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Finding common ground: Assessing the Co-location potential of California's blue food and clean energy sectors

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ABSTRACT

California is striving to expand its 'blue economy' to meet growing demand for marine resources, including seafood and renewable energy. As a result, there has been a growing competition for ocean space. Co-location, multiple sectors (e.g., aquaculture and renewable energy) operating in the same ocean space at the same time, is one potential approach that can reduce competition amongst stakeholders. However, there has been limited quantitative investigation into the potential of co-located systems along the California coast. Using a combination of observation and model outputs across four ocean sectors (aquaculture, wave energy, wind energy and wild capture fisheries), we quantify the co-location suitability of at least two of the sectors along the California coast (0.0404° resolution) by calculating a Co-location Suitability (CLS) score (0 – no suitability to 1 – perfect suitability). We find a clear trend of higher CLS scores in the waters offshore of Northern California, but the steep bathymetry limits the potential for aquaculture and wave production based on current technological and/or cost constraints. Notably, we find climate extreme thermal events, (i.e., marine heatwaves) will likely exacerbate regional differences in suitability with typically cooler Northern regions performing better. This research provides an initial framework for evaluating co-location potential and its ability to increase the efficiency of marine space-use in crowded seascapes in California waters and beyond.

1. Introduction

As demand for food and energy intensifies with a growing human population and a changing climate, the marine environment is becoming a necessary part of creating the needed supply (Jouffray et al., 2020; Gephart et al., 2021; Backwell et al., 2024). Global ocean governing bodies have accelerated development of the 'blue economy', which refers to the socially and environmentally sustainable expansion of ocean development (Bennett et al., 2019; Smith-Godfrey, 2016). Seafood (aquaculture and wild capture) and clean energy (wind, wave, and tidal) production are key sectors in a growing blue economy but are largely being developed and managed independently of each other, which can lead to ocean crowding, conflict and inefficient use of marine resources (Buck et al., 2008; Gimpel et al., 2015; Lester et al., 2018a). Co-location of marine activities – defined as ocean multi-use that "takes place in the same place and at the same time" (Type 3; Schupp et al., 2019) – may offer an opportunity to increase efficiency and support a more sustainable use of marine space. Indeed, a major component of marine spatial planning (MSP) – a decision-making approach that seeks to reduce the conflicts and impacts often found in traditional marine sector planning – is 'making space' (Lester et al., 2018b). A departure from single-sector planning, MSP strives to integrate multiple sectors for sustainable and long-term ocean planning (Santos et al., 2019). Co-location is emerging as part of the solution to the MSP issue of space in some regions, including the North Sea (Buck et al., 2004; Schupp et al., 2019; Gonzales et al., 2024). Unlike the North Sea, however, quantitative assessments of co-location's potential are largely absent for most areas around the world (Gonzales et al., 2024), including the United States (U.S.). Despite this, quantitative assessments are regarded as essential for more rigorous and sound MSP (Lester et al., 2020). Some U.S. specific quantitative research has recently emerged on the East coast (Hasankhani et al., 2023; Calhoun et al., 2025; Ewig et al., 2025), highlighting the challenge of siting for co-location without impacting other ocean activities (Ewig et al., 2025). Although methodologically informative, these studies limit their evaluation of co-location potential to two sectors. Given that the West coast is developing a diverse suite of blue economy sectors (Morris et al., 2021; OPC, 2021; Freeman et al., 2022; BOEM, 2025), evaluations that capture more than two sectors are essential for understanding

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co-location potential within its dynamic regional context, especially at this initial planning stage. Co-location assessments for the West coast, however, remain limited and a potential missed opportunity to better plan for our food and energy futures.

California – home to a growing population of 38.9 million people (United States Census, 2024) and roughly 1100 miles of coastline (OPC, 2020) – is focusing on the expansion of clean energy and potentially marine aquaculture in ocean spaces where incumbent sectors (e.g., wild capture fisheries) have competing interests. In the last decade, a total of 373,267 acres of federal waters off the coast of California (<1 % of California's federal waters) have been leased for offshore wind development (BOEM, 2025) to meet national and state renewable energy goals (SB 100, 2018; The White House, 2021; Zhang et al., 2022). Similarly, wave energy has been regarded in the United States as a form of marine renewable energy that could deliver needed clean power to the grid (LiVecchi et al., 2019) and a pilot project has been deployed off of the California coast (CalWave, 2022). Simultaneously, momentum is gaining towards planning for sustainable expansion of marine aquaculture, including identification of the federal Aquaculture Opportunity Areas (AOAs) in the Southern California Bight (SCB) (Morris et al., 2021; OPC, 2021). In addition, the California coast has highly productive waters, resulting in a commercial fishing industry that landed over 100 million pounds of seafood in 2023 alone (CDFW, 2025) and one of the largest marine protected area networks in the world (CDFW, 2022). Although California currently lacks a formal and comprehensive marine spatial plan (Lester et al., 2021), as it moves forward with these initiatives to expand its blue economy, the state will have to rely on some level of MSP as a means of ensuring a sustainable use of ocean resources.

MSP efforts would be particularly useful for California's marine aquaculture industry. California consumes more seafood by total volume than any other state in the United States (Love et al., 2020; Fong et al., 2022). Despite this, local aquaculture production, including marine, remains limited relative to seafood consumption in the state (Fong et al., 2024a), leading to a state-led priority for expanding sustainable aquaculture (OPC, 2021); this is in parallel to federal efforts to provide pathways for offshore aquaculture in California (Morris et al., 2021). Most of California's aquaculture operations are either nearshore or inland (CDFW, 2020; Fong et al., 2022). Currently only one open-ocean (i.e., exposed) and one offshore (>3 nm from shore) aquaculture farm exist in California (see Buck et al., 2024 for definitions): Santa Barbara Mariculture, a small 25-acre farm off the coast of Santa Barbara that cultures blue mussels (Fujita et al., 2023) and Ocean Rainforest, a pilot seaweed farm expected to expand to a 2000-acre farm off the coast of Ventura, CA (USACE, 2024). Notably, both ocean aquaculture operations are situated in the Southern California Bight. Research has shown that MSP frameworks can help evaluate regions for economically and environmentally sustainable aquaculture development in the U.S. (Morris Jr et al., 2025) and southern California (Lester et al., 2018b). Additionally, further bioeconomic modeling has been conducted to assess the impact of mean annual changes in environmental conditions on cultured bivalve growth and production across southern California (Sainz et al., 2019). But there is a dearth of understanding surrounding how co-located aquaculture would align with modeled single-sector aquaculture production along the entire California coast, and how extreme oceanographic conditions (e.g., marine heatwaves) could alter the spatial patterns of production.

Marine aquaculture in the U.S. will be affected by climate change (Fong et al., 2024b), and global models have projected bivalves may be particularly vulnerable (Froehlich et al., 2018; Free et al., 2022a). Most studies have focused on average changes, but the growing threat of marine heatwaves (MHWs) – acute, anomalously warm increases in ocean temperature – have been linked to disruptive and potentially long-lasting negative social and ecological consequences (Frölicher and Laufkötter, 2018; Wei et al., 2021; Free et al., 2023). Understanding the impacts of MHWs is especially important given that these warming events are expected to increase in length, frequency, and extent (Oliver et al., 2018; White et al., 2023). In California, one of the most intense MHWs ever recorded hit the northeast Pacific Ocean in 2014–2016, widely known as "the blob". Since "the blob", researchers retrospectively have sought to understand its impacts on marine ecosystems and resiliency (Cavanaugh et al., 2019; Rogers-Bennett and Catton, 2019; Freedman et al., 2020), including substantial evidence of the negative impact on wild capture fisheries (Jardine et al., 2020; Fisher et al., 2021; Samhouri et al., 2021; Free et al., 2023). The effects of extreme warming on aquaculture are thus far unstudied in the region (White et al., 2023). However, recent research has projected the effect of warming waters on aquaculture in California, finding that southern latitudes will likely suffer from warming waters more than northern latitudes and that bivalves, on average, appear less resilient to climate change compared to finfish and seaweeds (Fong et al., 2024b). Thus, extreme warming in California is likely an important driver of change to the food system that should be considered in the planning of its development and expansion, such as prioritizing species that perform well under warmer conditions in specific regions (Fong et al., 2024b). In fact, the need to account for climate in California's aquaculture industry was echoed by aquaculture practitioners in the state (Ward et al., 2022). Leveraging historical data to evaluate how changing average and extreme oceanographic conditions might impact aquaculture production – particularly that of climate vulnerable taxa, such as bivalves – is important for future 'climate smart' marine aquaculture planning (Clements and Chopin, 2017; Free et al., 2019; Fong et al., 2024b).

In this study, we combine a suite of California specific model outputs and data for the clean energy and aquatic food sectors – both sectors garnering more attention in California's growing blue economy – to assess the ability of multiple industries, especially marine (bivalve) aquaculture, to operate in the same ocean space, at the same time along the California coast. Specifically, we create a Co-location Suitability (CLS) Model to assess production of four ocean sectors (offshore wind, wave, marine aquaculture, and wild fisheries) and identify regions along the California coast that maximize production of emerging industries (i.e., offshore wind, wave, and marine aquaculture) while minimizing the overlap with the incumbent sector (i.e., wild capture fisheries). In doing so, we employ the Type 3 definition of "co-location" outlined by Schupp et al. (2019). While this definition only requires a moderate to low level of connectivity between users, it still requires parties to work together to "actively facilitate the presence of one another" in shared spaces (Schupp et al., 2019). We also model the influence of MHWs on marine aquaculture, comparing the difference in spatial growth patterns of farmed mussels along the coast to better understand how climate might affect co-location potential. By providing this modeling approach of evaluating spatial overlap of marine sectors, we hope to highlight the potential for compatibility between ocean-users and its role in planning for a more efficient and sustainable blue economy in California's future.

2. Methods

We combine data from four distinct ocean sectors (marine aquaculture, wave energy, offshore wind energy and wild capture fisheries) to examine areas of spatial and temporal overlap across the entire extent of California waters, and thus co-location potential (Fig. 1). Notably, this framework is similar to approaches taken in other co-location suitability work (e.g., Gimple et al., 2015), some of which find that suitability mapping is a useful tool in reducing uncertainties in MSP (Maldonado et al., 2022). While we do not conduct economic modeling in this study, basic economic information for all sectors is available to provide additional context (Fig. S2, Table S2, Table S3).

2.1. *Spatial resolution*

Datasets from the four ocean sectors in this study were collected at varying resolutions (Table 1). Given that the wave energy layer has the coarsest resolution (Table 1), this cell size is used for the model output

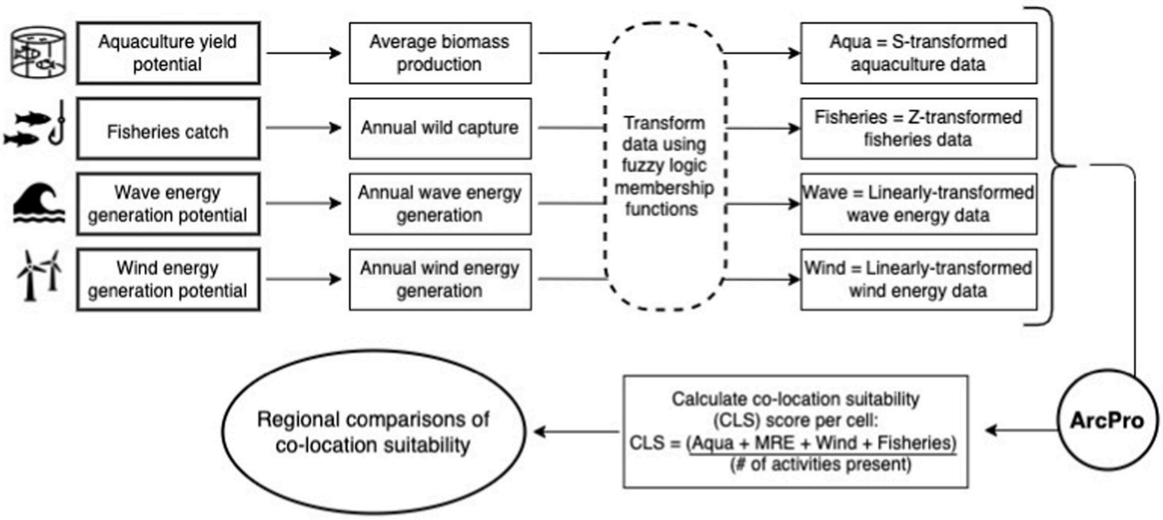

Fig. 1. Co-location suitability methodological framework.

Table 1
Variables and data sources for ocean sectors. The * indicates a conversion from meters to degrees, calculated at the equator.

Sector	Source Type	Variable	Resolution	Source/ Reference
Aquaculture	Dynamic model	Annual bivalve biomass production (kg/yr)	0.0300°	Kooijman (1986); Lester et al. (2018b)
Fisheries	Observed data	Average annual catch (lbs)	0.0033°	Free et al. (2022b)
Wave Energy	Observed data	Omnidirectional Wave Power (kW/m)	0.0404°	Klise et al. (2020)
Offshore Wind Energy	Discrete model	Annual Wind Energy Generation (MWh)	0.0023°*	Wu et al. (2023)

(ESRI, 2025). While some situations (e.g., high data certainty) allow for finer resolutions of combined layers (Riley et al., 2024), the data in these layers are too variable to meet these assumptions (Arnone et al., 2016). Our model output extent ranges −117.03°–126.45° longitude and 31.21°–42.09° latitude (decimal degrees).

2.2. Production models and data

2.2.1. Aquaculture

Aquaculture is demonstrated by modeling annual biomass production potential (kg yr^{-1}; Fig. 2) of the Mediterranean mussel (*Mytilus galloprovincialis*) using a dynamic energy budget (DEB) model (Kooijman, 1986; Muller and Nisbet, 2000; Rosland et al., 2009; Sarà et al., 2012). The Mediterranean mussel (*M. galloprovincialis*) is a widely present and commercially important aquaculture species in California (California Sea Grant, 2025), making it an appropriate taxa for this evaluation. The DEB modeling approach is based on the work of Kooijman (1986), and more recently expanded upon by Lester et al. (2018b) and Sainz et al. (2019) in California. We chose this model based on the precedence of its application in California waters (Lester et al., 2018b; Sainz et al., 2019), but other aquaculture models could be employed in future studies to compare model bias (e.g., the FARM model; Ferreira et al., 2007). The DEB model considers the metabolic performance of a species – in our case *M. galloprovincialis* – to evaluate the growth and survival of seeded mussel lines, estimating the amount that can be produced for harvest in a given year based on monthly growth and survival. *M. galloprovincialis* species was chosen to represent aquaculture growth potential in this assessment because bivalves are frequently considered for co-location with other ocean activities (Gonzales et al., 2024) and the Mediterranean mussel is a permitted, commercially grown species in California (Lester et al., 2018b).

The DEB model is largely driven by food availability (i.e., particulate organic carbon), but also accounts for oceanographic conditions (current speed, sea surface temperature, mixed layer depth, and particulate organic carbon) and is scaled up to farm dimensions. Modeled mussel farms were assumed to consist of 100 lines, each with 13,000 vertical feet per line and 100 mussels per foot per line. Each modeled farm covered 4 km^2, based on the dimensions laid out by Sainz et al. (2019) and Lester et al. (2018b). Depth of the farms are constrained to the mixed layer depth (i.e. the depth of the thermocline; mean ± SD = 16.279 ± 7.206 m) in that region. While mortality due to inhabitable temperatures and food is considered, other sources of mortality (e.g. predation) are not accounted for in the model under the assumption this is eliminated through farming interventions. Monthly measurements of input data (i.e., particulate organic carbon, current speed, temperature, mixed layer depth) are compiled for 18 months, making one full mussel harvest cycle. A full table of parameters is available in Table S1, many of which were gathered from the (Kooijman, 2010; AmP, 2024).

$$M\ (gC) = MV + ME + MR \quad \text{(Eq. 1)}$$

$$TM\ (kg) = Indiv{*}M/(1000{*}C) \quad \text{(Eq. 2)}$$

Total biomass of an individual mussel (M) in grams of Carbon (gC) is calculated by adding the structural biomass (MV), reserve biomass (ME), and reproductive biomass of the mussel (MR) (Eq. (1)). Here, MV, ME, and MR represent the three categories of biomass that comprise the total biomass of an individual mussel, measured in gC for its useful interpretation of metabolic success (Kooijman, 2010). The total biomass of the simulated farm (TM) in kilograms (kg) is determined by multiplying the number of mussels (Indiv) by the modeled biomass of an individual mussel (M), divided by the proportion of Carbon per mussel (3.4 % C; Haamer, 1996) (Eq. (2)). This model is not applied to marine regions along the California coast that are >200 m deep, because the industry cannot currently be economically viable in locations that exceed this depth (Gentry et al., 2017). Using MATLAB Version R2024b, production is modeled at 5000 randomly sampled points in the study region and interpolated to the full study region. The detailed modeling assumptions and code are provided on Zenodo (https://zenodo.org/records/17545767).

Sensitivity tests of the model are run with changes to assumed

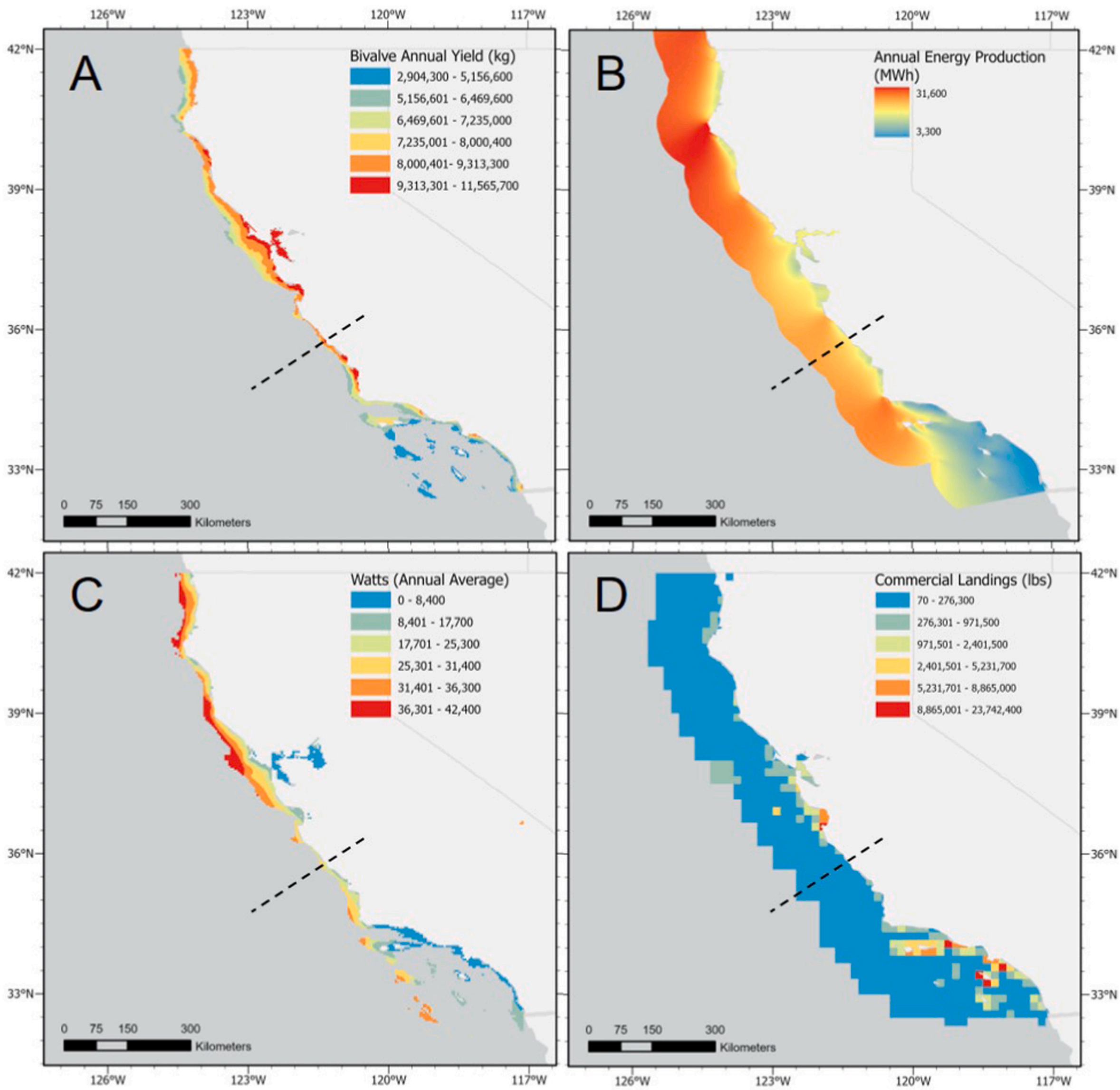

Fig. 2. Raw production data of ocean sectors that were used in the Co-location Suitability Model: A) aquaculture production (kg/yr), B) offshore wind generation (MWh), C) wave energy (kW/m), and D) commercial fisheries catch (lbs/yr). All production is reported as value per cell and cell sizes are reported in Table 1. The boundary between Northern and Southern California is delineated by the black dashed line.

natural mortality levels and the Arrhenius temperature parameter – a metric that describes the relationship between temperature and an organism's metabolic rate – to gauge consistency in results (Fig. S1). These two parameters were selected for sensitivity testing because of their impact on mussel growth. Modeled mussel production was also examined in response to warming waters, which is described more below.

2.2.2. *Wave energy*

Wave energy yield is calculated using omnidirectional wave power output data (kW/m; Fig. 2) derived from National Marine Energy Atlas (NREL, 2024), averaged from 2008 to 2010, and spatially applied to ocean waters off of the California coast, accounting for regional wave characteristics (i.e., significant wave height, wave period, bathymetry). The wave energy converters used in this calculation were single-body point absorbers with a water plane area of 12.57 m^3. These devices have a maximum power generation of 2030 kW (OpenEI, 2022). Using these metrics, mean annual wave energy generation is calculated for each cell, accounting for these varying sea-states (Kofoed and Folley, 2016). Similar to aquaculture, these data were constrained to regions that are ≤200 m deep, given the precedent of the industry to stay closer to shore, especially given the nascent stage of the industry. Production is modeled at 10,000 randomly sampled points in the study region and Kriging interpolation is then employed across the study region.

2.2.3. *Wind energy*

Offshore wind generation potential (MWh) is spatially modeled by first calculating the capacity factors for the California coast (Fig. 2), using Weibull parameters representing the seven-year average wind speed distribution at 100 m hub height (De Medeiros et al., 2015; Wu et al., 2023). The capacity factor is the ratio of the actual electricity generation to the maximum possible generation over a period of time and is a standard metric of a power plant's electrical generation performance. The turbines used in this calculation have a rated capacity of 7 MW, and we applied a wake effects loss of 8.9 % based on simulations performed in the System Advisory Model, in addition to availability (5.5 %), turbine performance (3.95 %), and environmental (2.39 %) losses (Wu et al., 2023). Mean annual wind power generation per unit area is calculated using capacity factors and assuming a capacity density of 5.2 MW/km2 (Borrmann et al., 2018). Therefore, changes in the wind generation potential (MWh) are driven by the difference in calculated capacity factors. Spatial calculations are limited to 50 nm offshore, due to data availability and the fact that transmission costs increase in proportion to the distance from shore.

2.2.4. Fisheries

The fisheries variable is represented by total annual catch (lbs/yr) across all finfish and invertebrate taxa, averaged annually over the years 2000–2020 (Miller et al., 2017; Wang et al., 2022; Free et al., 2022b, Fig. 2). Data are reported as landings – the amount of fish caught and brought to shore for sale and processing – and housed by California's Department of Fish and Wildlife. Landings were originally reported at a 10′x10′ resolution for nearshore blocks and up to 30′x30′ resolution for offshore blocks (CDFW, 2025). However, in processing, these data had to be resampled to a 0.0033° resolution to create a raster that could be combined with the other raster layers in this study. Regions that depict historically higher amounts of total landings are scored as being less optimal for co-location because these regions are considered valuable fishing grounds. We acknowledge that in some cases co-location is studied in scenarios where there may be higher levels of fishing, such as in the work presented by Stelzenmüller et al. (2016) in the North Sea. Of course, the amount of fishing is context dependent and will be relative to the region of study. Nonetheless, Stelzenmüller et al. (2016) reported several challenges and limitations of 'high fishing' co-location, such as safety and licensing regulations. Considering these challenges and the social dynamics of California's fishing industry (Ordoñez-Gauger et al., 2018), we instead chose to assign higher CLS scores with relatively lower levels of fishing for our region, based on total landings in a given spatial cell. Thus, in optimal CLS scenarios fishing still occurs, but at comparatively lower levels to reduce incumbent conflict with the other industries considered in this study.

2.2.5. Additional space uses

This analysis also incorporates fixed space uses that should be accounted for when considering ocean development off the coast of California. The spatial footprints for Southern California Bight Aquaculture Opportunity Areas, California's federal wind lease zones, state Marine Protected Areas, and National Marine Sanctuaries are all visually overlaid to the final model output and qualitatively assessed.

2.3. Accounting for marine heatwaves

To better account for varying physical conditions – which can provide insights into the potential siting consequences of climate change in a given region – we model bivalve production under two thermal scenarios: prior to and during an extreme marine heatwave, 'the blob'. Modeling bivalve production prior to the 2014–2016 Pacific 'blob' consists of using 18 months of physical input data (i.e. SST, POC, mixed layer depth, and current velocity), ranging from October 2012 through February 2014. Physical data spanning October 2014 through February 2016 is input to model bivalve production during the 'blob'. Average outputs from both scenarios across the full extent of the region are compared using a paired Mann-Whitney *U* Test and evaluated for spatial differences.

2.4. Transformations and suitability calculation

All input data are transformed to be on a scale of 0–1. Wind and wave energy are both transformed linearly, which agrees with precedence within the energy sectors (Kabeyi and Olanrewaju, 2023). This transformation indicates that a higher production output of wind or wave energy would be closer to 1, and lower output would be closer to 0. Aquaculture and fisheries production data are transformed using S-shaped (Eq. (3)) or Z-shaped (Eq. (4)) fuzzy logic membership functions, respectively (Fig. 1) (Vafaie et al., 2015; Theuerkauf et al., 2019; Morris et al., 2021). In this project, S-shaped fuzzy membership curves are applied to the aquaculture to reflect that increased production will result in a higher CLS score. While Z-shaped fuzzy membership curves are applied to the fisheries sector, indicating that increased production results in a lower contribution to the CLS score (i.e., less overlap is favorable). In these functions, x is the input value for each sector variable and a and b parameters define the functional shape of the normalized curve, either S-shaped or Z-shaped. In an S-curve, parameter a is equal to the minimum value of that sector's production and parameter b is equal to the maximum production value, and vice versa for the Z-curve. CLS score is evaluated by averaging the transformed quantities in each cell (Fig. 1; Eq. (5)). CLS scores are only calculated in regions with data available for two to four of the sectors in a particular spatial cell (i.e., score is not calculated in regions that only have data for one of the four sectors). The resulting CLS scores are within a range of 0–1, with 1 being perfectly suitable for co-location (at least two sectors) and 0 representing no suitability.

$$f_s(x;a,b) = \begin{cases} 0, x \leq a \\ 2\left(\frac{x-a}{b-a}\right)^2, a \leq x \leq \frac{a+b}{2} \\ 1 - 2\left(\frac{x-b}{b-a}\right)^2, \frac{a+b}{2} \leq x \leq b \\ 1, x \geq b \end{cases} \quad \text{(Eq. 3)}$$

$$f_z(x;a,b) = \begin{cases} 1, x \leq a \\ 1 - 2\left(\frac{x-a}{b-a}\right)^2, a \leq x \leq \frac{a+b}{2} \\ 2\left(\frac{x-b}{b-a}\right)^2, \frac{a+b}{2} \leq x \leq b \\ 0, x \geq b \end{cases} \quad \text{(Eq. 4)}$$

The CLS score is calculated for each cell and regional comparisons are made based on final combined values (Fig. 1). Note, co-location scoring in this analysis assumes equal weight to all sectoral contributions in a given cell. We did this because the goal of this paper is to evaluate co-location as a tool across multiple sectors, as opposed to giving priority to any single sector. Regions with collections of high CLS scores are considered to have more potential for co-location of ocean sectors compared to regions with low CLS scores because it reflects suitability between sectors with high productivity potential. Spatial cells without data for all four sectors exclude the missing sector from the CLS score calculation. Kriging interpolation is used to estimate the values between sample points for the aquaculture and wave energy inputs in ArcPro 3.3.2. A Mann-Whitney *U* Test is conducted to compare scores across regions (North vs South) and identify regions that are significantly different from one another, given our error is not normally distributed. Linear regressions are used to examine the relationship between CLS score and latitude/longitude and establish basic trends in directionality. These analyses are completed in R version 4.2.2 and RStudio Version 2024.12.1 + 563. All scripts and code are publicly available on Zenodo (https://zenodo.org/records/17545767) and the assiociated GitHub repository.

$$CLS = \frac{(\text{Aqua} + \text{MRE} + \text{Wind} + \text{Fisheries})}{(\#\text{of activities present})} \quad \text{(Eq. 5)}$$

2.5. Model output scenarios

We evaluated CLS under two scenarios: shallow (primary output) and deepwater. Given that both wave energy and aquaculture sectors are limited to a depth of ≤200 m, only production estimates for wind energy and fisheries are captured in the deeper waters off of California. Therefore, we chose to focus this study on shallow waters (≤200 m) to be able to draw conclusions about co-location potential across all four ocean sectors being evaluated. The deepwater scenario, using the full dataset from the fisheries and offshore wind sectors, was produced in a post-hoc evaluation to provide visualization of areas of compatibility for sectors that can feasibly operate in waters deeper than 200 m.

3. Results

Production varies across sectors and regions, with higher average values for marine aquaculture, offshore wind energy, and wave energy in the North and higher wild capture fisheries values in the South (Fig. 2). Wave energy, wind energy, and marine aquaculture all show 1.3x – 1.7x greater production in the North compared to the South. Moreover, fisheries production is almost 3x higher in Southern California, as compared to Northern (Table 2). Across the entire coast, aquaculture production output is highest in the nearshore shore (<3 nm) (mean ± SD = 7,658,600 ± 1,904,800 kg yr^{-1} per cell), with particularly high values in the San Francisco Bay (range: 9,949,600–11,565,600 kg yr^{-1}, mean: 10,758,900 ± 426,800 kg yr^{-1}) (See Table 1 for cell sizes reported as spatial resolution). This differs from the outputs for offshore wind and wave energy production, which are stronger in areas farther from shore (>3 nm from shore, max = 31,600 MWh yr^{-1} per cell and 42,400 Watts yr^{-1} per cell, respectively) and an order of magnitude lower in protected waters (min = 3300 MWh yr^{-1} per cell and 0 Watts yr^{-1} per cell, respectively), such as those in the San Francisco Bay and Southern California Bight (Table 3).

3.1. Co-location Suitability Model output trends

When we combine data layers into the Co-location Suitability (CLS) Model, all four sectors are captured in the coastal region ≤200 m deep, covering 29,500 km2 of ocean along the California coast (Fig. 3A) – an area roughly the size for the state of Massachusetts. The total CLS scores range from 0.040 to 0.988, with the average collective score trending toward only moderate co-location suitability (mean ± sd = 0.486 ± 0.155; Table 4). Within this range, CLS scores in Northern California (0.570 ± 0.079) are significantly higher (Mann-Whitney *U* test, p-value <0.05) than those in Southern California (0.349 ± 0.153). Reflecting this pattern and the individual sectoral production results, high (i.e., above the average) CLS scores are found in the waters North of San Francisco (0.388–0.829, mean: 0.600 ± 0.062), and low (i.e., below the average) scores in the Southern California Bight (0.040–0.721, mean = 0.305 ± 0.140) (Fig. 3A). The maximum CLS score is found in the protected, shallow waters of the San Francisco Bay (max = 0.988), largely driven by modeled bivalve production in this region.

A full deepwater scenario of the CLS model is also calculated post-hoc (Fig. 3B) but given the siting limitations of the aquaculture and wave energy industries this version only includes the inputs from wind energy and fisheries in waters deeper than 200 m. Similar to the shallow scenario, the deep-water scenario reflects a collection of high CLS scores in northern waters, particularly offshore.

As clear from the region trends, the CLS scores have a strong correlation with longitude and latitude. There is an average increase in CLS of 0.040 for every decimal degree increase in latitude (mean = 0.040*; 95 % C.I. = 0.039–0.042).* There is a negative correlation between longitude and CLS score (mean = −0.062; 95 % C.I. = −0.064 to −0.060), with CLS score increasing farther offshore (Fig. 4). The linear relationship provides a simplified average and directionality across a large space gradient.

California has a variety of additional space uses that will influence co-location suitability (Fig. 5). Approximately 1500 km^2 of federal waters offshore of California have already been leased for offshore wind (not co-located at present). In the deepwater co-location scenario, the area covered in these leases has an average CLS score of 0.660 ± 0.083. However, the deepwater CLS model accounts for only offshore wind and fisheries at this location due to the depth constraints to the other sectors. Thus, the values more reflect the comparatively good placement of wind that avoids wild capture hotspots in the Southern reaches of state waters. California also has a large network of protected waters and the National Marine Sanctuaries off the coast, totaling 43,200 km^2 of ocean space that will likely experience little to no development and, thus, have limited co-location potential. Lastly, the AOA in the Southern California Bight is a fraction of the other areas and notably resides in some of the least productive waters for aquaculture and co-location in the state. Given the uncertainty in the above-mentioned areas, which could promote or constrain co-location, we did not include them in our calculations but provide the overlap for reference (Fig. 5).

3.2. Aquaculture in warming waters

Modeled aquaculture production varied significantly (Mann-Whitney *U* test, p-value <0.05) in response to changing physical dynamics, specifically from 2012 to 2014 (prior to a marine heatwave) to 2014–2016 (during a marine heatwave) (Fig. 6). During the Pacific Marine Heatwave – also known as 'the blob' – mean sea surface temperature, averaged over 18 months and along the California coast, increased by 1.6 °C from an average of 15.2 °C ± 2.39–16.8 °C ± 2.34. In response, aquaculture production had only a slightly lower mean production (2012/2014 = 6,006,500; 2014/2016 = 5,645,700), but higher spatial variability (coefficient of variation 2012/2014 = 0.258, CV, 2014/2016 = 0.405) (Fig. 6A). In fact, across the two years, the production changes were spatially driven, increasing in Northern California (mean change ± sd = 1,161,300 ± 603,500 kg) and declining in Southern California (−864,900 ± 890,000 kg) (Fig. 6B).

4. Discussion

We found a clear food-energy co-location suitability gradient across the California coast with increased potential in the North and offshore, a function of the production gradient trends of the aquatic food and clean energy ocean sectors. While the gradient informs where co-location could be more likely optimized, there was no perfect location (i.e., co-location suitability = 100 %). We find a tradeoff between where wind is highest and wild capture is lowest and where aquaculture and wave energy are currently technologically feasible (≤200m). The coexistence of offshore wind and fishing has been a growing topic of interest and research (Buck et al., 2004; De Groot et al., 2014; Stelzenmüller et al.,

Table 2
Regional comparison of ocean sector production (model inputs) and the CLS score (model output).

Data Set	Minimum	Maximum	Mean	Median	Standard Deviation
Co-location (Nor Cal)	0.283	0.988	0.570	0.575	0.079
Co-location (So Cal)	0.040	0.721	0.349	0.349	0.153
Wave (Nor Cal; kW/m)	0	42,400	26,400	29,600	11,400
Wave (So Cal; kW/m)	1750	36,200	15,800	13,300	10,200
Wind (Nor Cal; MWh)	11,200	31,600	24,500	25,000	4300
Wind (So Cal; MWh)	3250	27,100	16,100	16,100	7380
Aquaculture (Nor Cal; kg/yr)	5,471,000	11,565,700	8,148,500	8,117,300	1,211,200
Aquaculture (So Cal; kg/yr)	2,904,300	10,826,700	5,893,300	5,886,200	1,699,600
Fisheries (Nor Cal; lbs/yr)	70	15,738,800	184,900	18,700	883,800
Fisheries (So Cal; lbs/yr)	120	23,742,400	546,500	33,700	2,082,100

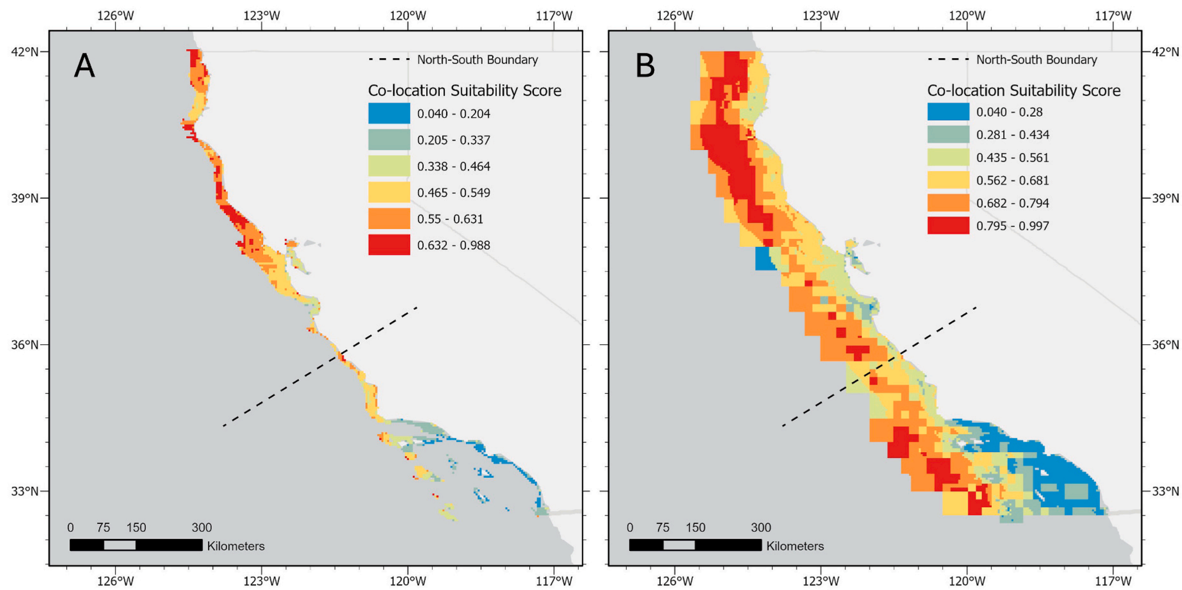

Fig. 3. Co-location Suitability Score for ocean space off the coast of California in A) the shallow (≤200 m) scenario and B) the deepwater (>200 m) scenario. Blue areas reflect low co-location suitability and red areas reflect high co-location suitability. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Production data of each ocean sector.

Data Set	Minimum	Maximum	Mean	Median	Standard Deviation
Wave energy (kW/m)	0.00	42,400	22,400	25,300	12,100
Wind (MWh)	3300	31,600	21,200	22,400	6200
Aquaculture (kg/yr)	2,904,300	11,565,700	7,253,400	7,383,900	1,802,600
Fisheries (lbs/yr)	70	23,742,400	514,000	33,900	1,902,000

Table 4
Transformed value of each ocean sector and the resulting Co-location Suitability scores.

Data Set	Minimum	Maximum	Mean	Median	Standard Deviation
Co-location Suitability Score	0.040	0.988	0.486	0.525	0.155
Wave	0.074	0.870	0.522	0.572	0.211
Wind	0.000	1.00	0.616	0.695	0.255
Aquaculture	0.000	1.00	0.510	0.530	0.284
Fisheries	0.000	1.00	0.591	0.630	0.223

2016), but our study begins filling the gaps relative to the other emerging sectors, critical for moving toward more sustainable ocean development (Gonzales et al., 2024, Morris Jr et al., 2025). Similar to other California marine aquaculture studies (Lester et al., 2018b), we find the farmed aquatic sector has substantial production potential, but is considerably technologically constrained, limiting its co-location potential currently. Lastly, federal AOAs are currently identified in the Southern California Bight, a region we calculate where co-location suitability is lowest and more vulnerable to changing ocean extremes. Ultimately, we provide the first composite assessment of co-location potential for California coastal waters, but the modeled interactions of co-located sectors and social dynamics of such efforts remain a needed line of investigation.

While both deepwater and shallow scenario outputs reflect a clear north to south gradient of food-energy co-location potential, regions of high co-location suitability are at odds with the current social dynamic between marine sectors. The region with high suitability offshore of Northern California is a result of high wind production potential and low fisheries landings, suggesting an area of compatibility between the two industries. However, current federal wind lease areas already exist in the waters offshore of Northern California (BOEM, 2025) and the establishment of these leased areas has come with notable resistance from the fishing community (Local Coast Outpost, 2022; CFRA, 2023), regardless of the relatively lower annual landings. Specifically, fishermen appear concerned about loss of fishable area which could impact their economic production (Local Coast Outpost, 2022; CFRA, 2023). Thus, the tension between just two maritime industries underscores the importance of social carrying capacity in the pursuit of co-location development (Gonzales et al., 2024). In fact, there has been research focused on the socio-economic impact of wind projects in lease areas, suggesting financial mitigation measures to meet the concerns that commercial fishermen have towards California's offshore wind projects (Willis-Norton et al., 2024). The mismatch between modeled versus real-world compatibility highlights the need for the consideration of additional dimensions – including social license to operate and economic impact – in evaluating co-location potential.

We identify a clear tradeoff between deepwater and shallow co-location potential, suggesting there is likely no "perfect spot" for multi-sectoral co-location in California waters. Previous work has noted that the combination of only fisheries and wind energy would fit the definition of 'multi-use' co-location (Schupp et al., 2019), but arguably capturing multiple emerging sectors would be beneficial in moving towards more sustainable ocean use (Gonzales et al., 2024). Due to our modeling assumptions, however, the high suitability areas offshore of Northern California in the deepwater scenario (>200m) excludes the emerging aquaculture and wave energy industries. Our study highlights California's steep bathymetry as limiting aquaculture and/or wave energy from aligning with the 'best' wind and fisheries combination (as

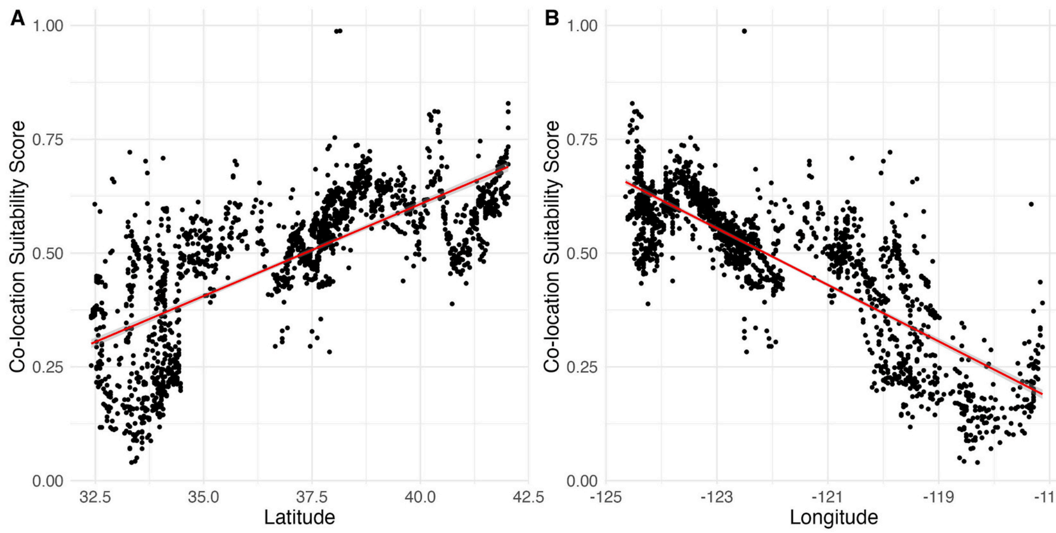

Fig. 4. Relationship between Co-location Suitability Score and A) latitude and B) longitude. Red dashed lines reflect linear regressions and gray shading depicts the 95 % confidence intervals for latitude (m = 0.040; 95 % C.I. = 0.039–0.042) and longitude (m = −0.062; 95 % C.I. = −0.064 to −0.060). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

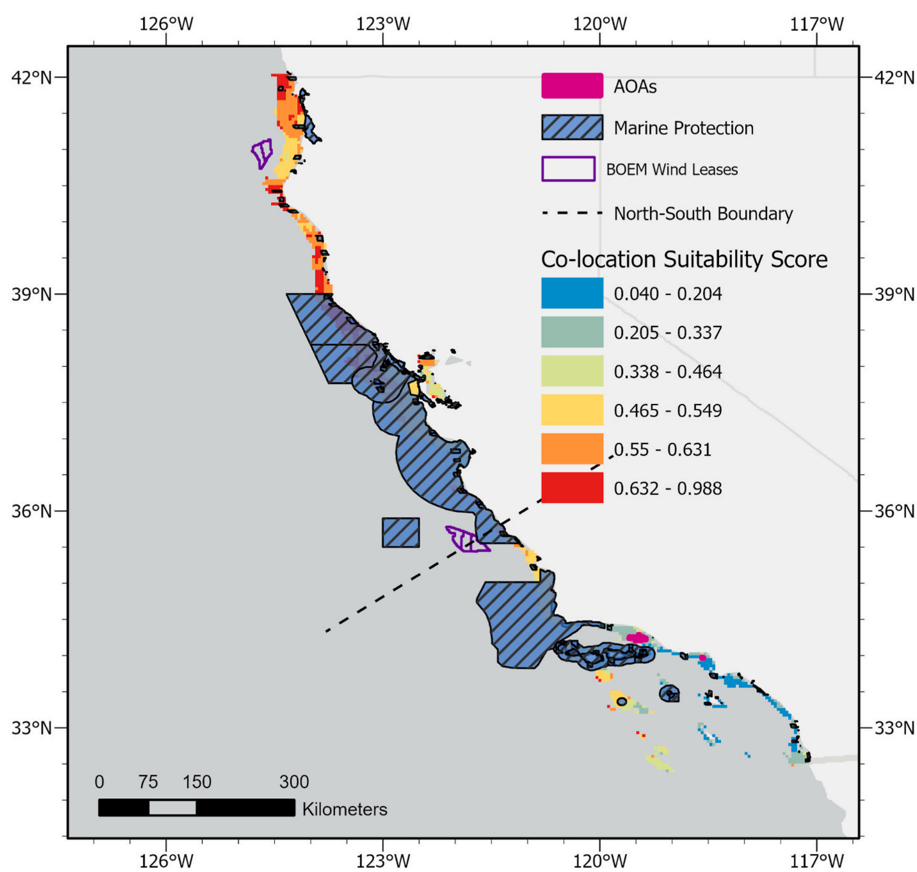

Fig. 5. Co-location Suitability Score for ocean space off the coast of California, accounting for additional spatial constraints (e.g., offshore wind leasing areas and marine conservation).

determined by production) due to technological constraints. Ultimately, we treat all sectors equally, when in reality there are going to be regional and national priorities determining what sector leads in development and what sector follows (Gonzales et al., 2024). In California, we hypothesize that aquaculture will likely have to fit into future wind plans if co-location is pursued between these sectors.

Aquaculture has potential to expand in California and help meet seafood needs (Fong et al., 2022), but the technological and logistical constraints of the industry limit its potential for co-location. The current leased regions for offshore wind energy are not only in waters that far exceed the precedent of a 200m depth limit of offshore farming operations, but also are in regions with strong wave energy, which can be a

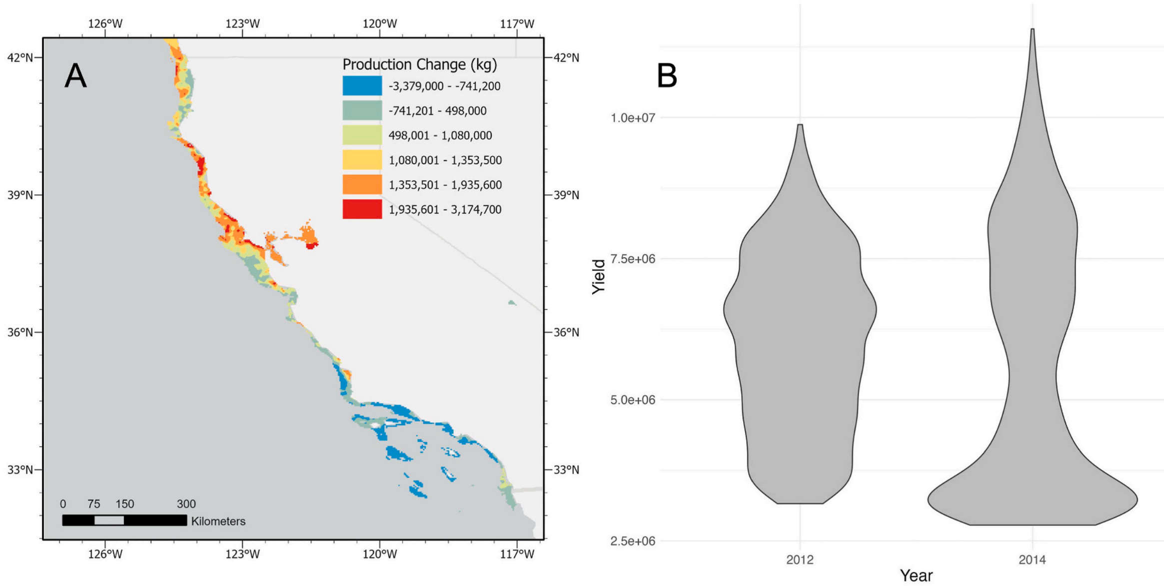

Fig. 6. Aquaculture production difference relative to a marine heatwave. Pane (A) shows spatial trends in variability, with blue regions reflecting a decrease in modeled aquaculture production during a marine heatwave and red regions reflecting an increase in modeled aquaculture production during a marine heatwave. Pane (B) shows the range of production values per spatial cell before a marine heatwave (2012/2014) and after a marine heatwave (2014/2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

threat to most aquaculture infrastructure (Fujita et al., 2023). Calhoun et al. (2025) recently performed an economic assessment of co-located aquaculture and wind systems on the East coast of the U.S., concluding that costs would need to be reduced (e.g., shorter distance from shore to reduce fuel costs) for low-trophic aquaculture to be profitable in wind lease areas. However, this type of economic feasibility analysis has not yet been applied to the West coast. Similarly, new research is emerging with hopes of harnessing novel techniques that can reduce the technical obstacles and improve the profitability of offshore aquaculture (Yue and Shen, 2022; Long et al., 2024), but the implementation of these techniques to offshore aquaculture in the United States remains far off. Alternatively, co-location of aquaculture and wave energy could hold more short-term potential, given that these sectors occupy similar depth ranges and that wave energy converters can be dynamic to fit both high wave energy and low wave energy environments (LiVecchi et al., 2019). In fact, the feasibility of wave energy and aquaculture co-location has been highlighted nationally as an opportunity for synergy (LiVecchi et al., 2019; Ewig et al., 2025) and has been a topic of recent investigation for the California coast (Garavelli et al., 2022). We find, however, changes in ocean conditions will also challenge aquaculture potential in more nearshore environments.

Dramatic swings in thermal conditions will impact aquaculture production along the California coast, exacerbating regional differences. Production output of bivalve aquaculture along the California coast is highest in Northern California, with maximum output in the San Francisco Bay. This production is largely driven by food availability, which is represented by particulate organic carbon (POC) levels. In comparison, production output was lower in Southern California, especially in the protected waters of the Southern California Bight. When evaluating bivalve potential across the state in response to extreme warming waters from the 2014–2016 MHW, aquaculture production increases in the North and decreases in the South, where warming waters disproportionately impact aquaculture (Fong et al., 2024b). Our results align with Fong et al. (2024b), who project that bivalve aquaculture under downscaled climate scenarios perform worse in Southern waters of the state. Although these findings may bode well for marine aquaculture production in Northern California, multiple aquaculture operations exist in the bight, including the state's two offshore/open water seaweed and mussel farms (Fujita et al., 2023). Moreover, eight federally evaluated Aquaculture Opportunity Area sites have been identified in the Southern California Bight (Morris et al., 2021). The discrepancy between aquaculture potential and the establishment of farms along the California coast points to the importance of climate forecasting in resilient and sustainable aquaculture planning. Accounting for these considerations more fully in future modeling – for aquaculture as well as other ocean sectors – would help paint a clearer picture of co-location potential along the California coast, particularly in the face of a changing climate.

This study compiles data and model outputs from along the entire California coast, providing a high-level snapshot of co-location potential. However, to fully grasp the accurate potential of co-locating ocean activities, subsequent evaluations of production and impacts should be conducted at a finer scale. More targeted, scaled down evaluations can help identify the type of co-location (i.e., combination of ocean sectors) that would be most successfully tailored to a region of focus and increase the accuracy of findings. For example, aquaculture is productive in nearshore, nutrient-rich waters, which drives the higher CLS scores in the San Francisco Bay. But measurements are largely dependent on the resolution of the data and models, which decline in these inland systems. Finer resolution focus would also allow studies to account for other environmental variables and ecological impacts, applying frameworks from single-sector analyses (e.g., Galparsoro et al., 2022). Not only would additional modeling increase the accuracy of findings, but it would also allow for region-specific data to be integrated, such as social license to operate in coastal communities (Whitmore et al., 2022). In aquaculture, social perception is recognized as a critical factor in the development of sustainable aquaculture (Byron and Costa-Pierce, 2013; Rubino, 2022), but social research is largely absent in aquaculture co-location approaches (Gonzales et al., 2024). Additionally, integration of error propagation analyses or other methods of accounting for error, would be useful in capturing the certainty of modeled co-location potential outputs (Phillips and Marks, 1996). Similarly, a bioeconomic assessment accounting for demand limitations would be a more accurate representation of the potential, especially for aquaculture (Lester et al., 2018b; Costello et al., 2020; Calhoun et al., 2025). While this study provides a useful snapshot of coastwide co-location potential across California, more resolute social-ecological modeling will be crucial to study the potential interactions and impacts – physical (e.g., downwelling, drag) and financial (e.g., insurance, liability) – of co-locating food and energy together. For example, fine scale modeling has shown that co-location of marine renewable energy with aquaculture can increase energy production on a local level, but this synergy is dependent on the arrangement of the systems and the flow dynamics of the region (O'Donncha et al., 2017). Lastly, future work would benefit from accounting for additional ocean-users (e.g., shipping lane, national defense zones) and environmental considerations (e.g., Essential Fish Habitat, Habitat Areas of Particular Concern) in the mapping evaluation. The cumulative effects of various such considerations will influence the spatial planning process and accounting for them will produce a more realistic depiction of co-location development within a broader MSP framework.

This study provides important insights into the potential of co-location of aquatic food and clean energy to bolster California's blue economy. By evaluating standardized production of multiple sectors, we can better understand where ocean industries can be developed in the same marine space at the same time to increase efficiency of ocean space-use. We found co-location suitability is high in the Northwest waters offshore of California, but that certain sectors are more compatible than others. California is a large state, so we recommend further investigation into food-energy co-location at the smaller community scale to accommodate for more detailed social-ecological feedbacks and trade-offs for a given area. Physical forcing (e.g., MHWs) and logistical constraints (e.g., aquaculture technology) are crucial components in understanding co-location potential, in addition to social acceptance by coastal communities. Recently, renewable energy has been deprioritized at the federal level in the United States (The White House, 2025a), while expansion of the seafood sector is being promoted (The White House, 2025b). In times of uncertainty and change, we hope that innovative approaches to MSP will foster a dynamic and robustly sustainable blue economy that serves all of California's ocean-users.

CRediT authorship contribution statement

Claire Gonzales: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Grace Wu:** Writing – review & editing, Validation, Resources, Methodology. **Halley Froehlich:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.108009.

Data availability

All code and data are available on Zenodo (https://zenodo.org/records/17545767). Datasets from our analyses can be made available upon request.

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