5 larger regions (Table 1; Fig. 3). Of these clusters, British Columbia (a cluster in itself) had the strongest enabling conditions (highest PESTLE scores) overall and had higher participation than other clusters, although sample sizes were too small to determine a significant difference between all groups (Fig. 5; Supplementary Fig. 4).

To our knowledge, ours is the first in-depth study of the state of the NA kelp-economy that evaluates local community participation (as a proxy for community benefit) and includes organizations at all stages of kelp production (harvest and aquaculture), down-stream application, as well as restoration, stewardship, and research. In fact, we are unaware of a similar study anywhere else in the global seaweed sector (recognizing that our authorship team was limited to publications in English and Spanish). Research has shown tropical seaweed aquaculture has resulted in direct community benefit, particularly for women, through employment in the global south (Sultana et al. 2023). For instance, C-

Weed Mwani (<https://cweed.com/>) in Tanzania has formed community-based partnerships where they provide training, support, and payment to farmers for seaweed grown before they collect, store, and distribute the collective yield. Conversely, farmer cooperative efforts have been found to be negative experiences for some communities in Malaysia due to factors such as poor social cohesion, complex marketing, and limited participation in decision-making (Nor et al. 2017). Similarly, obscure and/or financially fraudulent practises within some cooperatives led to the eventual collapses of said cooperatives in the Philippines (Andriesse and Lee 2021).

5.1 Limitations

We acknowledge that this work is limited in that the accuracy of our data is dependent on the detail of information provided by organisations and state/provincial agencies in the public space. For instance, some organizations may not prioritize updating websites or social media and therefore may be represented inaccurately in this study. Moreover, we do not intend to say that a participation score of 1 is necessarily “a bad thing” or equal across organizations. For example, we did not distinguish between large or small organizations in our participation scores and recognize that smaller organizations might simply have less capacity to engage in collaborative work. Likewise, an organization may generate community-benefits in ways that are not captured by our scoring system (e.g., by being a part of the community, employing local people, contributing to local economies). Finally, we reiterate that the environmental scores are based on data prior to 2016 (see Krumhansl et al. 2016) and the current trends of kelp may differ from those used here. Nonetheless, we believe that these methods are useful to complete similar overview analyses of other Blue Economy sectors and identify both opportunities to develop more equitably as well as to course correct current systems.

5.2 Global Outlook

Outside of Asia, Europe is the next largest aquaculture-based producer of kelps (mostly *Saccharina japonica* or kombu), specifically in the Faroe Islands and Norway (Cai et al. 2021). In addition, Norway, France, Iceland, and Ireland are some of the top global wild-harvest producers of kelp (in 2019; Cai et al. 2021). North America parallels Europe’s kelp-economy in both scale (i.e., a small number of organizations involved) and strategy (i.e., developing within broader multi-sector Blue Economy plans) (Barbier et al. 2020; Cai et al. 2021). Further, NA and Europe have similar social-ecological challenges that increase production costs, including high labour and operating costs, limited growing seasons, complex licensing landscapes, and the requirement of using wild stock for seed (Cai et al. 2021; Jueterbock et al. 2025; Koch et al. 2026). While there are initiatives looking into how to obtain social license to operate for seaweed aquaculture (e.g., Billing et al. 2023) which discuss the merits of forming farmer cooperatives (e.g., Orr 2022), or public consultation in harvest permitting (e.g., Greenhill et al. 2021), we did not find studies looking at community-derived benefits in the European kelp-economy.

As mentioned, Asia dominates seaweed markets globally. Significant government investment, research, and technological innovation (e.g., automation) as well as selective breeding of cultivated strains have made South Korea, China, and Japan world leaders in seaweed cultivation (Hwang and Park 2020;

Hwang et al. 2020; Hu et al. 2021, 2024; Park and Hwang 2022). East Asian markets are driven by human food applications, as well as other developed global markets including those for agar, alginate, carrageenan, and aquaculture feed (Cai et al. 2021; World Bank 2023). Still, the World Bank predicts that seaweed applications are largely untapped and that demand will grow by an additional USD 11.8 billion by 2030, largely through developments in markets for biostimulants, pet and animal feed, nutraceuticals, alternative protein, fabric, bioplastics, and (over the longer term) construction materials and pharmaceuticals (World Bank 2023).

To compete in these global markets, a major challenge for the production side of the NA kelp-economy will be lowering production costs. Although there are many factors that influence production costs and what is competitive in an end market, estimated production costs per dry metric tonne range from ~\$2200 in Canada, ~\$4400 in Alaska, ~\$13900 in Connecticut, to ~\$24000 in Maine (Coleman et al. 2022). Increasing farm size can bring down costs; for instance, ~\$2600 USD per wet tonne from a 405 ha site in Maine has been calculated (Moscicki et al. 2025). However, as of writing, the largest farms were ~ 40 ha in the USA (AK) (NOAA Fisheries 2025) and ~ 70 ha Canada (BC) (Tamburello et al. *in prep*). In comparison, a preliminary estimation suggests that the USA in general would require a 1000 ha farm to decrease costs to the required \$100-\$300 per dry tonne to be competitive in biofuel markets, for example (Kite-Powell et al. 2022). Farms of this scale would likely meet significant pushback from coastal residents and need further, detailed investigation for environmental impacts. Thus, research in the near term should focus on other technological advancements and accompanying policy (e.g., gametophyte culture; (Coleman et al. 2022)) as well as site design and location optimization (Moscicki et al. 2025; James et al. 2026) to bring down production costs.

Importantly, as we argue in this research, kelp farming and harvest are not the only components of a kelp-economy (Gutzmann and Cisneros-Montemayor 2026). The focus on kelp conservation has been increasing in recent years with international efforts (e.g., the Kelp Forest Challenge (Eger et al. 2024a), Green Gravel Action Group (Wood et al. 2024)) aiming to fill the gaps created by limited kelp biodiversity policy globally (Beattie et al. 2025). Given the immense importance of wild kelp for global social-ecological systems (see Introduction), it is critical that kelp production is supportive of, and ideally beneficial to, conservation and restoration efforts. However, these commercial and conservation-based goals are largely considered separately in research and policy. The seemingly divergent goals of production/conservation can be thought of as linked through different scales of human-kelp interaction (Gutzmann and Cisneros-Montemayor 2026), where the connection between production, stewardship, and restoration of kelp will become more important as kelp populations (farmed and wild) are increasingly threatened by changing ocean conditions.

5.3 Recommendations for a Regenerative Kelp Economy

In the face of the challenges the NA kelp-economy faces, we argue that it is critical that the NA kelp-economy uses a Blue Economy lens to guide the sector as it develops. Kelps form some of the most important marine ecosystems globally (Eger et al. 2024a) and is therefore more than a “resource” to be extracted in the most sustainable way or grown with the highest yield. Conversely, kelp conservation

cannot ignore the utility and social benefit of extraction and product development. Our work emphasizes the following recommendations to course-correct the current kelp-economy towards a more regenerative future:

1. Disclose the species of kelp utilized. Ultimately, the kelp-economy depends on the biology and ecology of kelp, both wild and farmed, which in turn requires an ocean environment that is conducive to its growth. Different species of kelp have different geographic ranges and environmental tolerances, and even within species, kelps have been found to have localized genetic and phenotypic specificity (e.g., Starko et al. 2020; Gonzalez et al. 2023; Pontier et al. 2024; Dykman et al. 2025; Bemmels et al. 2025). While what kelp species is used may be known internally to governance bodies (e.g., through harvest and cultivation licenses), we found that there is a lack of transparency and corporate accountability in the sector at present with only ~ 33% of organizations listing species publicly. Further, because there are numerous concerns around the impacts of kelp mariculture to the genetic integrity of wild kelp populations, in addition to the genetic diversity of cultivated kelp itself (Campbell et al. 2019; Mendes et al. 2024; Purcell et al. 2025, Tamburello et al. *in press*) genetic diversity might ideally be documented as well. However, analyzing tracking genetic diversity would likely need to be surveyed at regional scales due to costs and technical expertise required (Tamburello et al. *in press*).

2. Policy and Legislation should be fit to purpose. While determining L and T scores, we observed that all locations have permitting systems that overlap with, or are tacked onto, other forms of aquaculture (e.g., shellfish). Thus, regulations might not be fit to purpose and can act as a barrier to entry, particularly as the sector scales (Mendes et al. 2024; Kosichuk et al. 2024; Kotowicz et al. 2024; Martone et al. 2025; Koch et al. 2026). Emerging seaweed-specific standards like the ASC-MSC Seaweed Standard ecolabel (Aquaculture Stewardship Council and Marine Stewardship Council 2018) may offer guidance for developing legislation fit for seaweed aquaculture. Further, this need for specific legislation is not isolated to seaweed aquaculture but applies to downstream processing and applications as well; for instance, kelp producers in BC have spoken about challenges in needing to meet food handling safety regulations intended for raw fish and shellfish which do not apply to kelps (Reidlinger 2025). Moreover, additional research into the legal landscapes at all stages of the kelp-economy would be beneficial; for example, such as has been done for kelp restoration policies in California (Cleveland 2024).

3. Accelerate authentic collaboration. While this paper makes the case for increased community/Indigenous participation, leadership, and ownership, this must be done in a place-specific manner. Our findings suggest that, broadly, regions should focus on improving the PESTLE conditions in which they scored low to enable the sector. At a finer scale, funding and other development programs should work to balance Indigenous and community autonomy with the realities of location-specific capacity. For instance, investors typically seek a certain level of assurance and reciprocal investment from a community when building a business and thus regions should consider what capital (e.g., financial, social, human) is needed for a community to meaningfully engage (Cascadden et al. 2021). However, we caution against regional programs which incentivize disingenuous partnerships or increase community burden. For example, funding programs which *require* an Indigenous partner can increase

engagement burden on Indigenous Nations and Tribes and partnerships may form out of necessity rather than aligned vision and values, risking exploitation (Reidlinger 2025). Thus, while specific Indigenous funding pathways are important to equitably grow a kelp-economy, they should be partnered with other capacity building initiatives such as those focused on training programs, access to expert advice, access to reliable internet, equipment, and supporting personnel, etc. A deeper analysis of social networks within the kelp-economy can assist in identifying which of these gaps should be prioritized, and how, in a community-specific manner.

4. Regenerate within the sector. Developing a regenerative sector requires good-faith collaboration as well as increases in natural, built, human, social, and financial capital across the system (Mang et al. 2016; Regenesys Institute for Regenerative Practice 2019). No one actor needs to provide all five capitals to the system, however, as social networks allow for reciprocal exchanges and overall increases in capital. Essentially, by breaking siloes between kelp-economy participants, organizations with different interests and projects can all work towards a common vision. Networking initiatives are already in place in North America, for instance, Green Wave has recently launched a “Seaweed Source” platform to link seaweed producers with buyers (<https://www.greenwave.org/seaweed-source>) throughout North America, and a National Kelp Community of Practice is in development across Canada.

The barriers to and boundaries of kelp-economies can differ greatly from one country to the next, where in the global North the most important are socio-economic (Koch et al. 2026). Based on our findings, the kelp-economy does not inherently generate more direct benefits for local communities than other natural resource industries just because producing seaweed can be innately low-input. Indeed, although a kelp-economy certainly has high potential for local community and ecological benefits (e.g., through restoration), these are actively facilitated or dissuaded by regional political and social conditions. Hence, this research ground-truths recent work which tempers the expectation that seaweed will be an equitable, climate and biodiversity panacea, instead calling for deeper evaluation of the social, economic, and environmental conditions surrounding the industry (Nishihara et al. 2025; Reidlinger 2025). To approach the kelp-economy’s Blue Economic potential, there remain challenges and opportunities for organizations to steward and utilize kelp in ways that are regenerative to both nature and society.

Declarations

Data Statement

Data is available in the Supplementary Material.

Competing Interests

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Data Availability

Data is available in the Supplementary Material.

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Figures

State of North American Kelp Mariculture

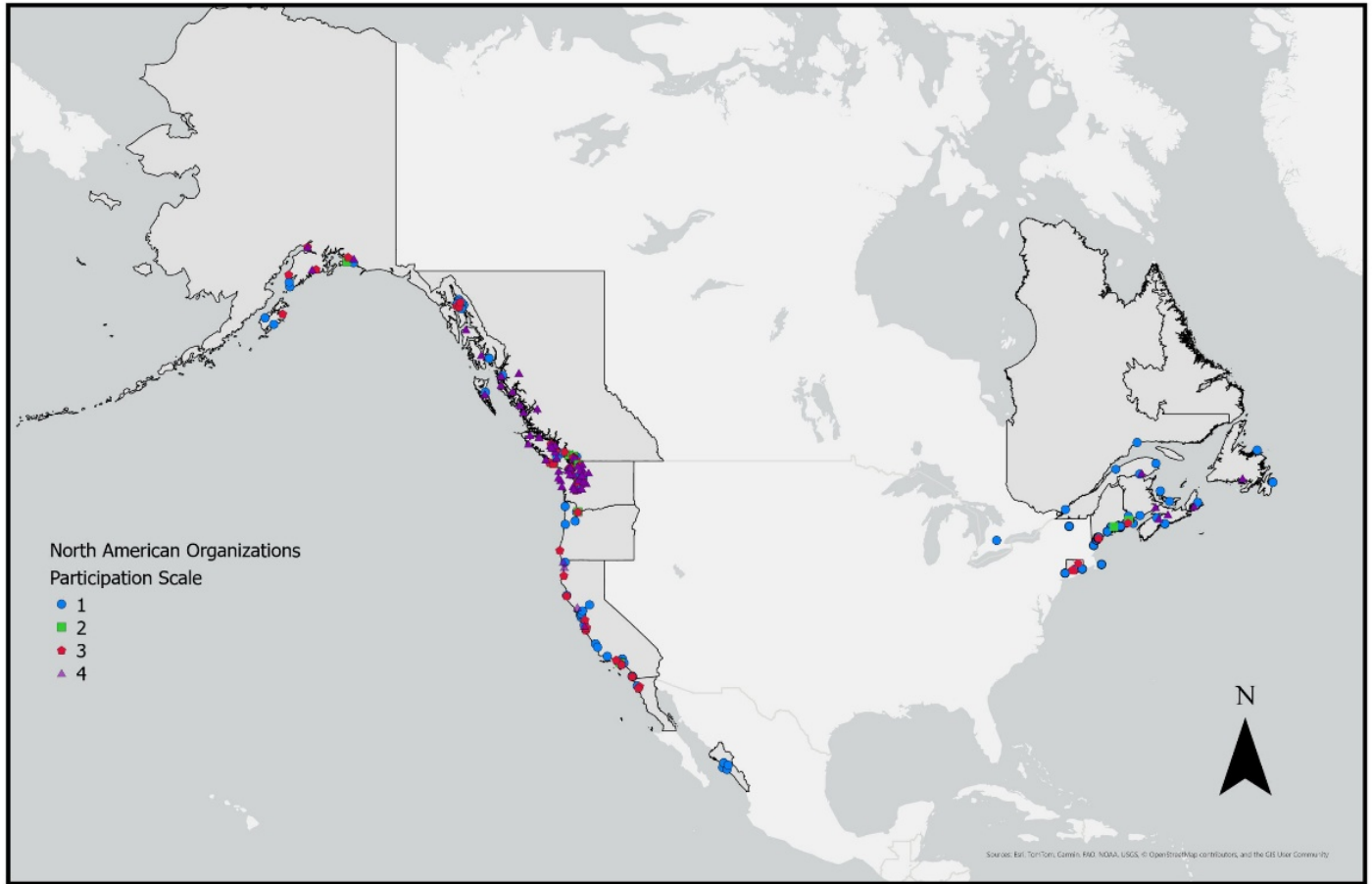


Figure 1

Map of kelp-economy organizations in North America. Outlined states and provinces represent those with ≥ 3 organizations which were carried to the next stage of the analysis. To see regions in more detail, see the Supplementary Material.

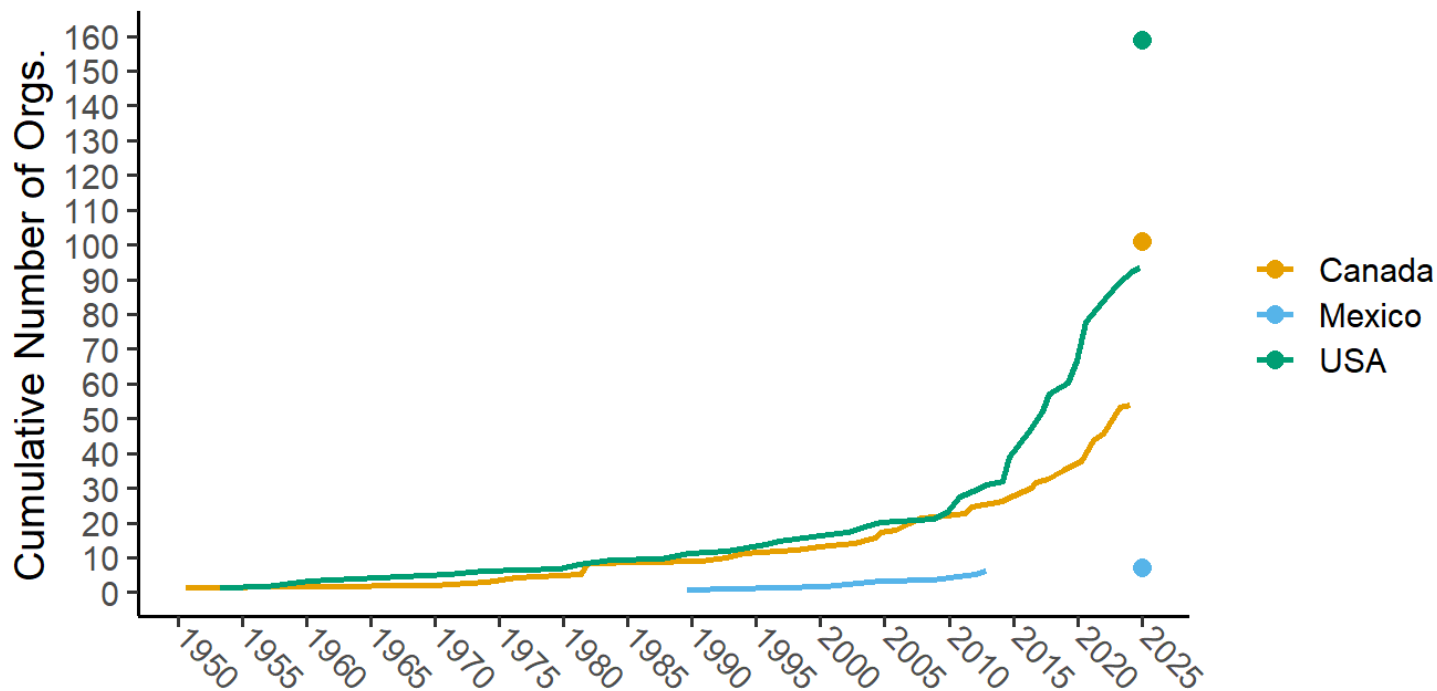


Figure 2

Cumulative number ($n = 267$) of kelp organizations in Canada (yellow), the USA (green) and Mexico (blue) through time. Points denote the total number of active organizations in 2025 as not all organizations provided a date of establishment.

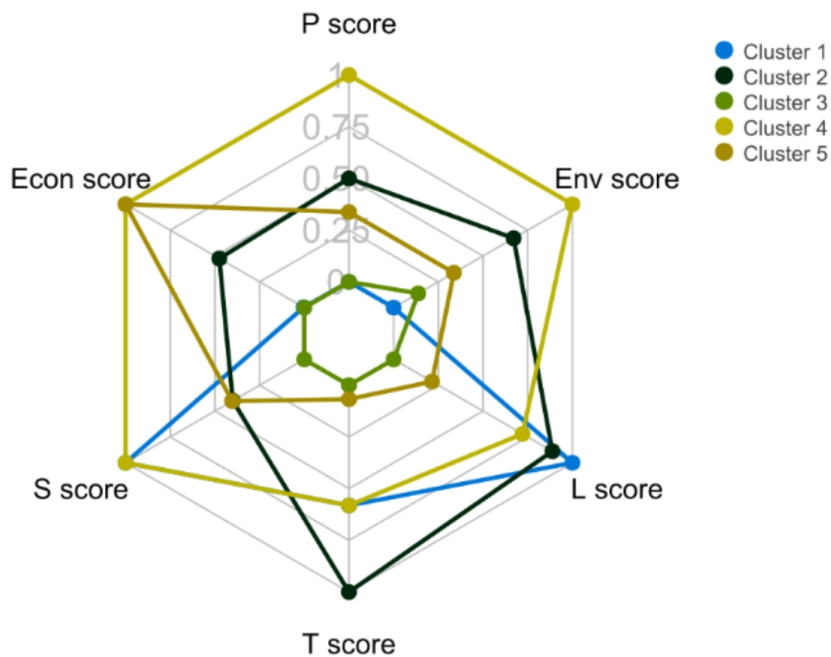
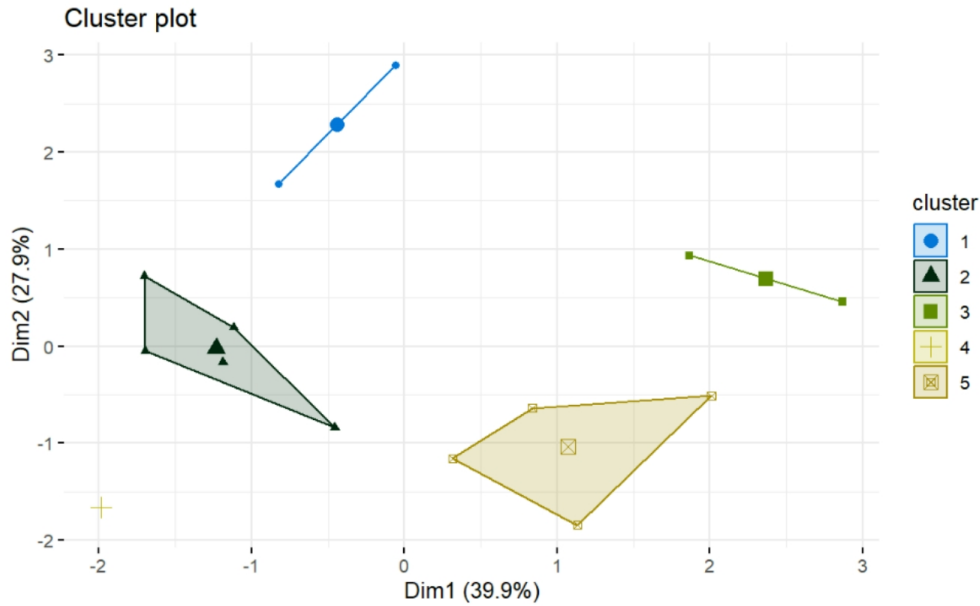


Figure 3

(top) regional clusters (cluster 4 appears in the bottom left corner) of evaluated states/provinces (n=14) based on their k-means for PESTLE scores; and (bottom) average PESTLE scores across clusters, scaled from 0-1 (grey values). Points further from the center represent higher PESTLE scores. The following state/provinces make up each cluster: 1= Sinaloa, Baja California; 2 = New Brunswick, Newfoundland,

Prince Edward Island, Nova Scotia, Quebec; 3 = Connecticut, Oregon; 4 = British Columbia; 5 = Alaska, California, Maine, Washington.

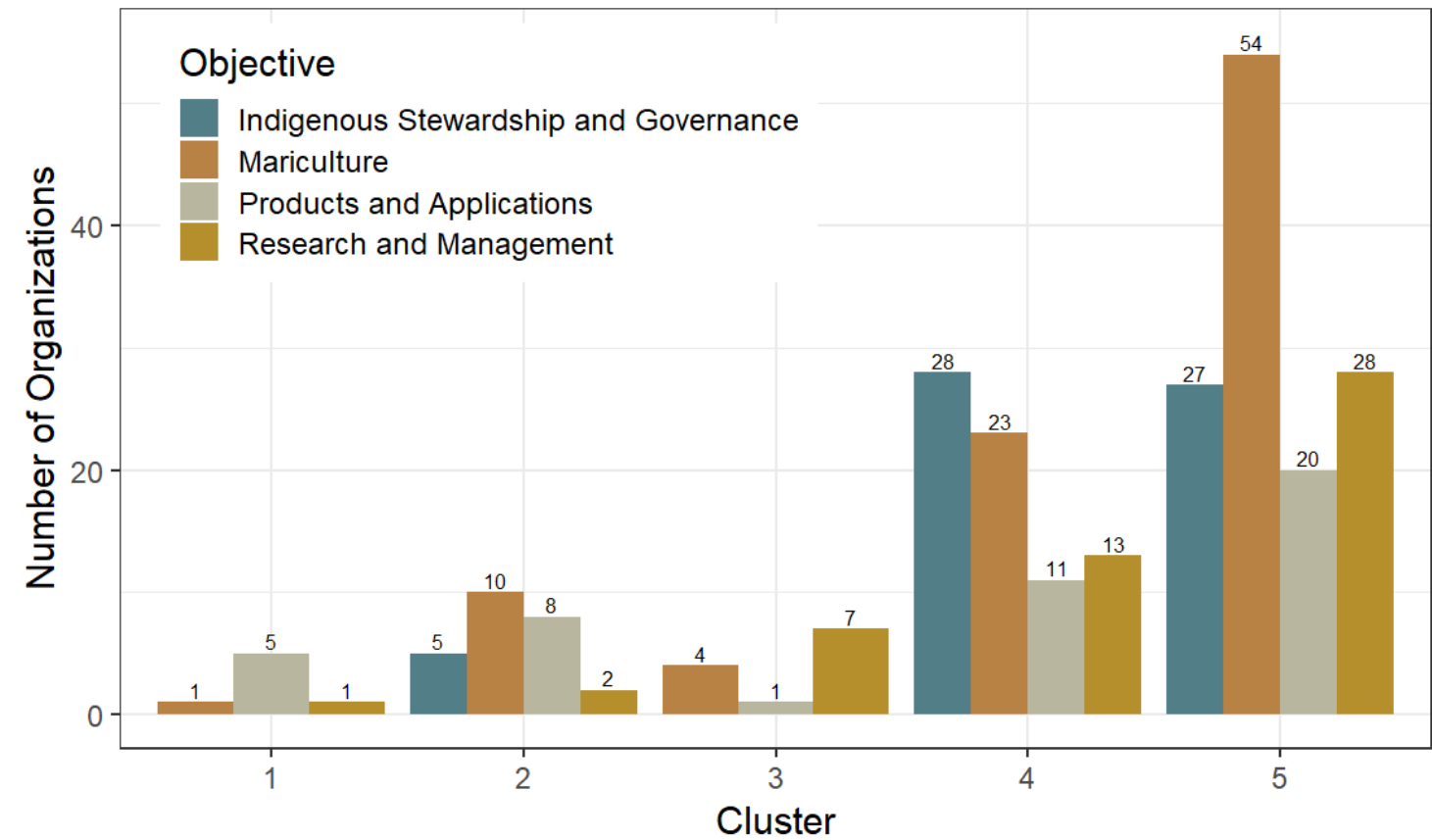


Figure 4

The distribution of objectives across clusters. The objective category for ‘mariculture’ represents the spectrum of harvest, farming, seed propagation, and restoration. The following state/provinces make up each cluster: 1 = Sinaloa, Baja California; 2 = New Brunswick, Newfoundland, Prince Edward Island, Nova Scotia, Quebec; 3 = Connecticut, Oregon; 4 = British Columbia; 5 = Alaska, California, Maine, Washington.

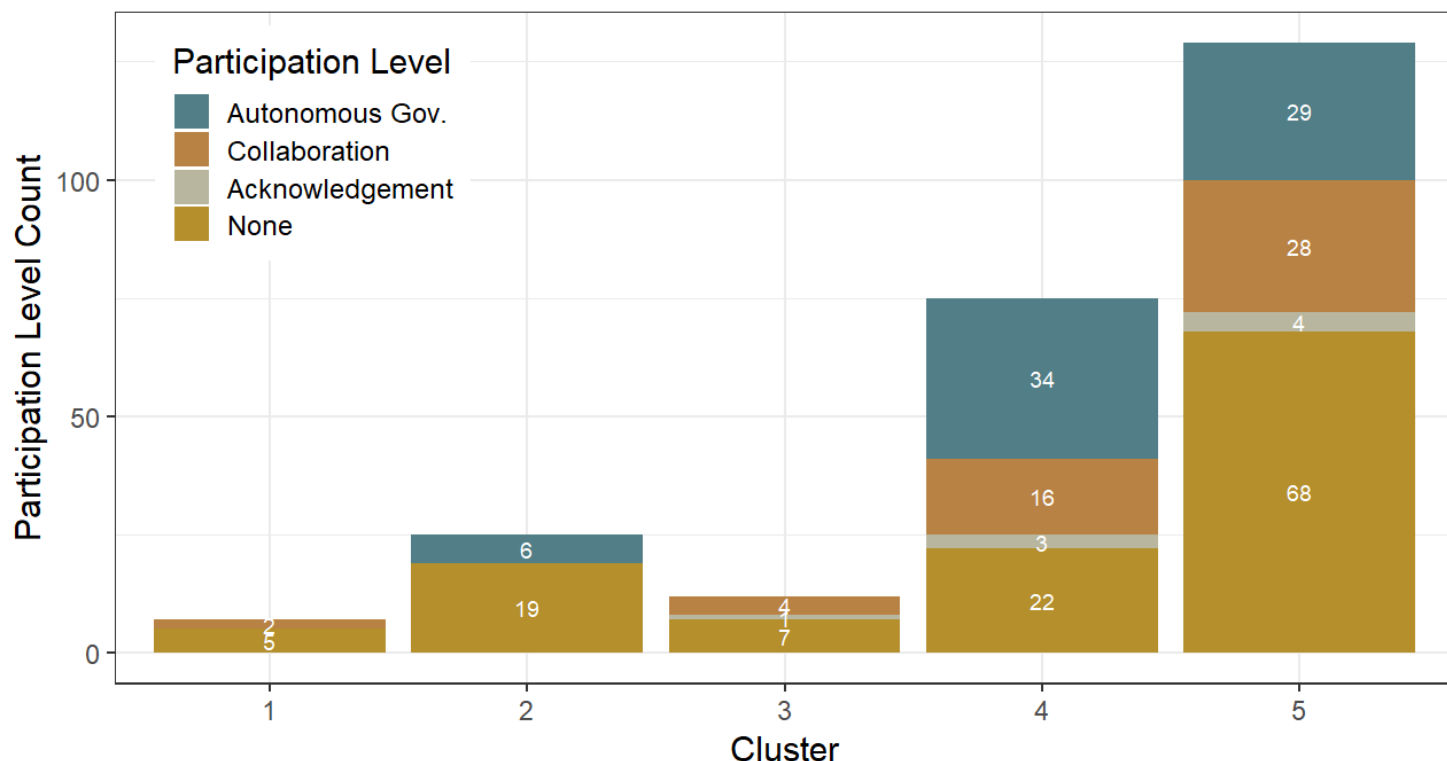


Figure 5

The distribution of participation scores across clusters. Cluster 4 had a significantly higher mean participation score than clusters 2 or 5 ($p < 0.00$). The following state/provinces make up each cluster: 1 = Sinaloa, Baja California; 2 = New Brunswick, Newfoundland, Prince Edward Island, Nova Scotia, Quebec; 3 = Connecticut, Oregon; 4 = British Columbia; 5 = Alaska, California, Maine, Washington.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialKelponomicsGutzmannetal.docx](#)
- [KelponomicsGutzmannetal.2026Database.csv](#)