nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-03249-1 OPEN

Marine spatial planning makes room for offshore aquaculture in crowded coastal waters

S.E. Lester [1], J.M. Stevens[2], R.R. Gentry [3], C.V. Kappel [4], T.W. Bell [5], C.J. Costello[3], S.D. Gaines[3], D.A. Kiefer[6], C.C. Maue [7], J.E. Rensel[8], R.D. Simons [5], L. Washburn[9] & C. White[2]

Marine spatial planning (MSP) seeks to reduce conflicts and environmental impacts, and promote sustainable use of marine ecosystems. Existing MSP approaches have successfully determined how to achieve target levels of ocean area for particular uses while minimizing costs and impacts, but they do not provide a framework that derives analytical solutions in order to co-ordinate siting of multiple uses while balancing the effects of planning on each sector in the system. We develop such a framework for guiding offshore aquaculture (bivalve, finfish, and kelp farming) development in relation to existing sectors and environmental concerns (wild-capture fisheries, viewshed quality, benthic pollution, and disease spread) in California, USA. We identify >250,000 MSP solutions that generate significant seafood supply and billions of dollars in revenue with minimal impacts (often < 1%) on existing sectors and the environment. We filter solutions to identify candidate locations for high-value, low-impact aquaculture development. Finally, we confirm the expectation of substantial value of our framework over conventional planning focused on maximizing individual objectives.

[1] Department of Geography, Florida State University, Tallahassee, FL 32306-2190, USA. [2] Center for Coastal Marine Sciences, 1 Grand Avenue, California Polytechnic State University, San Luis Obispo, CA 93407, USA. [3] Bren School of Environmental Science & Management, 2400 Bren Hall, University of California Santa Barbara, Santa Barbara, CA 93106, USA. [4] National Center for Ecological Analysis and Synthesis, 735 State Street, Suite 300, Santa Barbara, CA 93101, USA. [5] Earth Research Institute, 5843 Ellison Hall, University of California Santa Barbara, Santa Barbara, CA 93106, USA. [6] Department of Biological Sciences, University of Southern California, Los Angeles, CA 90089, USA. [7] School of Earth, Energy & Environmental Sciences, Stanford University, Stanford, CA 93405, USA. [8] Rensel Associates Aquatic Sciences, 4209 234th Street NE, Arlington, WA 98223, USA. [9] Marine Science Institute & Department of Geography, University of California Santa Barbara, Santa Barbara, CA 93106-6150, USA. Correspondence and requests for materials should be addressed to S.E.L. (email: slester@fsu.edu)

This century is marked by the rapid emergence and intensification of human uses of the oceans that present immense economic opportunity, but if not managed properly, could lead to an over-crowded and dysfunctional seascape with serious environmental impacts and costly socio-economic conflicts[1, 2]. Thus, there is a need for ecosystem-based approaches to planning that can strategically and comprehensively balance the location, type, and intensity of ocean user groups, or sectors, across the seascape. Marine spatial planning (MSP) is a place-based, multi-sectoral decision-making approach that is being widely promoted for reducing the conflicts and impacts commonly encountered in conventional sector-by-sector planning[3–6]. In theory, comprehensive and proactive consideration of inter-sectoral interactions and environmental impacts can contribute significantly to the value of MSP over conventional planning[5, 7, 8]. Specifically, conflicts and impacts can be assessed and avoided using an analytical tradeoff analysis that leverages bioeconomic models and explicitly considers sector objectives in the planning decision process[4, 5, 9].

The vast majority of examples of MSP adhere to only some of the attributes of an idealized MSP analytical process[10]. In particular, compared with siting sectors one at a time[5], rarely are multiple sectors sited concurrently, such as coordinated designation of fishery, recreation, aquaculture, and shipping areas[8, 11, 12]. Further, planning is often guided by an implicit consideration of tradeoffs[13, 14], rather than strategically using an analytically defined objective function that considers explicitly the response of each sector in the system. The benefit of an analytical objective function that considers each sector's unique responses to spatial plans is that all stakeholder groups can evaluate a plan's effect on the objectives they value[4, 12]. Some studies have combined different sector responses into a composite metric[15, 16], compromising precision compared with a comprehensive objective function. Others consider some sectors' responses explicitly and others only implicitly (e.g., because their objectives are assumed to be met[12]). Thus, a key gap for MSP science is development and demonstration of an analytical approach for comprehensive, coordinated, and strategic planning—referred to for convenience here as the "full" MSP analytical model—and assessment of its value relative to conventional management.

Planning for offshore aquaculture represents a prime opportunity for MSP[17, 18]. Escalating seafood demand and global seafood trade[19], the near fully exploited state of most wild-capture fisheries, and limited space and resources for expansion of land-based and coastal aquaculture all make offshore aquaculture the next frontier of seafood production[20, 21]. Indeed, nearly all projected growth in seafood production over the coming decades is anticipated to come from aquaculture[22], and offshore aquaculture is a rapidly emerging industry with potential for huge economic and societal benefits[23]. Defined here as occurring beyond the nearshore (> ~20 m depth), offshore aquaculture comprises multiple sectors cultivating different marine species using various farming technologies[24, 25].

Despite significant potential benefits of offshore aquaculture development, there remain concerns about its environmental impacts and conflicts with other sectors[25], creating social and political opposition to development[26]. For example, in the United States, aquaculture development has been slow in large part because of social opposition and complex and uncertain regulatory and permitting policies[26]. These roadblocks present a significant opportunity for better planning. However, different types of offshore aquaculture produce unique conflicts and impacts—with each other, with other sectors, and with the surrounding environment—that cannot be summarized by a single metric. Further, the location of a farm can have a significant influence on the type and severity of impacts and conflicts with other uses. Thus, optimal siting of offshore aquaculture is a complex MSP problem requiring comprehensive (balancing existing and emerging sector objectives), coordinated (planning multiple emerging sectors simultaneously), and strategic planning (optimized using an analytically defined objective function that explicitly considers the objectives) across the seascape.

We developed, demonstrated, and tested the value of a MSP analytical model that strategically identifies the location, size, and type of offshore aquaculture farms in relation to a suite of existing ocean activities and environmental concerns. We focused on the Southern California Bight, USA (SCB; Fig. 1a), an area with strong interest in and concerns regarding offshore aquaculture development. We constructed spatial bioeconomic models of the productivity and profitability of three representative sectors of aquaculture with industry potential in the SCB: Mediterranean mussel longlines ("mussel"), striped bass pens ("finfish"), and sugar kelp longlines ("kelp"), and applied these models to over 1000 1-km^2 planning units (sites) that could possibly be developed for aquaculture (Fig. 1b–d). We also developed models of four key existing "sectors" in the SCB, representing key stakeholder concerns, that could conflict with or be impacted by aquaculture development: the wild-capture California halibut fishery, as halibut use the same soft-bottom habitat that would be developed for aquaculture ("halibut"); the environmental health of the marine benthos that could be degraded by hypoxic conditions caused by excessive organic material released from fish farms ("benthic"); the quality of ocean views from public and private lands that could be blemished by aquaculture surface structures ("viewshed"); and the risk of disease spread among fish farms connected by ocean currents, as disease could compromise the economic viability of aquaculture and the health of the SCB ecosystem ("disease"). We then integrated the 7-sector meta-model with an analytical tradeoff analysis to derive optimal spatial plans for the development of mussel, finfish, and kelp aquaculture that simultaneously minimize inter-sectoral impacts and maximize individual sector values. In the optimization, we considered a range of sector-specific weighting factors to reflect alternative societal preferences and/or levels of political influence for how much and what types of aquaculture development are desirable and what degrees of impacts are acceptable.

We identify thousands of optimal spatial plans, and map a small subset of those plans that could be especially informative for decision-making. Optimal plans have minimal impacts to a wild fishery, viewshed quality, and the health of the benthic environment, and minimize the risk of disease outbreaks, while generating significant revenue and seafood supply from marine aquaculture development. We find that by using our model, sector values can be substantially increased (by millions of dollars) and impacts can be reduced (to < 1%), compared to using conventional approaches to spatial planning. More generally, our rigorous and flexible framework can minimize tradeoffs arising from the inevitable expansion and intensification of a wide variety of human uses of the oceans.

Results

Sector tradeoffs. Solving the objective function for all combinations of the seven sectors, each with one of six weighting factors (ranging from low to high priority for maximizing/minimizing the value or impact of the sector), we identified $6^7 = 279{,}936$ optimal spatial plans (i.e., exact analytical solutions given the sector values and sector weights specified in the objective function). Collectively, the plans delineate a 7-dimensional "efficiency frontier" of optimal MSP solutions (Fig. 2a). Each solution represents a SCB-wide aquaculture development plan (location and type—mussel, finfish, kelp or none—across 1061 1-km^2 potentially developable sites) that best minimizes sector impacts and maximizes sector values to the extent possible and relative to their level of socio-political preference (applied as weights).

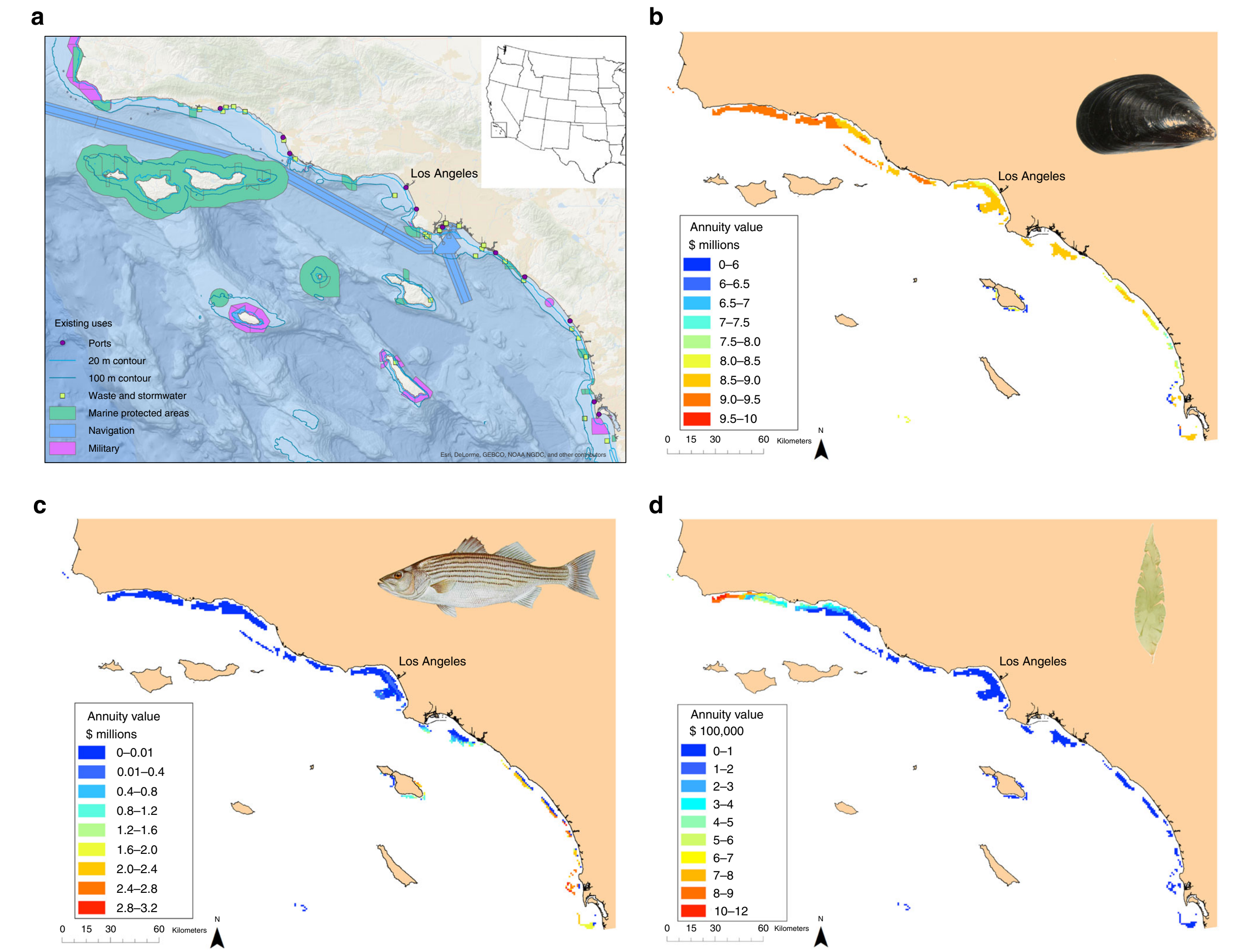

Fig. 1 Study domain, spatial constraints, and potential value for aquaculture development. **a** Select regulatory and logistical constraints to aquaculture development in the SCB. Potential annuity ($/year) in each developable site for (**b**) mussel, (**c**) finfish, and (**d**) kelp aquaculture sectors. Mussel image in **b** from https://commons.wikimedia.org/wiki/File:HPIM1476a.jpg

Although aquaculture development in the SCB could cause considerable conflicts and impacts, explicit mediation of this problem with tradeoff analysis reveals that such outcomes need not be severe, particularly when aquaculture is restricted in its levels of development. For example, unrestricted development of mussel farms could reduce halibut fishery value by ~7%, a relatively low percentage that nonetheless represents >$100,000 in lost annuities (equivalent annual annuity of net present value (NPV)) to that sector. In contrast, we found strategic development of up to 25% of the maximum value of mussel aquaculture to reduce the value of the halibut fishery by a mere 0.2%, or just ~$3700 in lost annuities, while generating ~$2 billion in annuities to the mussel aquaculture industry. Further, the most profitable sites for kelp and finfish aquaculture are concentrated away from the halibut fishery's most valuable areas, and thus under MSP those aquaculture sectors can be nearly fully developed with virtually no impact on the fishery. MSP also results in minimal viewshed impacts (<1% reduction in value) when the three aquaculture sectors are limited to <25% of their full development value and they avoid key locations near populated coastal areas. Similarly, disease risk is concentrated in specific areas due to ocean currents generating high levels of connectivity among certain sites. As a result, MSP can suppress the risk of disease spread by avoiding siting finfish farms in highly connected sites, while still generating up to 88% of potential maximum finfish aquaculture value.

MSP can also mediate competition between aquaculture sectors. Mussel farming is profitable throughout our study region and if developed first could preclude nearly all finfish and kelp aquaculture development (Fig. 1b). Yet optimal spatial plans allow for profitable development of all three aquaculture types; for example, finfish and kelp aquaculture can achieve nearly their full potential value concurrent with mussel aquaculture achieving ~50% of its potential value. This outcome is not generated from simply developing mussel aquaculture where it does not conflict with the other aquaculture sectors, but rather from coordinated, strategic planning that considers the relative value of each site to all sectors. Strategic planning does not, however, guarantee avoidance of all tradeoffs. For example, the risk to benthic environmental health increases nearly linearly with each additional site developed for finfish aquaculture, because environmental effects from finfish farms are relatively consistent across the planning domain. On the other hand, in some cases (e.g., finfish and kelp aquaculture) there is no interaction, and thus no tradeoff between sectors, enabling each to potentially achieve its maximum value.

Development hotspots. Visualization of the frequency of development of each type of aquaculture in each site across all of the MSP solutions reveals locations that are generally favorable to

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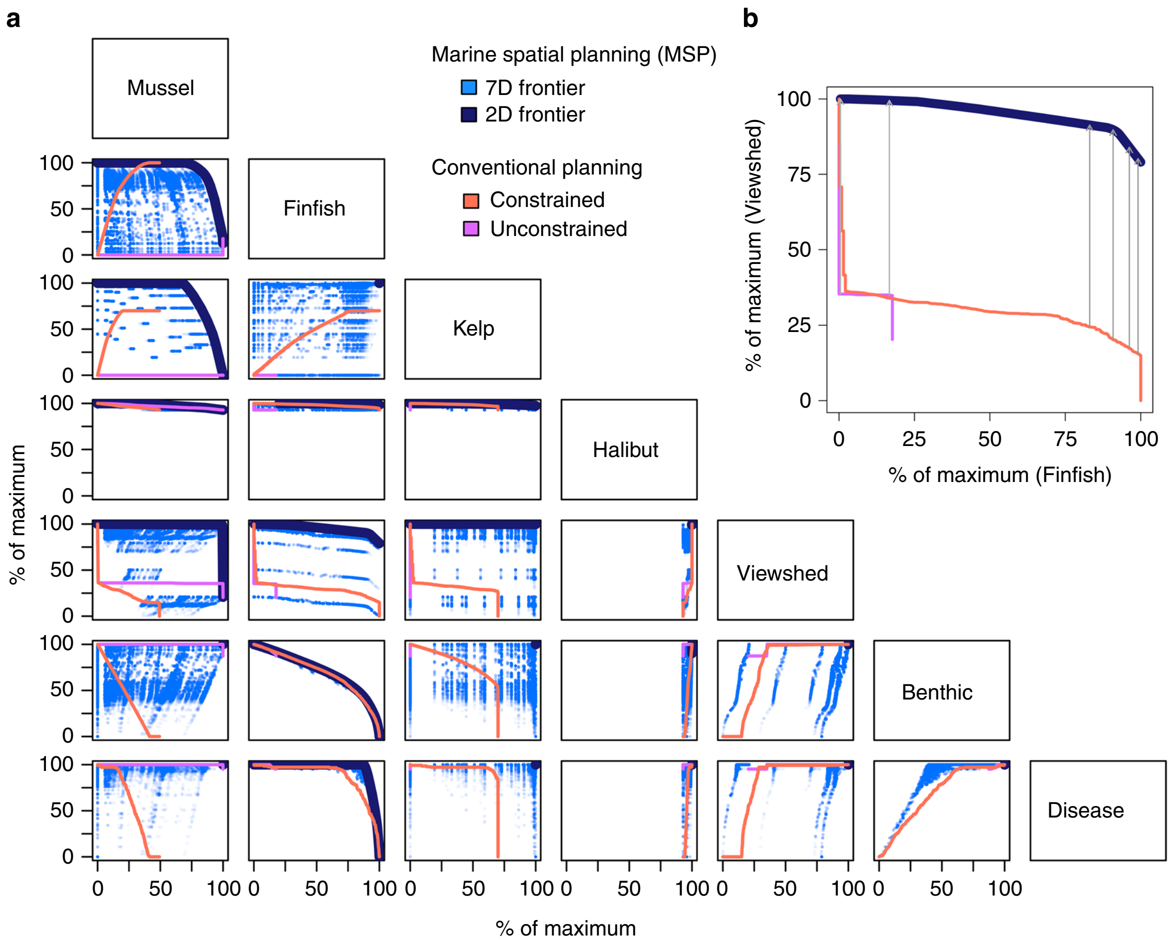

Fig. 2 Marine spatial planning and conventional planning outcomes. **a** Pairwise (2-D) and 7-D efficiency frontiers representing 279,936 optimal spatial aquaculture development plans determined by the MSP objective function, as well as outcomes from spatial plans expected under conventional planning (see legend). **b** Example with arrows showing the value of MSP over conventional planning

aquaculture development regardless of socio-political preferences for particular sectors (Fig. 3). Note, the visualization is not of just a set of estimated solutions to one parameterization of the MSP problem (e.g., as often done using Marxan with Zones[12]), but of all the optimal solutions derived for each of the weighting factor scenarios considered. Thus, the "hotpots" in Fig. 3 could guide a MSP process in the SCB by highlighting specific sites that will be more appropriate for development regardless of socio-political preference, providing a more tractable planning tool in cases where examining many possible optimal plans and/or precisely specifying the weighting preferences for all objectives is not feasible. Comparison of these hotspot maps (Fig. 3b–d) with the distributions of the aquaculture sectors' potential value across the SCB (Fig. 1b–d) reveals that MSP generates a substantial departure in development plans from those expected by single-sector planning focused solely on aquaculture profit. For example, under MSP the most consistently developed mussel sites are largely clustered in the central portion of the SCB (Fig. 3b), despite the most profitable sites for the sector being located in the north. Further, aquaculture development is minimized in the southern SCB where there are high-value halibut fishing grounds and where viewshed impacts would be highest.

Hypothetical planning exercise. To highlight the utility of MSP for identifying a set of spatial plans that meet specific policy objectives, we filtered the 279,936 MSP solutions to those plans for which the impact of aquaculture development on each of the existing sectors is no >5% of their value, while each of the aquaculture sectors must achieve at least 5% of their value. This procedure yielded 450 spatial plans (Fig. 4a). Despite the strict impact constraints, nearly a fifth of the developable sites are developed in this filtered set of spatial plans. Kelp farming, on average, achieves the highest relative value among the aquaculture sectors due to its relatively low impacts, and finfish achieves the lowest relative value, because it impacts all four existing sectors. These filtered results could inform regulators on how much development to allow (Fig. 4a), and where to develop (Fig. 4b) each type of aquaculture in order to meet a given policy specifying acceptable impacts.

Useful for a negotiation process is the ability for managers and stakeholders to compare a small number of distinct MSP solutions, or seed plans, that all generate acceptable outcomes. Accordingly, we used cluster analysis to identify five seed plans that represent the maximum amount of variation in spatial design among the 450 filtered plans (Fig. 5a). Although these plans specify different locations for development of the three types of aquaculture (Fig. 5b–d), they all achieve considerable aquaculture value ($589 million–2 billion, $33–51 million, and $80–$181 million in annuities to the mussel, finfish, and kelp sectors, respectively) while minimizing impacts to the existing sectors (0–5% impact). Even if modified by stakeholders, these plans are likely to produce near optimal outcomes[9].

Value of marine spatial planning. To assess the value added by our MSP approach, we compared solutions along the efficiency

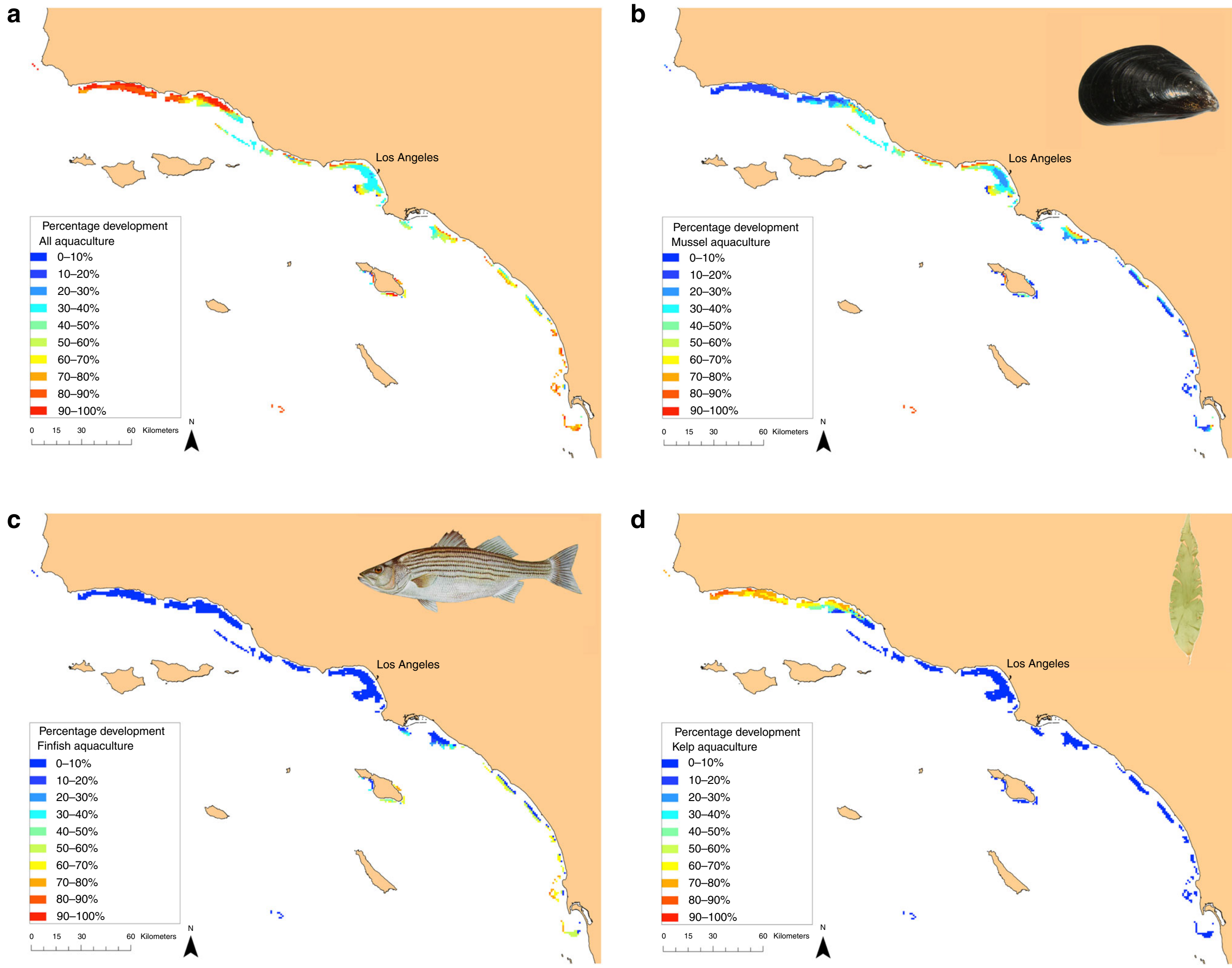

Fig. 3 Hotspot maps of potential development. The percentage of the 279,936 optimal spatial plans containing each site in its developed state for (**a**) any form of aquaculture, and (**b**) mussel, (**c**) finfish, and (**d**) kelp aquaculture

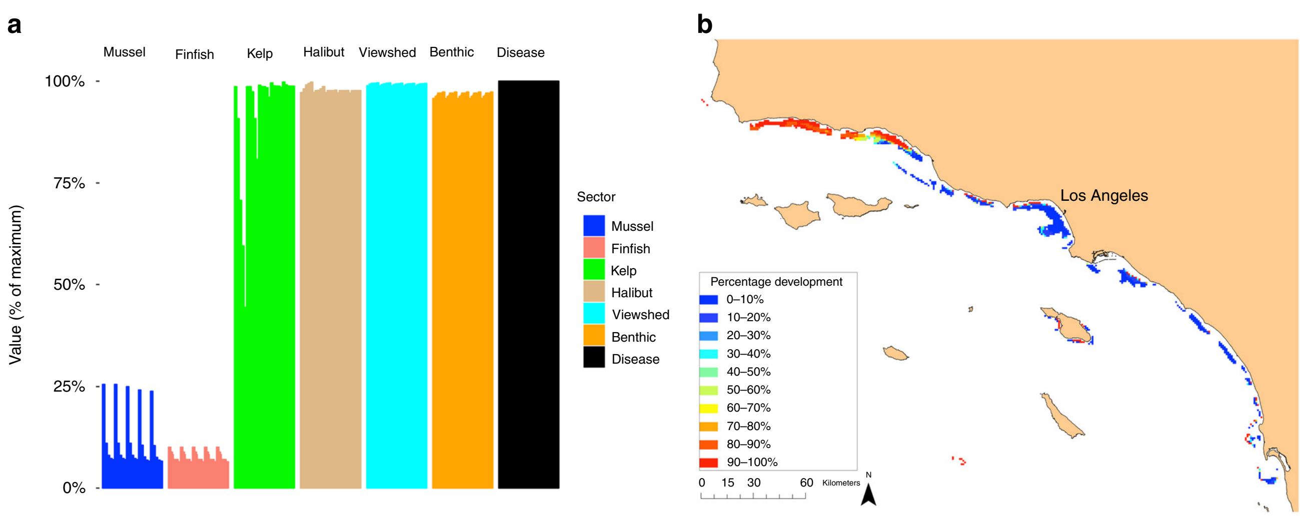

Fig. 4 Hypothetical planning exercise. **a** Subset of optimal spatial plans in which each aquaculture sector achieves > 5% of its maximum possible value, and no existing sectors are impacted by > 5%, resulting in 450 plans. **b** Given these 450 plans, percentage of plans in which each site was developed for aquaculture

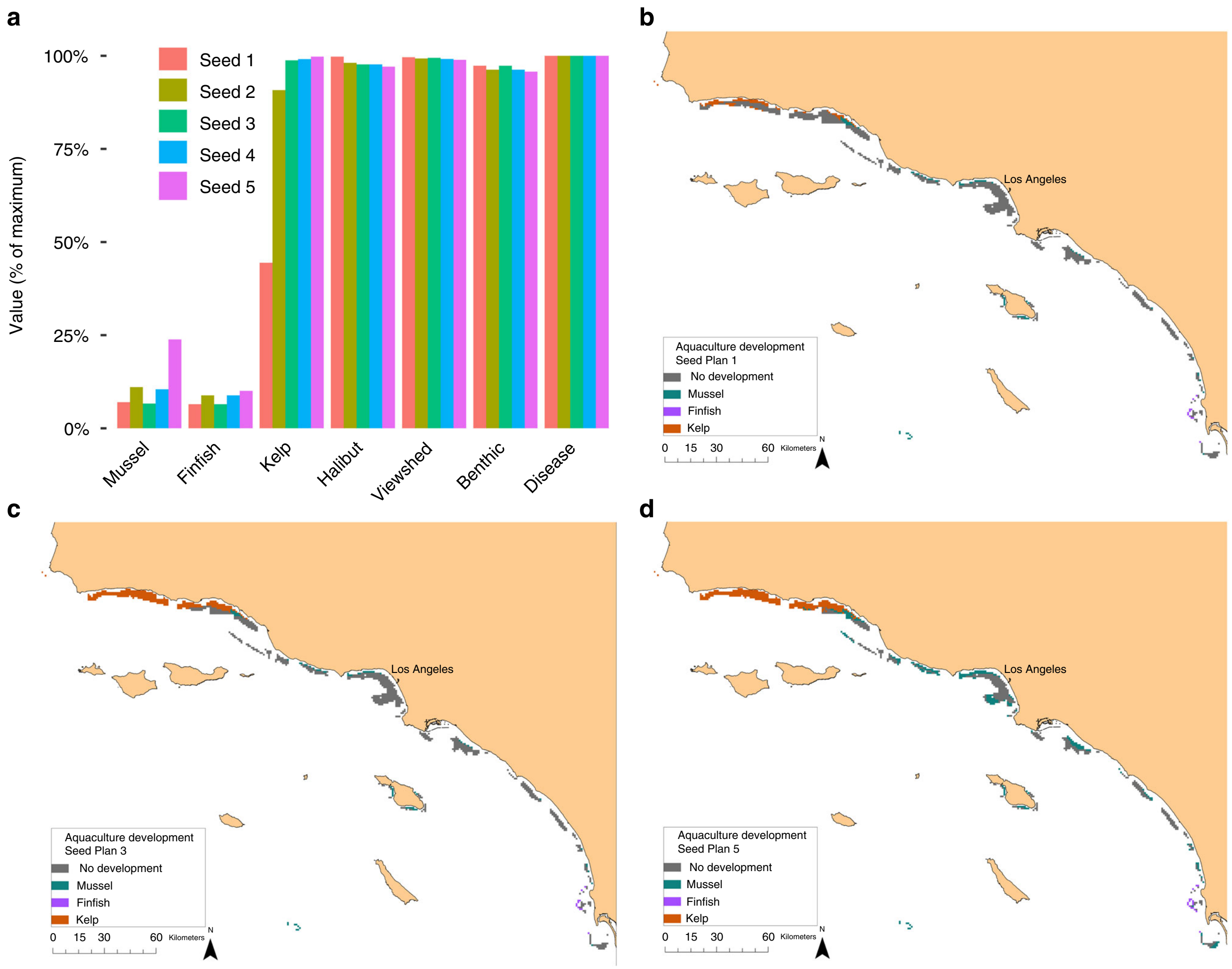

Fig. 5 Seed plans selected from the filtered set using cluster analysis to represent maximum variation in spatial planning design. **a** Resulting value of each sector in each seed plan. **b–d** Maps of three of the seed plans as indicated in the legend of panel **a**

frontier with outcomes expected under modeled representations of conventional planning. We assumed that conventional planning considers individual values and cumulative impacts of the aquaculture sectors but is neither comprehensive (considering individual impacts) nor coordinated (via simultaneous planning, Fig. 2b). We considered two possible characterizations of conventional planning: unconstrained aquaculture development, and constrained development that drives a balanced footprint of mussel, finfish, and kelp farms. For both conventional planning approaches, we found that every sector does as well or better with MSP (Fig. 6). For the four existing sectors, the benefits from MSP typically range 0–100% and increase with the level of aquaculture development. For the aquaculture sectors, the benefits from MSP also range 0–100%, but typically decline with aquaculture development.

The value of MSP is sensitive to the type of conventional planning examined (Fig. 6). MSP benefits finfish and kelp aquaculture little relative to constrained planning, but substantially (often doubling their values) relative to unconstrained planning that allows the mussel sector to dominate aquaculture development because of its superior value/impact ratio at most sites. For existing sectors, constrained conventional planning performs similarly to MSP at low levels of aquaculture development, because regulating for an equivalent footprint among the three aquaculture sectors restricts mussel development, thereby limiting impacts initially. However, the efficiency of this approach compared with MSP deteriorates at higher levels of aquaculture development because kelp and finfish sectors are allowed to develop low value, high impact sites, relegating mussel development to lower mussel value sites.

Discussion

MSP is widely acclaimed as an essential tool for reducing conflicts among management objectives[7]. But current scientific frameworks and applications rarely achieve the trifecta of comprehensive (balancing existing and emerging sector objectives), coordinated (planning multiple emerging sectors simultaneously), and strategic (optimized using an analytically defined objective function that explicitly considers the objectives) planning. We developed a generalizable approach to execute a “full” MSP analytical model constructed to meet these objectives and demonstrate its utility when applied to the challenge of offshore aquaculture development in California. Offshore aquaculture in California, as in many other regions, is being met with some opposition from environmental regulators, coastal residents, and commercial ocean users[25, 27, 28]. However, as an emerging use that could contribute to economic development and sustainable seafood production, aquaculture offers a ripe opportunity for proactive planning. By modeling different types of offshore

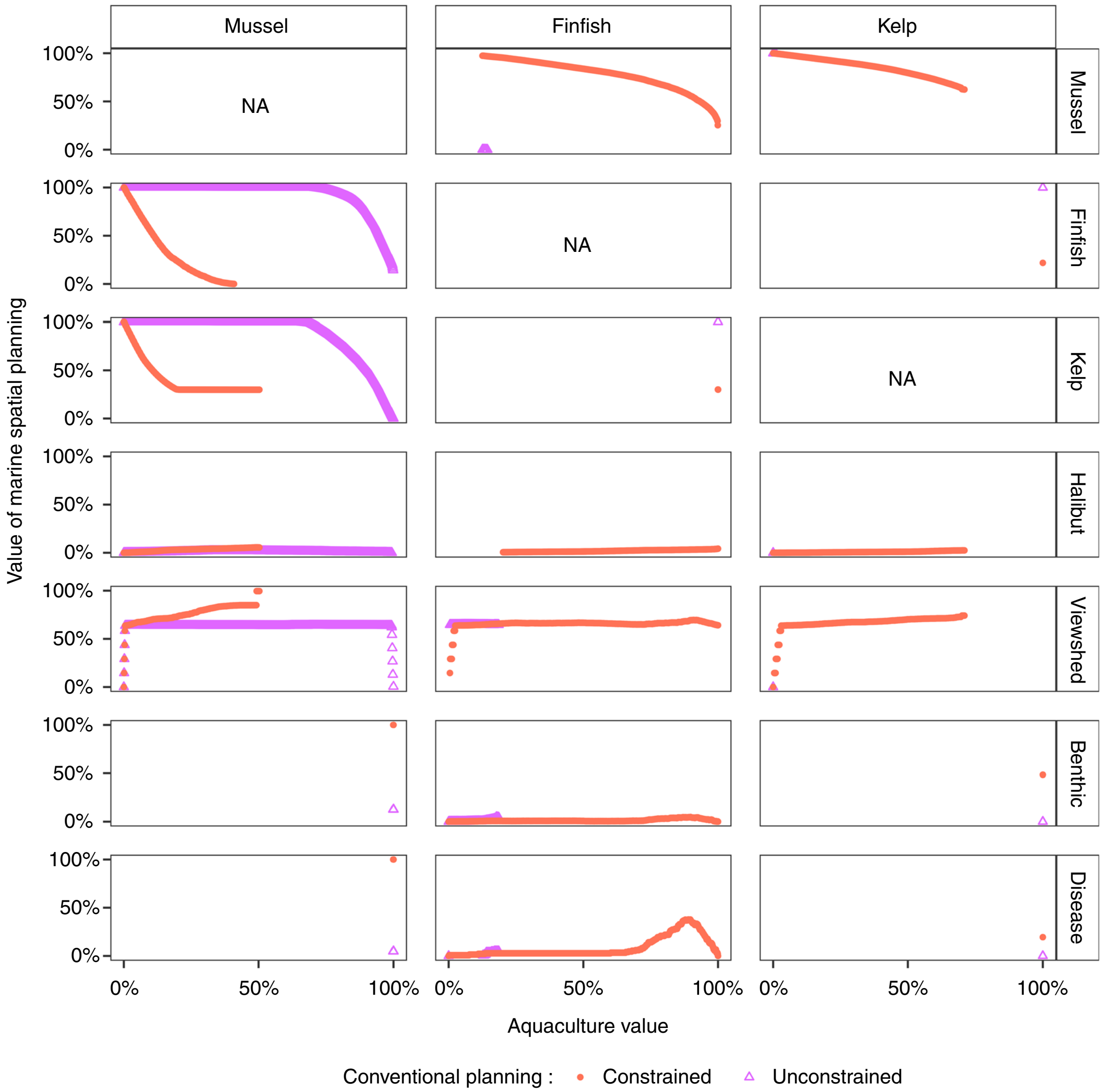

Fig. 6 Value of MSP in relation to constrained (red filled circles) and unconstrained (pink open triangles) conventional planning, and for each sector in relation to level of development of each aquaculture sector

aquaculture and its potential impacts on different ocean uses and the environment, and integrating multiple objectives into a tradeoff analysis, we provide a method for spatial planning that is comprehensive, coordinated, and strategic.

Our analytical approach and case study results yield several important insights. First, dramatic tradeoffs were unavoidable only at high levels of aquaculture development. Using MSP, it is relatively easy to minimize and in some cases eliminate tradeoffs when aquaculture is kept at moderate levels of development. Further, these moderate levels still generate substantial economic returns for the aquaculture industry. For informational purposes, we looked across the full range of potential aquaculture development (0–100%), but in practice the starting point for the SCB (i.e., its current state) is almost no offshore aquaculture, and regulatory constraints restrict substantial development[28]. In the coming decades, the region is likely to experience only modest development (e.g., < 50 km^2, equating to <30% maximum total potential value per aquaculture sector in our model). Consequently, the region of the tradeoff curves that is most relevant for guiding strategic aquaculture development in southern California suggests that MSP could greatly improve aquaculture without significant negative consequences for existing uses or the environment.

Conducting MSP obviously will not eliminate stakeholder opposition to development, or its impacts. Given widespread negative perceptions of aquaculture that have been reinforced by the media and various interest groups[26], there is the need for public education about the actual impacts and benefits expected from aquaculture development when guided by scientifically informed planning, as described by this study. Additionally, our model includes only some of the potential impacts of aquaculture development; there may be other "costs" that we did not consider (e.g., genetic transfer from farmed to wild stocks, reducing the latter's fitness[29]) that could influence our results and stakeholder perceptions of aquaculture. Importantly, previous work on spatial planning for offshore aquaculture has focused primarily on identifying suitable sites in terms of technological and biophysical constraints for the farm and farmed species or accounting for potential impacts[30–33]; exploring interactions and synergies between offshore aquaculture development and other economic uses of the ocean (e.g., wind farms, oil platforms, nearshore aquaculture[34–36]); or examining tradeoffs with another single objective[37]. However, none of this work has used a multi-objective tradeoff analysis and optimization to inform siting decisions. Our finding of potential compatibility between aquaculture development and a suite of existing ocean uses and management priorities, thus, represents an advance of this existing literature.

We also demonstrate that values of the seven sectors under MSP typically exceed and are never lower than their values under conventional planning. This increase in value from MSP is sometimes as high as 100%, even under low levels of aquaculture development (e.g., viewshed impact can be nearly entirely eliminated when finfish development is limited). These relative values translate into significant absolute benefits, for example, up to millions of dollars in annuities to aquaculture sectors and tens of thousands of dollars in avoided lost annuities to the halibut fishery. The precise value of MSP varies depending on the reference form of conventional planning, but, importantly, the basic qualitative result that MSP provides higher value is insensitive to the exact definition of conventional planning. MSP's value to existing sectors increases with the level of aquaculture development because, at high levels, greater potential impacts from poor planning are at stake and can be avoided using MSP. This result highlights the value in using MSP to design a comprehensive master plan guiding future potential development rather than using strategic models to site individual farms one at a time. Furthermore, as the level of development of one type of aquaculture increases, the value of MSP to the other aquaculture sectors declines, because MSP restricts their development in order to protect existing sectors from impact. Thus, in industries like aquaculture or offshore energy with multiple emerging sectors, sectors lagging in development would benefit from promoting MSP of the entire industry from the start.

The value of MSP is positive because, unlike conventional planning, MSP explicitly considers sector tradeoffs, seeking solutions that efficiently maximize value and minimize impacts[4, 5, 38]. This value can provide a powerful incentive to adopt an improved analytical model for guiding MSP. This incentive is aligned for new industries, who are likely to face less opposition while still gaining access to valuable locations; for existing sectors, who recognize the inevitability of new development and seek to minimize the negative impacts they experience; and for planners and policy-makers, who are interested in efficient outcomes that make society better off. While the likelihood and pace of new uses in the oceans is variable around the world, there is a general trend towards new development including aquaculture, renewable energy, oil and gas extraction, and seabed mining[39]. In parallel, there is widespread concern that traditional approaches to marine management have failed to protect the environment and existing uses[2, 40]. With this comes considerable momentum in many places for MSP and for improved analytical frameworks to guide this planning[14, 41, 42], and often the locations leading the way are those facing impending new uses[5, 43]. Our comprehensive approach to spatial planning provides a platform for delineating and allocating rights and responsibilities among the various stakeholders affected by the planning process.

This study generates a methodological advance over previous research that has applied spatial bioeconomic models and tradeoff analysis to MSP[9, 10, 12, 44]. Similar to our study, Yates et al.[15] coordinated development of multiple emerging ocean sectors (wind and tidal energy); however, unique responses by different existing sectors (fisheries) were not considered explicitly in their objective function, limiting their ability to derive optimal solutions. Metcalfe et al.[16] similarly combined their analysis of sector responses (among independent fisheries, in their case), limiting the optimality of their solutions. White et al.[5] did consider unique sector responses in their MSP objective function; however, their analysis considered development of only one emerging sector (wind energy) within a much smaller planning domain (84 sites). As a result, they were able to use a heuristic to estimate (but not necessarily identify) the MSP efficiency frontier. Expanding the analysis to consider multiple emerging and existing sectors and several management options per site within a larger planning domain (1061 sites) complicates the problem substantially (i.e., the discrete choice space becomes unwieldy). We solved this issue by developing an optimization algorithm that quantifies sector responses to each possible planning decision on a site-by-site basis and identifies spatial plans in relation to the sum of these weighted values. By explicitly comparing alternative spatial plans in this way, the complexity of the planning problem is reduced, and reliance on a heuristic eliminated (i.e., exact solutions are derived). The computational time saved enables the framework to be applied to alternative sector weighting scenarios, not just alternative estimates of solutions to a few unique parameterizations of the framework[11], in order to assess the potential range of tradeoffs among the sectors in the system. Further, because our framework evaluates all sector objectives explicitly, we are able to provide details about the tradeoffs specific to each sector-by-sector interaction. But perhaps most notably, models of additional sectors can be integrated into the framework, making it flexible for informing real-world MSP processes.

A downside of our approach is that it requires static models. Accordingly, to account for sectors expected to react dynamically and uniquely across sites (e.g., the halibut fishery, via larval spillover, adult movement, and redistribution of fishing effort), we used static models for identifying optimal plans, but then used dynamic models to simulate the actual outcome of each MSP and conventional planning solution for the halibut fishery (similar to the approach used by[16]). This two-step approach enabled us to estimate the actual, dynamic implications to the alternative spatial plans, in contrast with previous analyses based entirely on static models, e.g., Marxan with Zones[12, 15].

As with any attempt to model numerous ocean uses and their complex interactions, we made simplifying assumptions that may affect our results. For example, we assumed best-management practices within each aquaculture farm, including low farm densities within each site. We also assumed sufficient global seafood demand to maintain constant prices[21]; such an assumption could fail at high levels of aquaculture development, though probably not for a region the size of the SCB[21]. For existing sectors, our estimates of impacts were necessarily based on indirect and/or incomplete metrics due to data and model limitations. For example, our proxy for ecosystem health was flux of organic material from fish farms to the benthos, which at high levels can generate hypoxic conditions hazardous to marine organisms (but at low levels might actually be beneficial for the ecosystem). For disease, we focused on viruses, because they are difficult to contain with best-management practices (e.g., with antibiotics) and present a high risk for propagating new diseases[45], but we acknowledge there are other important types of diseases. Finally, we focused on three representative types of aquaculture and four existing sectors of high concern. However, there are other classes of aquaculture not captured by our study (e.g., integrated multi-trophic aquaculture), as well as other sectors that could be impacted by aquaculture (e.g., marine mammal and seabird conservation; shipping and navigation) or co-located with it, e.g., ocean wind farms[34]. If important sectors are missing from our analysis, then the spatial planning solutions will not necessarily be optimal (though they may be close[9]). However, with high-quality spatial data and a detailed understanding of their interactions, these other sectors could be integrated into our MSP framework.

There is considerable evidence that MSP is more likely to succeed when there is a participatory process with adequate stakeholder engagement[46–48], thus it is important that our analytical approach can operate within the realities of socio-political planning processes. Ideally, scientists and managers would discuss and validate model outputs with stakeholders and adjust the models accordingly[9]. Practical and local knowledge from stakeholders can also be integrated with scientific knowledge, including within a tradeoff analysis, to produce more effective environmental policy[49–51]. This information could subsequently inform the delineation of rights and responsibilities to various stakeholder groups, using the spatial planning outputs as an overall framework, much like would occur in a zoning process on land with property rights and responsibilities within each zone. A potential hurdle to using our approach in a participatory process is that the vast number of optimal plans identified may be daunting for stakeholders and planners. However, we have shown ways to distill such a large set of optimal results into simple guidelines for informing planning (hotspot maps), as well as how to select from the numerous optimal results a subset that is more manageable to review (filtered and seed plans from the hypothetical planning exercise). Finally, an important next step is for technical modeling approaches like the one presented here to be translated into user-guides for managers and policy-makers so that cutting-edge analytical approaches can inform practical decision-making.

We provide an analytical advance over previous MSP approaches that allows comprehensive, coordinated, and strategic planning for multiple emerging and existing sectors. We applied our framework to offshore aquaculture, which is expected to grow rapidly worldwide and is likely to become an essential component of future food production. Our case study is set in southern California, a crowded coastal marine ecosystem with diverse management objectives representative of many highly populated coastlines around the world. There and elsewhere, strong interest in offshore aquaculture development by government and industry is rivaled by diverse opposition driven by perceived spatial conflicts with existing resource users and environmental impacts[25]. The methods and findings from our study may temper opposition because they show that carefully planned aquaculture can generate high-value while ameliorating negative effects to existing sectors. We also demonstrate that conventional planning, even while including environmental regulations and moderate coordination among sectors, remains less effective compared with our MSP approach—a result that corroborates previous studies on marine spatial planning[5, 8]. Although we focus on aquaculture development in the SCB, our models can be adapted to aquaculture development elsewhere (including outside of the United States), to sectors beyond aquaculture, and to spatial planning in areas where there are opportunities for simultaneously managing existing and emerging ocean sectors, provided there are sufficient data[52]. Our approach opens up new opportunities for improved ocean management to achieve sustainable and productive use of marine resources.

Methods

Study domain. See Supplementary Table 1 for an overview of the steps in our MSP analytical model. We first defined our case study domain to encompass the Southern California Bight (SCB), stretching from Point Conception in northern Santa Barbara County, California to the US-Mexico international border south of San Diego, California. We divided the area into a 1-km^2 resolution planning grid (ESRI ArcGIS 10.2 Tool: Create Fishnet), resulting in a model domain containing 6425 1-km^2 planning units or "sites." All geospatial data layers used the California Teale Albers NAD83 projection.

Fixed constraints on offshore aquaculture development. Fixed constraints were applied to determine whether a given 1-km^2 "site" was potentially developable for each of the three types of aquaculture. First, based on current practice in the offshore aquaculture industry, we applied a depth constraint of 20–80 m for mussel and kelp aquaculture and 30–100 m for finfish aquaculture. Minimum and maximum depths in each site were calculated in ArcGIS using the Southern California Coastal Relief Model (Supplementary Data 1; ArcGIS 10.2 Tool: Zonal Statistics as Table). A site was considered potentially developable for a given aquaculture type if its minimum and maximum depths fit within the aquaculture type's depth constraint.

Second, to identify locations with appropriate bottom type for aquaculture development, and to quantify habitat availability for use in the wild-capture halibut fishery model, we mapped soft and hard bottom substrate across the SCB using best available data. In state waters (0–3 nm from shore), the most comprehensive dataset for this purpose was compiled for the California Marine Life Protection Act process and made publicly available by the California Department of Fish and Wildlife (CDFW) (Supplementary Data 1). To fill gaps in the CDFW data and extend the dataset beyond state waters, we used the California Geology Series statewide continental margin habitat layer, downloaded from the Seafloor Mapping Lab of California State University, Monterey Bay (SFML) (Supplementary Data 1). Both data layers classify seafloor into soft sediment (sand and mud), hard bottom (rock, boulders, and gravel), mixed hard and soft, or unknown. We merged these two datasets to make a comprehensive data layer for the SCB. In order to fill a remaining gap in seafloor habitat data in the San Diego area (i.e., an area classified as "unknown"), where there has been particular interest in finfish aquaculture development, we classified higher resolution (10 m) bathymetry data, collected by the California Seafloor Mapping Program but at the time not yet publicly released, into hard and soft bottom (Supplementary Data 1). Hillshade and Vector Ruggedness Measure (VRM) layers were derived from the bathymetry and provided for our use by L. Wedding (personal communication, Stanford University, unpublished data; Supplementary Data 1). Based on the range of thresholds used previously by SFML to classify similar data e.g., in ref. [53], we applied a rugosity threshold of 0.0004 to the VRM layer as the classification cutoff between hard vs. soft bottom. This specific threshold produced the best classification, based on visual comparison to the hillshade layer. We then used the classified data to fill in unknown habitat in the area off of La Jolla, CA. We were unable to obtain further data to fill other gaps in the substrate data layer (2725 1-km^2 sites were classified as "unknown").

Existing offshore aquaculture permit holders and applicants in California are required to demonstrate that their farms are not proximate to or above hard bottom habitat and will not negatively impact such habitat[54, 55]. For this reason, we assumed that each site must have 100% soft bottom habitat to be considered developable. Hard bottom and mixed soft and hard bottom could not be developed, and we also conservatively prohibited unknown areas from development. Future habitat mapping could fill unknown habitat gaps and potentially expand the developable area for aquaculture in the SCB.

Third, we assumed aquaculture would be restricted from sites with certain human uses or impacts. All uses and designations that we assumed would preclude aquaculture development were mapped and overlaid with the planning grid, and intersecting grid sites were classified as undevelopable. Specifically, we eliminated marine protected areas (MPAs) that prohibit aquaculture and/or any modification of the seafloor, including the Channel Islands National Marine Sanctuary (CINMS) (Supplementary Data 1; Fig. 1a). Although the Marine Protection, Research, and Sanctuaries Act of 1972 that defines policy for CINMS does not explicitly prohibit aquaculture, it does prohibit modifications to the seafloor[56]. We interpreted this as indicating that mooring of buoys and lines for aquaculture within CINMS would not be allowed. We also excluded existing offshore energy infrastructure (i.e., oil rigs), military zones, anchorages, and Traffic Separation Scheme shipping lanes, all mapped using the de facto MPA data layer provided by the National Marine Protected Areas Center (Supplementary Data 1; Fig. 1a). Lastly, we limited aquaculture development from the vicinity of offshore, subsurface treated wastewater effluent outfalls and major river mouths (Supplementary Data 1; Fig. 1a), in accordance with current water quality regulations[28], by excluding sites containing outfalls or river mouths, as well as the eight immediately adjacent sites, based on estimates from the region of the average dilution and dispersal distances of wastewater and stormwater runoff plumes[57–61]. Lastly, for each aquaculture type, sites with negative value (NPV and annuity) were assumed to be undevelopable.

After accounting for all of these regulatory, logistical, and economic constraints to aquaculture development, 1061 sites were determined to be potentially developable for one or more types of aquaculture (Supplementary Fig. 1). We recognize that some of the constraints we included might be more flexible than our analysis assumed (e.g., aquaculture could be co-sited with decommissioned oil rigs; CINMS could allow aquaculture moorings) and that conversely, we might be overlooking some fixed constraints (e.g., classified military zones).

Bioeconomic models. We constructed spatially explicit models to estimate the distribution of value of three emerging aquaculture sectors and four existing sectors impacted by aquaculture development. For each aquaculture sector we developed a bioeconomic model estimating annual yield and profit (Supplementary Fig. 2) for all developable sites given a specified fixed farm design for each type of aquaculture. We also took into account environmental conditions (e.g., water temperature, surface currents, particulate organic carbon levels, nitrate concentrations, photosynthetically active radiation, depth, distance to port, and wave height) in each site and accounted for start-up costs followed by fixed farm operational costs specific to each type of aquaculture (Supplementary Fig. 3), assuming static market conditions. Mussel and kelp aquaculture models were modified from published individual growth models and scaled up to the farm level[62, 63]. Finfish aquaculture was modeled using the aquaculture siting, production and impacts model, AquaModel[64]. For each aquaculture type in each site, we amortized annual profits from each site, π_t^i, in relation to an economic discount rate, δ (5% in this case), and then summed the discounted profits to estimate the NPV to the sector over a 10-year time horizon[65, 66].

$$\mathrm{NPV}^i = \sum_{t=0}^{T=10} \frac{\pi_t^i}{(1+\delta)^t} \quad (1)$$

We also estimated the equivalent annual annuity of each sector's NPV, which represents the series of even cash flows received by a given sector over the 10-year time horizon for site i. Note that annuity is simply NPV multiplied by a constant.

$$C^i = \frac{\delta(\mathrm{NPV}^i)}{1-(1+\delta)^{-T}} \quad (2)$$

A 10-year time horizon (starting with the present year) was chosen due to the rapid projected growth and innovation in the aquaculture industry, which is expected to generate high turnover of aquaculture technology on a decadal scale[67]. This timeframe also matches the permit renewal cycle specified for aquaculture in US Federal waters of the Gulf of Mexico according to the recently implemented offshore aquaculture Fishery Management Plan[68].

Sites without positive profits for an aquaculture type were set as undevelopable for that type. These economic constraints, in addition to the regulatory and logistical constraints, resulted in 1011 potentially developable sites for mussels, 329 for finfish, and 325 for kelp. Admittedly, as a nascent industry, aquaculture technology and expertize is likely to show considerable improvements in the future, which could lower costs and increase production and revenue, resulting in a larger number of developable sites, but we focused this analysis on current economic and technological conditions. We considered the full range of development across the planning domain (i.e., development of 0–100% of profitable sites for each aquaculture type).

We constructed models to estimate aquaculture impact on four existing "sectors" that represent common social concerns with offshore aquaculture development.

Wild-capture fisheries: We modeled spatial and temporal population dynamics of California halibut, *Paralichthys californicus*, including larval dispersal based on a Regional Ocean Modeling System (ROMS), and adult movement in relation to inter-site distance and habitat quality (Supplementary Fig. 4). We assumed sites with aquaculture development would be closed to halibut fishing (e.g., due to risks of gear entanglement) and estimated resulting changes in fishery yields and profits from commercial and recreational harvest (Supplementary Fig. 5). The equilibrium output of this dynamic model was used for determining MSP and conventional spatial plans, but then we estimated the value of the fishery in relation to the plans using the fully dynamic model.

Viewshed quality: We estimated visual impacts as the number of coastal residents and visitors who could see a farm in each developed site, using a cumulative viewshed model in ArcGIS with coastal population density, visitation rates to state parks and beaches, coastal elevation, and distance to the farm as input data, and assuming that mussel and kelp farms are visible within a 3-km radius and finfish farms are visible within an 8-km radius (Supplementary Fig. 6a, b).

Benthic environmental health: We used AquaModel[64] to estimate the spatial distribution and rate of total organic carbon flux from fish farms to the seafloor as a proxy for effects on the benthic ecological community (Supplementary Fig. 6c). Although low levels of organic material could be harmless or even beneficial to the benthic community, we conservatively assumed that higher levels of flux correspond to increased benthic impact, as higher delivery rates of organic material increase the risk of hypoxic conditions.

Disease risk: We focused on assessing viral disease risk, because bacterial disease has been relatively well controlled through vaccines and antibiotics in modern finfish aquaculture. To assess the spatial planning dimension to viral disease risk, we assessed the oceanographic connectivity of viral particles among finfish farms because farm location and density in relation to ocean currents could influence the risk of disease transmission and system-wide outbreak. We estimated the relative risk of virus spread for finfish farms as the sum of the eigenvector centrality indices of the developed sites, calculated using a connectivity matrix derived for all developable sites using a ROMS parameterized for marine virus life history (Supplementary Fig. 6d). Mussel and kelp farms have received less attention for their potential disease risk and are unlikely to pose a threat to the benthos in the offshore environment, so were assumed to have no impact on these sectors. See the Supplementary Notes for a detailed description of each of the models mentioned above, Supplementary Data 1 for spatial data layers used in our analyses, and Supplementary Data 2 for model parameter values and supporting references.

Tradeoff analysis. We developed a spatial selection model that considers interactions among the seven sectors and optimizes management decisions based on weighted socioeconomic priorities for each of the sectors in maximizing their gains or minimizing their impacts. The tradeoff analysis contains the above-described seven sector models (mussel, finfish, and kelp aquaculture, and halibut fishery, viewshed, benthic impact, and disease risk), which are used to estimate spatially explicit potential values of each sector in response to each form of development at each site in the study domain. These seven models are combined by the tradeoff analysis into a meta-model that is solved in relation to a MSP objective function. The objective function considers the potential value of each site by each sector in relation to four separate development options (no development, mussel development, finfish development, kelp development). These values are weighted and then summed across sectors to calculate an aggregate metric at a site for each development option. For a given set of sector weights, the goal of the tradeoff analysis is to determine what development option should be chosen at each site in order to maximize the aggregate metric in the MSP objective function. The solutions generated for all weighting scenarios represent the set of optimal MSP development plans for the three aquaculture types in the SCB.

Currently, no offshore aquaculture exists in the SCB, and planning procedures for determining the number and location of suitable sites, and the level of acceptable impacts on existing sectors, are in the preliminary stages[28]. To simulate the full range of possible relative socioeconomic priorities across the sectors (aquaculture and existing), we assigned priority weights to each of the seven sectors. Each sector's weight ranged from 0 to 100% in increments of 20% (i.e., $\alpha^n = 0, 0.2, 0.4, \ldots 1$, for each sector n). Evaluation of all sector-by-weight combinations generates $6^7 = 279{,}936$ weighting combinations among the seven sectors. Each combination is then evaluated within the tradeoff model, whereby we optimize each unique objective function to identify optimal spatial plans.

Let $V_{n,i,p}$ be the value to sector n at site i from pursuing development option p at that site. There are seven sectors ($n =$ {mussel, finfish, and kelp aquaculture; halibut fishery; viewshed; benthic health; and disease risk}), 1061 sites ($i = \{1,\ldots,1061\}$), and four development options ($p =$ {develop mussel aquaculture, develop finfish aquaculture, develop kelp aquaculture, and no aquaculture development}). $V_{n,i,p}$ depends on the "response" of a sector, at a site, to a particular development option. For each aquaculture sector, the response is the equivalent annual annuity (in dollars) generated to the sector if the site were to be developed for that type of aquaculture. For the halibut sector, the response is the annuity (in fishery yield) to the halibut fishery at the site if it is not developed for aquaculture, and otherwise zero if aquaculture is developed there because the halibut fishery is excluded from the site. For viewshed, the response is no impact (i.e., no reduction in number of person views of a site) if there is no development there, partial impact if mussel or kelp are developed there, and further impact if finfish is developed there because its surface structures are visible from farther away and thus by more people. The response of the benthic environmental health and disease risk sectors is impact (i.e., elevated TOC and risk of outbreak) at a site if the site is developed for finfish aquaculture, and otherwise no impact. Let $R_{n,i,p}$ indicate these responses. We define the maximum response by a sector across all sites and options as $\overline{R}_n \equiv \max_{i,p}\{R_{n,i,p}\}$. Given these definitions, the values are given as follows:

$$V_{n,i,p} = \left\{ \begin{array}{ll} R_{n,i,p} & \text{if } n = \{\text{aquaculture, halibut}\} \\ \overline{R}_n - R_{n,i,p} & \text{if } n = \{\text{viewshed, benthic health, disease risk}\} \end{array} \right\} \quad (3)$$

The reason why values are calculated differently for these two classes of sectors is that for the aquaculture and halibut sectors, the response is positive, so a higher response increases the value, while for the other sectors, the response is negative, so a higher response decreases the value (so that a higher response indicates less impact).

The final step is to scale the values so they have comparable units. To do so, we scale each sector's value by the domain-wide value that would be attained if the ideal development option to the sector was selected at each site. The result is the scaled value to sector n from applying option p in site i, $X_{n,i,p}$, as follows:

$$X_{n,i,p} = \frac{V_{n,i,p}}{\sum_i \max_p (V_{n,i,p})} \quad (4)$$

The scaled values $X_{n,i,p}$ are unitless, range from 0 to 1, and indicate the proportional contribution of development option p at site i to sector n's sum total potential value. This formulation allows us to compare the implications of alternative development options across multiple sectors in multiple sites. The ultimate goal is to select the ideal option at each site. Because society may place different weights on the various sectors, we allow for a weighted value. Let α_n represent the weight placed on sector n, so the overall value to sector n at site i from implementing option p is given by $\alpha_n X_{n,i,p}$. Summing over all sectors gives the comprehensive (all sectors) value from option p at site i, as follows:

$$\sum_n \alpha_n X_{n,i,p} \tag{5}$$

Because the goal is to select the option that maximizes this value at site i, the maximized value at site i is given by the following objective function:

$$\mathrm{Obj}_i = \max_p \left(\sum_n \alpha_n X_{n,i,p} \right) \tag{6}$$

Evaluation of the above objective function for all $i = 1,\ldots,1061$ aquaculture developable sites generates an MSP solution indicating the optimal location and type (mussel, finfish, kelp, or none) of aquaculture development across the domain, given sector-specific weights α_n. Replication of the analysis across a range of weights for each sector generates a set of optimal plans that collectively delineate the 7-D efficiency frontier of MSP solutions (Fig. 2a). In practice, we generated $6^7 = 279{,}936$ MSP solutions representing six weights $\{\alpha_n = 0, 0.2, 0.4,\ldots 1\}$ applied to each of the seven sectors.

Conventional planning. Given the absence of offshore aquaculture development currently in the SCB, and that planning procedures for offshore aquaculture are only in their preliminary stages[28, 69], it is unknown how exactly aquaculture development in the SCB would proceed if directed by a "business as usual", or conventional, approach to planning. In the absence of MSP, a conventional strategy to planning and/or site selection could be driven primarily by the potential economic value to the aquaculture industry. However, this assumes that the industry would be unrestricted in choosing sites for development (apart from assumed fixed constraints like shipping lanes, military areas, MPAs, hard bottom habitat, etc.). Such unrestricted development is unlikely to occur in the SCB due to already established regulations on coastal and offshore development, and regulations for the leasing of state water bottom[28]. In both cases, the State of California mandates that all aquaculture sites demonstrate minimal negative effects on both the environment and existing ocean users (e.g., the existing sectors considered in this study[28]). In this case, conventional planning of aquaculture would not be based solely on potential economic value to the industry. Instead, the aquaculture industry would be expected to consider how to minimize impacts to the environment and existing sectors concurrent with selecting high-value sites for aquaculture. Accordingly, in our model of conventional planning we assumed aquaculture development would focus on sites that have both a high economic value to the aquaculture industry and small negative impacts to existing sectors. To simulate this process, we developed a ratio to determine the suitability of each site for development by each aquaculture sector: the annuity value of the aquaculture sector if the site were developed, divided by the scaled value of the most impacted existing sector at the site if that aquaculture sector were developed there. The rank order of sites in relation to their suitability index was then used to simulate a range of levels of development of aquaculture (1–1061 of the developable sites across the domain) under conventional planning.

We further considered two approaches to conventional planning that reflect variance in the permitting process among the three aquaculture sectors. One approach, "unconstrained conventional planning", promotes free market competition among the three types of aquaculture by allowing the choice of where and what type of aquaculture to develop to be driven solely by the suitability index (compared across sectors and sites). Alternatively, social or political factors may require a more equitable level of development among aquaculture industries. To account for this possibility, we also modeled a "constrained" approach to conventional planning, which regulates for an equal level of development among the three aquaculture farm types. In this case, the first site chosen for development is that with the highest suitability in relation to any type of aquaculture; the second site is that with the highest suitability in relation to the two remaining types of aquaculture; and the third site is that with the highest suitability for the remaining type of aquaculture. The pattern is repeated—maintaining an equal number of sites per sector but also allowing each to choose for development its most suitable sites among those available—up to a set level of development (maximum all 1061 sites; Supplementary Fig. 7a, b). At high levels of development, kelp and finfish aquaculture exhaust their available sites for development; in this case, the selection process focuses on only the sector (s) with available sites.

Spatial plan outcomes. Outcomes of the spatial plans derived (under MSP and conventional planning) were calculated for each of the seven sector in terms of their cumulative value achieved across all 1061 developable sites scaled relative to their potential minimum and maximum cumulative values across the sites:

$$O_n = 100 \left(\frac{\sum_i X_{n,i,p} - \sum_i \min_{\forall p}(X_{n,i,p})}{\sum_i \max_{\forall p}(X_{n,i,p}) - \sum_i \min_{\forall p}(X_{n,i,p})} \right) \tag{7}$$

The result is the percentage value of each sector relative to its highest and lowest values possible for the sector. That is, for each aquaculture sector relative to zero value if not developed and the value achieved if it were fully developed across the domain; and for each of the existing sectors relative to its value if maximally impacted by full aquaculture development and its value if not impacted at all due to no aquaculture development. Thus, O_n is scaled relative to the status quo (no aquaculture development) and maximum development/impact. For the halibut sector, which has substantial value outside of the 1061 developable sites (e.g., at the Northern Channel Islands), we considered both developable and non-developable sites in the calculation of its maximum cumulative value in order to not inflate our estimate of the impact of aquaculture on the halibut sector, and thus the halibut fishery's lowest value is ~93%. These outcomes are shown in Fig. 2. We also calculated the NPV and annuity outcomes of the spatial plans for the three aquaculture sectors and halibut sector that could be evaluated in dollars.

Value of MSP. The value of MSP relative to a form of conventional planning was the change in outcome to a sector under the two planning approaches being compared, relative to a specified percentage of development for each aquaculture type achieved by both planning approaches. To do this, we first linearly interpolated the 2-D MSP efficiency frontiers in Fig. 2 so that they were continuous functions that could be directly compared to the conventional model outcomes. For each point on a 2-D efficiency frontier we then calculated the difference in value to a sector between the efficiency frontier and the conventional planning outcome with the same level of aquaculture development of each farm type, as illustrated in Fig. 2a. The resulting value of MSP over constrained and unconstrained conventional planning approaches is plotted in Fig. 6. When the same level of aquaculture development does not exist between MSP and a form of conventional planning (e.g., because constrained conventional planning limits mussel aquaculture from reaching full capacity), then the two forms of planning cannot be compared directly, resulting in the incomplete-looking lines in Fig. 6.

Cluster analysis. Following Linke et al.[70], we calculated the Bray-Curtis dissimilarity index between each filtered seed plan, represented by an integer vector of the development choice at each site. The solution, a matrix of pairwise differences among the plans, was visualized with a hierarchical cluster tree (dendrogram) based on the single linkage algorithm using Euclidean distance and with the number of leaf nodes set to the number of unique spatial plans. Visual inspection identified five clusters, all with multiple spatial plans, representing the complete set of filtered plans. The solution matrix of the Bray-Curtis indices was also visualized in a non-metric multi-dimensional scaling (nMDS) plot using the default Kruskal's Stress 1 criterion. With the aim of covering the maximum amount of variation in spatial design among the filtered set, one seed plan was selected from each cluster based on which one was farthest from the centroid of the nMDS plot.

Code availability. Model source code and input data necessary to run the model are available for download at https://github.com/AquacultureSpatialPlanning

Data availability. Output data are available on Github (https://github.com/AquacultureSpatialPlanning), and spatial data layers used in our analysis are available on request from the authors.

Received: 28 January 2017 Accepted: 31 January 2018
Published online: 05 March 2018

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Acknowledgements
Funding for this project was provided by NOAA Sea Grant (#NA10OAR4170060, California Sea Grant College Program Project #R/AQ-134), The Waitt Foundation, and The Gordon and Betty Moore Foundation. We thank the California Seafloor Mapping Program and CSUMB's Seafloor Mapping Lab for habitat data, S. Denka for assistance running AquaModel simulations, F. O'Brien for AquaModel technical support, T. Ursell for assistance modeling halibut movement, and Catalina Sea Ranch, Santa Barbara Mariculture, Hubbs-SeaWorld Research Institute, and Ocean Approved for information for the aquaculture models.

Author contributions
S.L., C.W., R.G., S.G., C.C., and L.W. designed research; S.L., C.W., J.S., R.G., C.M., C.K., T.B., and R.S. performed research; S.L., C.W., J.S., R.G., C.K., and T.B. interpreted results; D.K. and J.R. provided analytic tools; S.L., C.W., and J.S. wrote the paper; and all authors contributed to the supporting information.

Additional information
Supplementary Information accompanies this paper at https://doi.org/10.1038/s41467-018-03249-1.

Competing interests: The authors declare no competing financial interests.

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Supplementary Notes

An overview of the key steps for implementing the full MSP analytical model, including the significance of each step and a summary of how each step was implemented within this case study analysis, is found in Supplementary Table 1. In the following supplementary notes, we provide additional details about the component models used in our case study analysis.

Supplementary Note 1.

Ocean Circulation Model: A three-dimensional ocean circulation model (OCM) contributed to multiple parts of this study. The OCM is a high-resolution Regional Ocean Modeling System (ROMS) applied to the SCB region[1,2]. Implemented by Dong and McWilliams[2], the OCM is driven by realistic boundary conditions extracted from a nested ROMS solution for the U.S. West Coast with high-resolution air-sea forcing. Detailed information on the lateral and surface boundary conditions and model validation can be found in Dong and McWilliams[2] and Dong et al.[3]. The OCM has a 1-km horizontal grid and 40 vertical levels and covers the same area as the study domain. Results from the OCM consist of three-dimensional flow fields and temperature and two-dimensional mixed layer depth, which contributed to the aquaculture models, the larval dispersal component of the halibut fishery model, and the disease model. For the halibut model (Supplementary Note 9) and the disease risk model (Supplementary Note 13), the OCM was run from 1996-2002. For the aquaculture models, the OCM was run using environmental data from 2000 to 2001. This time period was chosen because it was a neutral-condition El Niño Southern Oscillation (ENSO) period[4], and thus represents “average” oceanographic conditions.

Supplementary Note 2.

Introduction to Aquaculture Production and Cost Models: To estimate the value of the three types of aquaculture farms (mussel, finfish, and kelp) we developed separate spatially-explicit bioeconomic models for each, then evaluated the models for sites that met the fixed constraints to aquaculture development. Each aquaculture model contains a production and a cost model. Production models estimate annual yield of a given aquaculture type (given a specified farm design for each type of aquaculture, described in detail below) within a site based on environmental conditions in that location (e.g. water temperature, currents, productivity, etc.). We then multiply that yield by a market price to determine annual revenue. Cost models incorporate effects of environmental conditions (e.g., wave height, depth) and geographic location (e.g., distance from port, depth) on operational and maintenance costs of the farm. Farm designs and cost estimates were based on aquaculture development plans from industry, which we then scaled to a 1-km^2 farm size. When necessary to respect confidentiality, we only report aggregated cost data. Additionally, much of the economic information provided by industry was preliminary, outdated and/or highly aggregated. Therefore, while the exact cost numbers are uncertain, they are internally consistent within an aquaculture type and thus are appropriate for evaluating spatial variation in aquaculture value. Given that offshore aquaculture is a relatively new industry (particularly for finfish), we expect significant technological improvements and knowledge acquisition over the coming years that are likely to change the productive output and operational costs of aquaculture. As for many new industries, we expect that in most cases these developments will make the industry more productive and more cost-effective, increasing the number of sites that would be profitable and providing a larger number of options for developing aquaculture while minimizing impacts and tradeoffs. Our models can be adjusted for these new scenarios in the future, and because of the rapidly evolving nature of the industry, we focus on spatial variation in productivity and profitability rather than absolute numbers.

For all farms, we assumed that costs (e.g., of fuel, labor) would not change over the 10-year evaluation period and that the farm equipment has a lifespan of at least 10 years. Since there is currently no cost for leases in federal waters, we excluded any lease cost in our models. There are costs associated with a lease in state waters[5], but we treated all sites equally in this respect so as to not bias development in favor of federal water sites. Deeper sites may have a larger bottom footprint due to the anchoring system design and therefore may be more difficult and costly to permit – issues that we do not explicitly address in our model. Some costs, especially administrative and maintenance costs, could decrease if the same company had farms in multiple sites, but we assumed that each farm is a separate, individually functioning entity and did not consider economies of scale.

For each aquaculture type, sites with negative value (NPV and annuity) were assumed to be undevelopable. These economic constraints, in addition to the logistical and regulatory spatial constraints (see Methods in main paper), restricted aquaculture development to 1,061 sites (Supplementary Fig. 1; 1,011 for mussel, 392 for finfish, and 325 for kelp). All calculations, unless otherwise indicated, were conducted using Microsoft Excel or MATLAB (MATLAB and Statistics Toolbox Release 2013a, The MathWorks, Inc., Natick, Massachusetts, United States).

Supplementary Note 3.

Mussel Aquaculture Production Model: The layout of modeled mussel farms was developed to reflect a feasible farm design for a 1-km^2 area based on industry practice within the Southern California region (Pers. Comm., B. Friedman, Santa Barbara Mariculture; Pers. Comm. P. Cruver, Catalina Sea Ranch). Specifically, each farm contains 100 longlines, each 210 m long and spaced 30 m apart. Each longline has 3,962 meters of fuzzy rope to which individual juvenile mussels are attached for grow-out; 328 individual mussels are seeded per meter of fuzzy rope. Thus, each farm consists of ~130,000,000 individual mussels. Growth of individuals in the production model continues until the summed weight of all individuals reaches 2,948,350 kg (an average of 0.023 kg per whole mussel), at which point a harvesting event occurs. Harvesting was assumed to be continuous throughout the year, meaning that lines are re-stocked immediately following harvest. We assumed farms can operate at full capacity every year over the 10-year evaluation period. Average annual yield for a farm was multiplied by an assumed wholesale price of farmed mussels of $3.30/kg to estimate the farm's annual revenue (Supplementary Fig. 2a). The wholesale price was approximated based on informal discussions with industry representatives, and is consistent with the ex-vessel value of *Mytlius edulis* landings in 2016 of $3.71/kg based on National Marine Fisheries Service commercial landings statistics (https://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index).

We used a dynamic energy budget model (DEB) to predict mussel growth[6]. DEB models have been used in ecological literature to describe energy fluxes in individuals, and have previously been applied to the growth of species under aquaculture conditions[7-9]. We parameterized the model based on the Mediterranean mussel (*Mytilus galloprovincialis*), since this is the only commercially grown mussel in southern California and is the most likely target species for future shellfish aquaculture development in the region[10]. The DEB model describes the rates at which an individual mussel consumes food and uses energy for growth, somatic maintenance, reproduction, and development. We assumed no natural re-seeding of the lines from mussel reproduction; spat procurement was included in the farm cost model. The rate of food consumption is primarily dependent on the size of the individual, food availability, and energy requirements at a given time. Growth parameters for the species followed Montalto et al.[11] and Kooijman et al.[12]. Food availability was determined using MODIS and SeaWiFS satellite derived spatial data to estimate the particulate organic carbon (POC) concentration in each developable site[13-15]. The OCM (Supplementary Note 1) also provided model inputs for each developable site including monthly average surface temperature, mixed layer depth, and current magnitude in the mixed layer, over years 2000 and 2001 neutral-condition El Niño Southern Oscillation years; [4]. See Supplementary Data 2 for a full list of model parameters.

The DEB model developed by Muller and Nisbet[6] was extrapolated to estimate the potential yield of an entire mussel farm. The DEB model estimates individual mussel growth as a function of food-carbon availability (for our purposes POC, measured in mgC). To apply this model to all mussels on a farm, we first modeled the dynamics of food availability within the entire farm array using a simple box-model approach. Using this method, the dynamics of food availability (and consequently mussel growth) are characterized by the input supply of POC into the volume occupied by the farm (the 'box') from the surrounding ocean, the consumption of POC by mussels within the farm, and the flux of POC out of the farm into the surrounding ocean. Next we made the following assumptions: 1) all mussels experience the same food availability regardless of position in the farm array, 2) POC concentration is uniform in the mixed layer, and 3) flux of water is constant throughout the volume occupied by the farm. Under these assumptions, the individual DEB model of mussel growth was applied to each mussel in the fixed-design farm array described above. The box-model of POC dynamics within the mussel farm is described as follows.

Under assumption (2) above, the rate of POC supply (in mgC s^{-1}), F_{in}, is calculated as the surface concentration of POC (in mgC m^{-3}), $X_{c(0)}$, multiplied by the flux of water (m^3 s^{-1}) entering the farm, r,

$$F_{in} = X_{c(0)} r \,, \qquad \text{(Sup Equ. 1)}$$

Where r is calculated as current speed, V (measured in m s^{-1}), multiplied by the cross-sectional area of the farm (measured in m^2), F_{area},

$$r = VF_{area} \,, \qquad \text{(Sup Equ. 2)}$$

And the cross-sectional area of the farm is computed as the width, W, of the site in which the farm is located (1,000m for 1km^2 sites) multiplied by the mixed layer, mld.

$$F_{area} = Wmld \,, \qquad \text{(Sup Equ. 3)}$$

Under assumption (3) above, F_{in} describes the rate of POC supply within each 'F_{area} x 1m' volume of the farm (in units of mgC). Given that the length of each site is 1000 m, the total POC input supply rate (in mgC s^{-1}) into the volume occupied by the entire farm array is 1000 x F_{in}.

The population of mussels within a given farm then consume available POC at a rate determined by,

$$C = nJ_x \,, \qquad \text{(Sup Equ. 4)}$$

where n is the number of mussels within a farm, and J_x is the scaled individual rate of food consumption, in mgC s^{-1} (parameter values and references are listed in Supplementary Data 2). Unconsumed POC then flows out of the farm at a rate, X_c, determined by mass balance at time (t). Therefore, under assumption (1), and using Sup Equ. 1-3, the dynamics of food availability over time (t) within the farm are governed by Sup Equ. 5, which states that the rate of change in total POC is the rate of supply minus the rate of consumption and the rate of outflow.

$$\frac{\partial POC}{\partial t} = 1000 X_{c(0)} r(t) - nJ_x - 1000 X_{c(t)} r(t) \,, \qquad \text{(Sup Equ. 5)}$$

Given this transition equation and the requisite input data (surface POC concentration, mixed layer depth, current speed), as well as mixed layer temperature (which is used in the DEB model), the time path of POC completely determines individual mussel growth, which (under all the previously stated assumptions) also completely determines farm-level yield and revenues.

Supplementary Note 4.

Mussel Aquaculture Cost Model: We developed a mussel cost model based on various industry projections for each 1-km^2 farm site that included both starting costs (including construction and equipment costs for the farm and hatchery) and annual operating costs (Pers. Comm., B. Friedman, Santa Barbara Mariculture; Pers. Comm. P. Cruver, Catalina Sea Ranch). Starting costs were assumed to be constant across locations and only incurred during the first year of production. Annual operating costs included two categories: fixed operating costs that are not sensitive to location, including vessel maintenance, vessel docking, and monitoring costs, and variable costs that vary in relation to farm location (described below). Fixed and variable operating costs then were combined into a single annual operating cost for each site and were combined with the starting costs in year one to estimate total average annual cost of the farm (Supplementary Fig. 3a). Annual revenue and costs were then used to calculate NPV and equivalent annuities (Eq. 1-2).

Variable (i.e. location-specific) operating costs, including fuel, labor, operations and maintenance costs, were estimated as follows. Fuel used for transport to the farm site was adjusted to account for distance from port. Locations of major fishing ports (San Diego, Mission Bay, Oceanside, Dana Point, Newport Beach, Long Beach, Redondo Beach, Marina del Rey, Port Hueneme/Channel Islands Harbor, Ventura, Santa Barbara, and Avalon on Catalina Island)[16] were digitized using Google Earth and their point locations imported into ArcGIS 10.2 (Supplementary Data 1). Distance to port was calculated for each site in the planning grid using the ArcGIS 10.2 Cost Distance tool, which calculates the distance to the nearest source (port) for each site in the raster, based on the least-accumulative cost over a cost surface (in this case, over-water sites are equally weighted and over-land sites are excluded so that travel is required to go around islands and headlands). We assumed two identical farm boats making trips to each farm: one going 5 days a week and one 3 days a week, resulting in 416 round trips to the farm site each year. Annual fuel costs (AFC) were thus approximated as:

$$AFC = \frac{TD_{port}F_eP_f}{s}, \qquad \text{(Sup Equ. 6)}$$

where T is the number of trips, D_{port} is the distance from port to the farm, s is the average boat speed, F_e is the fuel efficiency of the boat, and P_f is fuel price; see Supplementary Data 2 for parameter values.

Labor costs, L_t, were adjusted to account for the extra time it would take for transport to the farm site based on distance from port. We assumed that labor for each farm requires 8 workers to visit and service the farm 5 days a week, totaling 2080 worker days per year, and that each laborer would be paid $11 per hour, including for transport time to get to the farm site. Labor costs thus consist of fixed costs (8 hours per day for 2080 worker days) plus variable costs (transport time for every worker day), with labor costs increasing with distance from port to farm.

Operations and maintenance costs were adjusted to account for the increased costs associated with farming in locations with higher wave energy[17,18]. In order to account for this increased cost, we multiplied on-farm operations and maintenance costs (primarily consisting of labor costs; not including transport, seed, or hatchery costs) by a factor of 1.5 for sites which have a mean significant wave height greater than 1 m. While the exact relationship between waves and costs is not known and likely varies across operations, we based this estimate on the best available information from industry reports[18,19].

Total costs for on-farm operations and maintenance were also increased by 10% for farms located in greater than 50 meters depth. This cost increase accounts for SCUBA diving depth limits, which would likely result in higher costs for servicing to the anchoring systems or benthic monitoring (which is only a small part of total operational expenses) for farms located in deeper waters. Finally, the operational hatchery and seed costs were multiplied by the average number of growing cycles at each site per year (which depended on the productivity of the location). Taking all of these factors into account, the cost of operations amount to $2,123,576 to $3,219,202 per farm site per year, depending on the site.

Supplementary Note 5.

Kelp Aquaculture Production Model: There are no commercial kelp farms or kelp farm proposals in California, and thus our model of kelp aquaculture in Southern California is based on extrapolations from best estimates in the literature and from kelp aquaculture operations elsewhere. Most of our information on practices and design of kelp farms was informed by the kelp aquaculture industry[20] and a report issued by Irish Sea Fisheries Board on development and demonstration of seaweed aquaculture methodologies[21]. We parameterized our model based on the brown algae (kelp) *Saccharina latissima,* also known as *Laminaria saccharina*. Its farming methods are well known[20], and there is a proven high-end market for this product[22].

To model the growth and biomass production of kelp farms we used a dynamic individual growth model of *S. latissima* developed by Broch and Slagstad[23]. Parameters derived from Feldman and McClain[14] and OCM data were used to vary environmental conditions across sites (see Supplementary Data 2 for full parameter list). Additionally, we assumed that all kelp plants have access to the same amount of nutrients regardless of their placement within the farm, i.e., growth rates are the same for all individuals within a single farm[24].

We used a similar farm design for the kelp as was used in the mussel production model, with some notable exceptions. We assumed that kelp lines could be grown closer together than mussels, as they are generally cultivated closer to the surface, and do not require fuzzy rope for cultivation. As a result, we assumed that each kelp farm would consist of 200 lines, each 210 m long and set 20 m apart.

The overall start date and end date of a growing season was dependent on the seasonal availability of nitrate in each site. The growing season could potentially start as early as 1 October and end as late as 15 April of each simulated year (197 days). We chose to end the growing season mid-April because encrusting by bryozoans later in the season would likely decrease the value of farmed kelp[25]. Depending on the environmental conditions, the kelp may reach a maximum size before the end of the growing season. In this case, each individual kelp was trimmed by 75% and allowed to continue to grow until the end of the harvest season where it was subject to a final harvest. The trimmed plant area was then treated as harvested biomass and calculated for all sites.

There are two main markets for kelp – as a premium food product and as an ingredient in a diversity of products such as animal feeds and fertilizer, and as an emulsifying or stabilizing additive in products such as cosmetics and ice cream; [26,27]. There are also emerging markets such as the potential use of kelp for biofuels and in certain aquaculture feeds[28]. Currently the market for premium food products brings the highest prices[26]. However, it unclear how big this market is and at what level of production this market would become saturated. The type of operation that we modeled will only be profitable if a premium market is available. As a result we used a fixed market price of $3 per kg for all farms to calculate annual revenue (Supplementary Fig. 2b), acknowledging that this price may not be accurate if the premium market becomes saturated.

Supplementary Note 6.

Kelp Aquaculture Cost Model: Because of similarities in construction and servicing of kelp and mussel farms, the kelp cost model (Supplementary Fig. 3b) was based on the mussel cost model, and unless otherwise noted uses the same parameters, structure, and assumptions. For representing operational procedures particular to kelp farming[20-23], we made the following adjustments to the mussel cost model:

1. Starting costs were adjusted in three ways:
   - *Spacing:* Because kelp lines are placed more closely together than the mussel lines, starting costs were adjusted to account for the increased number of lines per farm.
   - *Longline gear and harvesting equipment reduced*: Loops of fuzzy rope are not needed for kelp farming, thus we eliminated the cost of the fuzzy rope from the equipment costs.
   - *Hatchery costs:* We approximated the start-up seed and hatchery costs based on the best available information. The Irish Sea Fisheries Board estimates the cost of setting up a hatchery to be $45,000[21]. This value was converted to US dollars at the rate of 1.43 dollars/Euro, which was the exchange rate in May of 2011 when the report was published. Since their case study farm is only 1/3 the size of the one used in our model, we multiplied this cost by three in order to represent potential farms in SCB in our model.

2. Labor needs for the farm were divided into the amount of labor required for seeding, maintenance, and harvest. The labor required for seeding was the same at all locations, but the amount of labor days needed for harvest depends on the amount of kelp produced (including final harvest and "trimming"). This harvest labor was calculated at the rate of 4 tons per day per person. The additional labor cost for transport was calculated in the same way as the mussel model.

3. Since our kelp model did not require multiple seeding events in a single year, operational seed and hatchery costs do not vary among farms, and thus were included in fixed rather than variable operational costs.

4. We removed the cost of mussel seed from the operating costs (since all kelp propagation is done in the hatchery).

5. We changed the yearly operational costs of the hatchery (included in fixed operating costs) to reflect the different hatchery process required for kelp. Costs were based on the Irish Sea Fisheries report, which estimates hatchery costs to be $130,871 annually[21]. We multiplied this cost by three (since our farm design is producing approximately three times the production of the Irish farm) to estimate the annual cost of a kelp hatchery.

Supplementary Note 7.

Finfish Aquaculture Production Model: To estimate the production of finfish aquaculture in the SCB, we used AquaModel[29-32], an advanced, proprietary, GIS-based modeling proprietary software package with a track record of being used by several domestic and foreign government agencies to estimate site-specific finfish aquaculture production and the associated benthic and water column environmental effects. AquaModel simulates the growth (based on a Von Bertalanffy growth function) and metabolic activity of cultured fish as well as the three-dimensional flow and transformation of nutrients, oxygen, and particulate wastes in adjacent waters and sediments. The fish growth and physiology components of the model consist of a nutrient budget for carbon, oxygen, and nitrogen, based on functions describing metabolism, ingestion, egestion, assimilation, respiration and growth as determined by the size of the fish, water temperature, dissolved oxygen concentration, swimming speed, feed rate and composition[33]. We focused on striped bass, *Morone saxatilis*, as the farmed species for finfish aquaculture because it has been modeled previously in AquaModel and was being considered for offshore aquaculture in southern California at the time of this study[34,35].

In our model, farm design and cost is based on a previous proposal by Hubbs-SeaWorld Research Institute [34] to develop a farm off the coast of San Diego in the SCB, and informed by personal communication with Hubbs-SeaWorld Research Institute aquaculture experts (Pers. Comm., D. Kent, Hubbs-SeaWorld Research Institute). Within a planning site we modeled one farm consisting of two rows of 25 m long by 25 m wide by 14.4 m deep surface cages in two rows of twelve cages each, for a total of 24 cages. The cages were stocked to a density of 0.2 kg fish per m^3 cage volume, with individual juvenile fish weighing 20 g at the time of stocking. Fish are then grown in the cages for 18 months ('grow-out period'). Environmental inputs into AquaModel that affect fish growth and vary for each location are monthly average surface and bottom temperature and mixed layer depth, annual average inorganic nitrate concentration calculated based on temperature[36], bathymetry, and the 3D continuous ocean currents through the farm, which are estimated by the OCM. The OCM flow fields consisted of 6-hour averaged three-dimensional horizontal velocity and temperature for every day between April 2000 and

October 2001. Oceanographic and biogeochemical parameters besides those mentioned above were held constant throughout our study domain. These constant input parameters were based on the default values for the striped bass module within AquaModel and adjusted as needed to reflect local conditions of the Southern California Bight (Supplementary Data 2).

AquaModel is a computationally-intensive program requiring a high speed computer or long processing times on normal desktop computers (it takes several hours on a desktop computer to simulate one farm, as model time steps are hourly or less in most cases). Therefore, it was impractical for us to run the model for all 913 potential finfish sites (of the 1,134 sites developed for aquaculture, 913 fell within the 30-100 m depth limits assumed for finfish aquaculture) in our study domain. To overcome this issue, we estimated biomass production based on the environmental conditions of a subset of the potential sites, and then extrapolated the results to the remaining sites. In order to choose sites that represented the full breadth of environmental conditions experienced in the SCB, we grouped similar sites together using cluster analysis based on average summer sea surface temperature, surface current, bottom current, and depth. We restricted temperature data to summer months for two reasons: (1) summer is the time of highest growth rates and greater environmental impact, and (2) summer and winter temperatures were highly correlated but summer temperature showed more differentiation among spatial locations. Previous studies have reported a strong relationship between temperature, metabolism, and fish growth [37], thus in our analysis we weighted temperature more strongly (40%) than the other three 3 variables (20% each for surface current, bottom current, and depth). The cluster analysis used the squared Euclidian distance and between groups linkage, calculated using SPSS statistical software, resulting in the 913 sites being grouped into 36 clusters. We chose this level of clustering because it balanced capturing differences in environmental conditions among sites with the time required to run the model for each site. We then randomly selected two sites from each cluster group to run in AquaModel (except for one group that only contained a single site).

Using the output from the 71 model runs, we used ordinary least squares regression, implemented in EViews8 software, to estimate finfish aquaculture farm production for the remaining 842 sites. We randomly divided the two observations of each cluster into a training and test set. The training set observations, along with relevant environmental conditions (mean surface summer temperature, mean surface summer current, mean bottom summer temperature, mean bottom summer current, average annual inorganic nitrate concentration, mean winter mixed layer depth, and depth of the seafloor beneath the aquaculture farm) were inputted into a forward stepwise regression model algorithm in order of highest correlation coefficient to identify potential linear models for forecasting finfish biomass in a given site. We then performed cross validation with the test data set to evaluate the accuracy of each model and determine the best number of predictors; the predicted values were compared to the test set's actual values by calculating the test mean squared error, which was used as the primary performance indicator. We then selected the model with the lowest test mean squared error as our final model for predicting finfish biomass.

The final regression equation included mean summer surface current, mean summer surface temperature, mean winter layer depth, and inorganic nitrate as predictors for estimating finfish biomass production in the remaining 842 sites ($R^2 = 0.983$, SE = 80948.03; see Supplementary Data 2 for predictor coefficients).

We assumed that the grow-out period from stocked juveniles to harvestable adults was 1.5 years. As a result, the estimated biomass was divided by 1.5 in order to calculate the average annual production of each developable site. We assumed that farms were not fallowed following harvest because our conservative farm design, water depths in which farms were sited, and current speeds in the Southern California Bight should preclude the need for fallowing. The model could be adjusted to include fallow years for contexts where that is the regulatory standard, which would result in far fewer sites being profitable for finfish aquaculture development.

The average annual production was then multiplied by a price of $8 per kg to determine average annual revenue (Supplementary Fig. 2c). This fixed price was based on price estimations of farmed striped bass[38].

Supplementary Note 8.

Finfish Aquaculture Cost Model: Costs for the finfish model were approximated based on projections for a previous industry proposal for southern California (Pers. Comm., D. Kent, Hubbs-SeaWorld Research Institute). The structure, parameters and assumptions of the fish cost model are consistent with the mussel cost model, with the following exceptions, many of which were determined by the aggregation level at which the data were shared with us (Supplementary Data 2; Supplementary Fig. 3c).

1. Starting costs were not calculated separately, but were instead incorporated into the annual operating expenses. This is due to the way that the fish cost data were aggregated, which integrated capital costs into yearly expenditures.

2. Since the proposed location of the farm for which we were basing our calculations was located in an area deeper than 50 m, we decreased the costs by 10% for all sites shallower than 50 m rather than adding costs for the deep sites (as was done with the mussel model).

3. All fish were harvested after 1.5 years, so there was no difference in the number of production cycles at each farm.

4. We estimated annual fuel costs directly as a function of distance from port (rather than estimating fuel consumption as we did with the mussel and kelp models). We calculated the annual cost of fuel at a rate of $15.00 per meter from port.

5. The production payroll costs were estimated to increase by $25.48 per meter from port. This was derived by multiplying estimated total labor costs by the percentage of employee time that would be taken up by transport to the site, and then dividing this by the distance from port.

Supplementary Note 9.

Halibut Fishery Biological Model: Aquaculture farms in the SCB could displace wild-capture fisheries. This conflict may be particularly strong (i.e., complete exclusion) for fisheries that use non-fixed gear (e.g., hook-and-line, trawls) to target fish that associate with nearshore soft-bottom habitat, as this type of activity would be prohibited in and around the farm because of concerns about gear entanglement. To represent this potential conflict, we modeled the *Paralichthys californicus,* or California halibut, fishery as it interacts with aquaculture development. *P. californicus* (hereafter referred to as halibut) is a flounder (Family *Pleuronectidae*) that associates with nearshore soft and mixed-sediment benthic habitat[39,40]. It is an important sport and commercial fishery species that is typically caught via hook-and-line, trawl, set gill net and trolling, and marketed as fresh fillet[41,42]. Commercial and recreational fishing occurs throughout much of the nearshore region of the SCB, except in marine protected areas and other designated restriction zones (e.g., military, anchorage, navigation). Overall, the SCB halibut fishery is considered to be well-managed at a population level approximately equal to that associated with maximum sustainable yield (MSY)[41].

We developed an age-structured population growth model to simulate the growth, natural mortality, movement and recruitment of individual halibut. We then integrated the population model with a halibut fishery fleet model containing spatial, size limit and fishing effort level regulations. In the resulting coupled bioeconomic model, fishery profit is a function of revenue from harvest and market price, less the cost of fishing in relation to fishing effort, local stock density and site distance from port. Model initial conditions were calibrated relative to current estimated mean distribution of halibut biomass in the SCB. In order to represent fishery values important to both the commercial and recreational halibut fishery, we focused on fishery yield as the metric of annual value. Values to parameters described below are listed in Supplementary Data 2.

The model contains 4,518 1-km^2 nearshore sites in the SCB covering all soft and mixed-sediment benthic areas within halibut's preferred depth range (≤90 m)[42,43]. Experimental trawling in the SCB determined halibut abundance to be highest in shallow habitats and to decline to near zero at 90 m depth [43]. To approximate that pattern, we fit a set of functions (linear, logarithmic, exponential and power univariate functions) to the abundance-depth data and chose the function with the highest fit, the logarithmic function ($y=a$*Ln(x) + b, where x=depth and y=frequency of halibut occurrence; R^2=0.97; Supplementary Data 2). For each site in the model we multiplied the value of the function at the site's mean depth by the area of soft and mixed-sediment habitat in the site to generate a relative index of habitat availability, or $H_i=A_i*y_i$, where A_i is area of soft and mixed-sediment habitat in site i and y_i is the depth at the centroid of site i (see Supplementary Fig. 4a for a map of relative habitat indices).

The population model kept track of the number of post-recruit fish of each age class in each site and year, and their size (total length; cm) and weight (biomass; kg) in accordance with Von Bertalanffy growth[44] and allometric weight-at-length functions:

$$L_t = L_\infty\left(1-e^{-K(t-t_0)}\right), \text{ and} \qquad \text{(Sup Equ. 7)}$$

$$W = aL^b, \qquad \text{(Sup Equ. 8)}$$

where t is age in years, L_∞ is the asymptotic fish length (i.e., mean maximum size), κ is fish intrinsic growth rate, and t_0 is theoretical fish age at size zero (Supplementary Data 2). The parameters a and b determine the multiplicative and exponential effect of fish length on biomass, respectively (Supplementary Data 2). Sexual maturity is reached for halibut at ~4 years old[16], and each year larvae are produced by reproductive-aged individuals at a rate proportional to their mass.

Halibut larval dispersal and site-to-site connectivity was estimated using a three-dimensional biophysical model, which consisted of the OCM (Supplementary Note 1) and a particle tracking model (PTM). The PTM was driven by six-hour averaged flow fields produced by the OCM that moved particles forward in time using a fourth-order accurate Adams-Bashforth-Moulton predictor-corrector method[45,46]. The PTM was validated against observational data from drifter experiments[47].

Larval connectivity was quantified statistically using the Lagrangian probability density function (PDF) method[46,48] that estimates larval connectivity from a source site to a destination site by quantifying the probability of particle displacement over a specified time period. To incorporate the larval life history of halibut, the particles were tracked for 25 days, the PLD of halibut larvae, and released from May through December, the spawning period for halibut[41]. Additionally, halibut larvae have been documented to perform diel vertical migrations[40], which was programmed into the PTM. The particle release frequency was set at 12 hours to meet the criteria for robustness in PTMs[49]. Following the methods in Mitarai et al.[46], the coastline of the SCB was evenly divided into 135 coastal sites of approximately 75 km^2 each. Annual connectivity matrices were calculated between the coastal sites for each spawning season from 1996-2002 and then averaged over all years. The individual 1-km^2 halibut sites were assigned the connectivity values for the nearest coastal sites, producing a 6,425 site by 6,425 site dispersal kernel, a subset of which covers all 4,518 sites in the halibut fishery model.

Populations in the model are regulated by density dependent mortality occurring between larval settlement and recruitment[50]. Site-specific settler-recruit relationships are regulated by a Beverton-Holt function[51]. Each year the number of ‘age one’ fish recruiting in site *i*, N_{i1}, is dependent on number of settling larvae arriving into the site according to the OCM-generated dispersal kernal, S_i, and parameters α, representing the maximum recruit survival rate, and β_i, which regulates the maximum number of recruits possible in that site:

$$N_{i,1} = S_i R_i , \qquad \text{(Sup Equ. 9)}$$

where

$$R_i = \frac{\alpha}{1 + S_i \beta_i} \qquad \text{(Sup Equ. 10)}$$

and

$$\beta_i = \frac{\alpha}{R_{\max} H_i} , \qquad \text{(Sup Equ. 11)}$$

and R_{max} equals the maximum number of recruits possible per unit habitat, and H_i is the habitat availability index in the site.

Jointly, α and R_{max} set the strength of density dependence and affect fish population biomass and potential yield biomass levels in the whole system. Thus, we chose α and R_{max} to achieve empirically-estimated levels of density dependence and biomass levels of halibut in the SCB. We used the compensation ratio (CR) as our measure of density dependence[52,53], where CR describes the ratio between the maximum possible larval survival and larval survival in the unfished state, and is estimated to be CR=16 (corresponding with a steepness parameter *h*=0.8) for Family *Pleuronectidae*[41,54].

The commercial and recreational SCB halibut fishery, in the aggregate, is considered to be well-managed and approximately achieving maximum sustainable yield (MSY)[41]. Also, empirical records exist of annual commercial and recreational halibut landings in the SCB. Thus, we set R_{max} to generate, under MSY management conditions, a biomass yield equal to that measured empirically for the fishery in the SCB. In the model, MSY management was achieved by setting total allowable fishing effort (TAE), regulated across the entire study domain and distributed among fishable sites in accordance with a fishery fleet model (see below), to the level that maximized total sustainable yield. Empirical measurements of halibut biomass yield in the SCB were determined using the stock assessment by Maunder et al.[41]. Total abundance of halibut landed per year in the SCB by the recreational fishery (Table B1.6.1 in Maunder et al.[41] was multiplied by the average weight of a landed halibut by the recreational fishery (2.7686 kg; the mean of the PDF of recreational landings by fish weight; Fig. B2.8.2 in Maunder et al.[41]). These annual estimates of recreational fishery biomass yield were added to the annual biomass yield for the commercial fishery (Table B1.6.1 in Maunder et al.[41]). Total annual biomass yields were then averaged across 2004-2010 to estimate an average total halibut fishery yield in the SCB (177,779 kg per year). We focused our evaluation on the the most recent years in Maunder et al.[41], 2004-2010, because they are the closest to the present and these years represent the fishery when it is estimated to have been highly stable and at near-MSY conditions. Thus, in the bioeconomic model and given a total allowable fishing effort level generating MSY, R_{max} was set to return a total equilibrium annual yield equivalent to 177,779 kg per year.

Movement of post-recruit halibut among sites was simulated using a 2-D diffusion model parameterized with data from a mark-recapture study of halibut in and around the SCB. The 2-D diffusion model was modified to account for preferential movement in relation to habitat quality. For the diffusion model we used a normalized Gaussian function of a 2-D probability distribution that quantifies probability of movement from focal site $i=x$ to destination site $i=y$ in relation to the rate of diffusivity of the species, D, distance between the sites, $r_{x,y}$, and elapsed time, d. The probability of movement is assumed uniform in all horizontal directions; the analytical solution to this 2-D isotropic diffusion equation is known as Green's function[55,56]:

$$G_{x,y} = \frac{e^{\left(-r_{x,y}^2/4Dt\right)}}{4\pi Dd}, \qquad \text{(Sup Equ. 12)}$$

where d=365 days/year and $r_{x,y}$ is the distance between the centroids of sites $i=x$ and $i=y$. For calculating site fidelity within a site, $y=x$. We assumed the system was closed with respect to halibut movement, and thus standardized Sup Equ. 12 so that the probability of movement from each focal site to all sites in the domain sums to one:

$$G_{x,y}^S = \frac{G_{x,y}}{\sum_{y=1}^{Y} G_{x,y}} \qquad \text{(Sup Equ. 13)}$$

When exhibiting directed movement, animals generally have higher movement rates toward sites of higher habitat quality (and/or will stay in their current site if it is of higher habitat quality than nearby sites). Following Cheung et al.[57], we modeled such behavior by incorporating a hyperbolic function into the calculation of halibut movement:

$$G_{x,y}^{S,k} = \frac{kG_{x,y}^{S}}{K + H_{i=y} \big/ H_{i=x}}, \qquad \text{(Sup Equ. 14)}$$

where k is a scaling factor representing the sensitivity of the calculated movement rate to changes in habitat quality[58], which is indicated in the denominator by the ratio of habitat quality relative to the focal site. Small values of k (e.g., k=0.1) result in high sensitivity to the habitat ratio, while large values (e.g., k=10) render adult movement rate insensitive to the habitat ratio. We used an intermediate value, k=2, used previously in the literature for marine fishery species[57]. Finally, to maintain a closed system of adult movement we rescaled the solution to obtain the realized rate of movement, $M_{i,i}^{a}$, that we used in the population model:

$$M_{i=x,i=y}^{a} = \frac{G_{x,y}^{S,k}}{\sum_{y=1}^{Y} G_{x,y}^{S,k}}, \qquad \text{(Sup Equ. 15)}$$

We used the exponential survival function for calculating post-recruit halibut mortality in relation to instantaneous natural mortality rate, M, and fishing mortality rate, F_i, which is equal to site-specific fishing effort multiplied by a catchability coefficient, $E_i q$, and applied only to legally-harvestable halibut age classes. Without loss of generality, we set q equal to 1. Legal-to-harvest age limit was set to 5 years old, corresponding with the legal-to-harvest size limit of 22 inches in total length for the SCB halibut fishery and the conversion from size to age determined by Sup Equ. 7-8. Instantaneous natural mortality rate was set to M=0.25, the average of female and male rates used in the stock assessment of the species in southern California by Maunder et al.[41]. Fishing effort (E_i) was determined in relation to TAE and the fleet model.

In site i, the number of fish of age $j+1$ at the end of the year, $N_{i,j+1\_end}$, is a function of the natural and fishing mortality rates in the site and of the population of fish age j at the beginning of the year:

$$N_{i,j+1\_end} = N_{i,j\_beginning}\, e^{-(F_i + M)} \qquad \text{(Sup Equ. 16)}$$

where F_i equals zero for all age classes j that are not legal to harvest.

For each legally harvestable age class, the site-specific proportional biomass loss due to mortality is equal to $1 - e^{-(F_i + M)}$. Of this mortality loss, the amount attributable to the fishery (as opposed to natural mortality) is proportional to the relative rate of fishing versus natural mortality in that site, $F_i/(F_i + M)$. Thus, in each year fishery yield per site per fishable age class j is:

$$Y_{i,j} = N_{i,j\_beginning}(1-e^{-(F_i+M)})(F_i/F_i+M) \quad \text{(Sup Equ. 17)}$$

Halibut also have a maximum age of ~27 years[41], although very few individuals reach it. At the maximum age, natural mortality is 100%.

Given the above parameter values, Supplementary Fig. 4b illustrates the model estimate of equilibrium virgin (unfished) spawning stock biomass of halibut across the study domain with F_i=0. At MSY our model estimated spawning stock biomass to be 24.24% of virgin spawning stock biomass; this has been considered a reasonable reference point of sustainable halibut fisheries management[41] and thus a indication that our model is representing the status of the fishery resonably well.

Supplementary Note 10.

Halibut Fishery Economics and Fleet Model: Commercial and recreational halibut fishing is restricted by numerous conservation, military, navigation and other regulated zones across the study domain. Thus in our model we restricted positive fishing effort from all sites within those areas (Fig. 1a).

In order to represent fishery values important to both the commercial and recreational halibut fishery, we focused on fishery yield as the metric of annual value (for calculating net present value and annuity), and, given that the fishery is considered to be well-managed and approximately achieving maximum sustainable yield (MSY)[41], in our model we set total allowable fishing effort (TAE) to the level that generated MSY. However, it is also of interest to know the potential economic value of the fishery in terms of profit. Fishery profit is a function of total revenue from harvest (TR) less the total cost of fishing (TC):

$$\pi = \sum_i (TR_i - TC_i), \quad \text{(Sup Equ. 18)}$$

Total revenue is a function of market price and yield,

$$TR_i = pY_i \quad \text{(Sup Equ. 19)}$$

We set price to p=\$10.67 per kg (\$4.84 per lb), equal to the ex-vessel dollar value divided by biomass landings of commercial halibut in southern California by year, averaged across 2004-2011, the years when the halibut stock assessment confirmed the catch and biomass to be relatively stable[41]. Linear and exponential regression of annual price in relation to biomass landings did not reveal a significant relationship that would be indicative of the presence of an inelastic demand curve (i.e., reduction in price with increased supply). We also used regression analysis to test for a negative relationship between annual price of halibut and biomass landings of California white seabass (white weakfish; *Atractoscion nobilis*)[41], which is a high-value seafood species with a mild, firm and flaky white meat that is marketed as fish fillet and is similar to the striped bass, *Morone saxatilis*, represented by our aquaculture finfish model. This regression analysis also returned non-significant results. Consequently, we assumed halibut price to be constant in our model analysis.

In our model, cost of fishing per unit area in each site was initially calculated in relation to the change in stock density in the site over the fishing period due to fishing (and natural) mortality.

$$TC_i^a = \int_{s_i=\left(N_{i,end}^{legal}/H_i\right)}^{s_i=\left(N_{i,beginning}^{legal}/H_i\right)} c\left(s_i\right)\partial s \qquad \text{(Sup Equ. 20)}$$

where s_i is the biomass density of legal-to-harvest fish in site *i.* Marginal cost, $c(s_i)$, is a decreasing function of resource stock density in the site (i.e., $c'(s_i)<0$; i.e., higher fish stock density reduces per-unit harvest cost). We modelled marginal cost of fishing to be inversely proportional to local fish density, $c(s_i) = \theta/s_i$, where parameter θ determines the stock density below which marginal cost equals price and thus fishing is expected to naturally cease (higher values of θ represent species that are intrinsically more expensive to harvest)[59,60]. Fishing cost and its effect on fishing behavior are difficult to quantify[61], but in general it is sometimes assumed that marginal cost equals price when the legal-to-harvest fish stock is reduced to 10% of its virgin carrying capacity, and at this level represents the "break even" stock density below which it is unprofitable to fish and the fishing naturally ceases[16,60]. Ten percent of virgin stock density also is commonly considered to indicate collapse of a stock and its associated fishery[62]. Consequently, we set θ in order to produce a marginal cost equal to price at a fish stock density equal to 10% of the mean virgin legal-to-harvest stock density across the study domain. Cost was then converted from per unit area to per unit site, $TC_i^p = TC_i^a H_i$.

Cost of fishing also is expected to be a function of travel distance to the fishing ground[63]. To include this factor, cost of fishing in a site was modulated in relation to its level of isolation,

$$TC_i^{\gamma} = TC_i^p\left(1+\gamma D_{i-port}\right), \qquad \text{(Sup Equ. 21)}$$

Where γ is a scaling parameter and D_{i-port} is the distance in meters from site *i* to its nearest port. Finally, cost is incurred by the fishery to the extent that the observed reduction in stock density is due to fishing effort, as opposed to natural mortality. Consequently, the cost in a site to the fishery is a function of the proportion of morality in the site due to fishing versus natural mortality,

$$TC_i = TC_i^{\gamma}\left(\frac{F_i}{F_i+M}\right) \qquad \text{(Sup Equ. 22)}$$

Empirical data on the spatial distribution of halibut landings were used to set the travel cost scaling parameter γ. Empirical measurements of commercial and recreational halibut fishery yield in the SCB were determined using Pacific Coast Fishery Geographic Information Systems fisheries landings data ("PacCoastFisheryGIS" data) generated under the California Department of Fish and Wildlife Statewide Marine Protected Area Management Project. The spatial resolution of the data corresponds with the California Department of Fish and Wildlife 1' (~10 km) fishing blocks, of which there are 87 in the SCB in our model domain. Overall, the empirical data indicates halibut landings to be concentrated along the mainland and near ports (Supplementary Fig. 5a), supporting the assumption that travel cost influences the spatial distribution of fishing effort[63].

Using the PacCoastFisheryGIS data, we "tuned" γ in order to minimize the sum of squared error (SSE) between the empirical data and our model estimate of the proportion of total biomass landings in the study domain from each reporting block. The tuning procedure generated minimum SSE=0.017113, and linear correlation between the empirical and model values of R^2=0.62. The resulting model estimate of the spatial distribution of landings is shown in Supplementary Fig. 5b. Given the tuned value of γ (6.0708e-05), travel costs increased total annual fishing cost in a site by a factor of ~0-4 along the mainland and ~2-7 at the Channel Islands, depending on their specific distances from the nearest port.

In the California halibut fishery and other limited-entry fisheries, the spatial pattern of fishing effort (e.g., fishermen, boats) among sites is expected to be a function of the relative value of the sites; this pattern can be estimated using a fleet model[16,64,65]. Consequently, we determined the spatial allocation of the total allowable effort (TAE) by the fishery using an ideal free distribution[66] fleet model, such that average profits (profit per unit effort) were equal among all fishable sites (i.e., those that contain halibut and are non-MPA, non-military, aquaculture, etc. sites; Supplementary Figs. 1 and 4a). Note that this behavioral model of fleet dynamics, while potentially representative of the actual relationship between vessel and resource distributions in fisheries[67,68], is not necessarily expected to produce the optimal pattern of spatial effort distribution (e.g., by a sole owner or fishery cooperative) that maximizes the total value of the fishery[69]. MSY management was achieved by setting total allowable fishing effort (TAE), regulated across the entire study domain and distributed among fishable sites in accordance with the fleet model, to the level that maximized total equilibrium yield. As explained above, parameter R_{max} was set to achieve a MSY matching that estimated empirically (177,779 kg per year).

Equilibrium MSY management was used as the initial conditions in the model when evaluating effects of aquaculture development on the halibut fishery. Given an aquaculture development plan, sites with aquaculture were closed to halibut fishing immediately (i.e., in year 1) and continuing through year 10 (the end of the evaluation time horizon), and Net Present Value of the halibut fishery was calculated in response to this closure (Eq. 1-2).

In order to make the halibut bioeconomic model compatible with the tradeoff model framework, which required static models for our optimization approach, we assumed fisheries value in each of the 10 years following aquaculture development to be represented by the yield values generated under MSY conditions, but with zero yield in the new closures due to the aquaculture farms. This simplification excludes the ecological dynamics of larval dispersal and fish spillover, and socioeconomic dynamics affecting changes in the spatial distribution of fishing effort among fishable sites, that are present in our dynamic model and could occur in response to new closures from aquaculture farms. However, our focus on static model values is not expected to generate significantly different results compared with if the fully dynamic model were incorporated into the tradeoff analysis, for two reasons. First, the halibut fishery already is managed at MSY, and thus there are unlikely to be dramatic ecological or fleet behavior changes from closing some sites to fishing. Second, the time horizon is short (10 years), limiting the development of a long-term dynamic response to a change in management decision; i.e., the short-term dynamic response is not much different than the static response estimate. Both of these reasons are supported by Brown et al.[70], which specifically compared dynamic and static models for conducting MSP. Nonetheless, in order to provide the most accurate estimates possible, once an MSP solution (i.e., aquaculture farm design on the 7-D efficiency frontier) had been identified by the tradeoff model, we then evaluated its effect on the halibut fishery using the fully dynamic bioeconomic model. In that case, sites with aquaculture were closed to halibut fishing, the bioeconomic halibut fishery model was simulated forward in time 10 years, and yield in each year was recorded. We also used the fully dynamic bioeconomic halibut fisheries model for evaluating effects of the plans derived under conventional planning. Consequently, we estimated and reported the actual effect on the halibut fishery of all of the aquaculture farm designs presented in this study based on the fully dynamic halibut model described above.

Supplementary Note 11.

Viewshed Model: New development can change the aesthetic qualities of a place. The potential impact of aquaculture development or other emerging uses on views and scenic values is a frequent concern expressed by stakeholders[71,72]. Though scant evidence exists that offshore aquaculture development decreases coastal real estate values[73], community members may still oppose aquaculture development because they are concerned about changes in scenic values and impacts on tourism, recreation, and property values. For these reasons, other regions have modeled and analyzed the visual impact of new aquaculture development on surrounding areas[73,74]. We developed a modeling approach that assesses how many people's views could be affected by placement of a farm in each site, incorporating both residential views and recreational views from state parks and beaches.

We ran the ArcGIS 10.2 Viewshed tool to identify all locations on land from which a given developable site would be visible within a defined radius of visibility. Based on previous work and our assumptions about farm design, we assumed that mussel and kelp farms would not be visible beyond a 3-km radius[75], while finfish farms would be visible up to 8 km away[73]. We assumed the height of a viewer on land to be 1.7 m tall (the average height of adult men and women in the United States) and infrastructure of all farm types would be primarily horizontal structures on the water plane (including linear patterns of buoys for kelp and mussels, net pens for fish, and navigational lighting for both), extending vertically less than 1 m. Inputs to the model were the locations of the centers of each developable site (a shapefile of points) and a high resolution (90-m) raster digital elevation model of land (DEM; Supplementary Data 1). Data were not available to incorporate trees or buildings into the DEM, though we acknowledge that both could affect actual visibility from a given location (i.e., blocking views or allowing farms to be viewed further away from an upper story of a building). We used an earth curvature correction factor and a refractivity coefficient of 0.13, the default settings for the Viewshed tool. This part of the analysis produced rasters of which sites on land can view each farm. We then determined how many people's views would be impacted given the distributions of residential populations and visitors to state parks and beaches within impacted sites on land, for each possible aquaculture site.

For residential views, we summed the number of people living in impacted view areas on land using a 30-m grid of human population density supplied by the Natural Capital Project[76]. For scenic and recreational views, we assessed which farms would be visible from state parks and beaches and calculated the number of park or beach visitors who would potentially be affected by that farm location, based on total annual visitor attendance data (day use and campers) from the 2011/12 Fiscal Year[77]. Because there are not data on where visitors spend time within a state park or beach, we assumed that a view of the farm from any part of the park or beach would affect all visitors. Also, we recognize that there are other important locations for scenic recreational viewing beyond state parks and beaches (e.g., county parks, coastal roads and highways), but we were not able to obtain consistent use data across our study domain for these other areas and so just focused our analysis on state parks and beaches. Lastly, it is important to note that not all state parks and beaches collect and/or report visitation data, so this dataset is far from complete, and should be treated as a demonstration of what is possible rather than a definitive estimate for where impacts would be highest. For an actual permitting or planning exercise, it would be important to fill gaps in the scenic and recreational dataset.

The outputs of the viewshed analysis were rasters of which sites on land can view each farm, summed residential population within the viewshed of each farm, state parks and beaches within the viewshed of each farm, summed annual visitors to state parks and beaches within view of each farm, and the total number of people whose views would be affected by each farm (summed across residential and park/beach visitors). For the calculation of value for this sector used in the tradeoff analysis, we combined residential and recreational views into a single metric representing the number of people whose views could be affected by the development of each site (Supplementary Fig. 6a,b). The weighting of residential versus recreational viewshed impacts could be adjusted to reflect the relative importance of the two components to stakeholders or decision-makers in a particular planning context. We chose to sum the number of people because there was not information for southern California upon which to judge the relative value stakeholders place on uninterrupted residential versus recreational views.

Supplementary Note 12.

Benthic Environmental Health Model: Offshore aquaculture can generate negative environmental impacts, particularly with regards to pollution, and limiting negative impacts is typically a key focus in planning for future aquaculture development[5,78,79]. The magnitude of these effects is generally heavily influenced by operational characteristics, such as species farmed, stocking density, and feeding strategy, but also by farm location[79] and thus spatial planning should take into account spatial variability in possible environmental impacts. Specifically, the physical and chemical characteristics of the surrounding environment, such as background nutrient levels, currents, and depth, are important in determining the fate and impact of any pollutants released from the farm[80,81]. Both fed and unfed aquaculture operations release particulate organic matter (such as feces, or uneaten feed in the case of fed aquaculture) that can settle to the seafloor where it can lead to eutrophication and local oxygen depletion in and near the benthos[82,83]. The community level effects of increased nutrients and decreased oxygen on the benthos can vary significantly based on the level of impact and background conditions; indeed, low levels of nutrient enrichment can have a minor effect and may even increase benthic biodiversity and biomass[84,85]. However, for the purpose of this analysis we take a precautionary approach that assumes that any changes to the benthic environment are not desirable. Generally deeper water and faster currents result in more diffusion of organic material, which will minimize any adverse effects, but also create a larger footprint of benthic areas potentially affected by the farm[80,81]. While shellfish operations have been shown to have benthic impacts in shallow sheltered areas, field studies of offshore shellfish operations have shown that there is unlikely to be any benthic impact in the deeper open ocean environments that are generally typical of offshore aquaculture operations[86]. We therefore focused on impacts to the benthos only from finfish aquaculture, since this impact often is listed as a primary concern by the aquaculture industry and public stakeholder groups[5,79].

Benthic impacts were estimated using AquaModel (Supplementary Note 7). Specifically, we used the model to estimate the total organic carbon (TOC) flux to the seafloor as a proxy for the risk of a given farm producing hypoxic or anoxic conditions on the seafloor near the farm. AquaModel simulates both the flux of particles containing organic carbon and the resuspension and re-distribution of these particles as they are assimilated by the benthic food web. We focus on organic carbon flux because organic carbon is the source of the potential problems to sediments (such as shifts to anaerobic bacterial dominance when the rate of deposition exceeds the aerobic assimilative capacity). Furthermore, the effect of additional organic carbon on the biogeochemical characteristics of the sediment and the microbenthic infauna are well understood [87], and these measures are the basis for all aquaculture sediment effect models. We calculated the average TOC flux to the seafloor (g per m^2 per day) at each aquaculture site to provide a relative measure of potential organic enrichment. This measure does not account for resuspension rates, so is a conservative index of potential effect and allows us to identify sites that may be at higher risk to experience benthic impacts. The model runs used to estimate TOC flux were the same as described in Supplementary Note 7 to estimate biomass production. The same method, including cluster analysis and stepwise regression, was used to extrapolate from the 71 sites that were run in AquaModel to estimate TOC rate for the 842 potential finfish sites that were not run in AquaModel (Supplementary Fig. 6c). The coefficients in the regression equation can be found in Supplementary Data 2 ($R^2 = 0.83$, SE = 0.055).

Supplementary Note 13.

Disease Risk Model: Risk of disease outbreak often is used as a justification for opposition to aquaculture development[79]. Two primary types of infectious agents are often identified as vectors for aquaculture disease, viruses and bacteria[88,89]. While the widespread use of antibiotics and vaccines have been very effective against bacterial pathogens, viral infection remains a significant problem for the aquaculture industry[90]. Viral disease risk appears to be highest for finfish farms (relative to shellfish and algae), due to the use of feed made from the carcasses of other fish species, which greatly increases the risk of exposure to novel pathogens[88,89]. Although the risk of viral disease outbreaks is strongly influenced by husbandry practices (stocking density, feed characteristics, etc.), there is also a spatial planning dimension to disease risk. Specifically, viruses could potentially travel between farms via pelagic dispersal, meaning farm design and farm density in relation to ocean currents could influence the risk of disease transmission and system-wide outbreak. We therefore focused on modeling oceanographic connectivity among finfish farms as an indicator of risk of viral disease outbreaks in relation to alternative spatial plans of finfish aquaculture development.

Marine viruses have life stages in which they are inside their host (e.g., a fish) and dispersing between hosts in the water[91]. Because finfish are contained within the farm pens, we focused on the dispersive stage of the virus in connecting farms and potentially spreading disease. To do this, we utilized the three-dimensional ocean circulation model (Supplementary Note 1). When outside of their hosts, viruses degrade rapidly within a matter of hours due to UV radiation[92]. Thus, in the OCM we simulated viruses with a dispersal period (akin to a "pelagic larval duration") of one day, in order to estimate the distance a single virus could travel within the study domain before being destroyed by UV exposure[49]. Using the simulation outputs we generated a probability density function (PDF), or dispersal kernel, for each developable finfish site given the fixed spatial constraints (see Methods in main paper). The dispersal kernel for disease transport was estimated using the same methods described for halibut larval dispersal (Supplementary Note 9), except that in the particle tracking models the particles were released year-round and only from sites that may be developed for finfish aquaculture (i.e., of positive NPV value to that sector), and they dispersed passively (i.e., no vertical migration or other behavior) for 24 hours.

We applied network analysis to the viral dispersal kernel to estimate relative risk of a system-wide disease outbreak of a given finfish farm plan. The goal of the network analysis was to calculate the degree of centrality of each potential fish farm site to all other potential fish farm sites, then use this information to penalize farm plans that develop highly central "hub" sites most likely to support disease transmission among farms throughout the study area. We did this by evaluating the eigenvector centrality for each potential finfish farm site in a proposed spatial plan. Eigenvector centrality is often cited as a primary way to identify disease hubs in weighted networks[93,94]. Unlike many other centrality metrics, eigenvector centrality takes into account the complete topology of the entire network, instead of just assessing the strength of direct connections, meaning that the centrality of a single node is dependent on both direct and indirect connections between nodes (in our case, farms). To calculate eigenvector centrality for each site we first estimated maximum potential disease risk by considering the scenario where all potential finfish aquaculture farms are developed. Using the dispersal kernel as the adjacency matrix for the disease network, we calculated the eigenvector centrality of each developable site using the equation from [95]:

$$Ax_i = \lambda x_i \qquad \text{(Sup Equ. 23)}$$

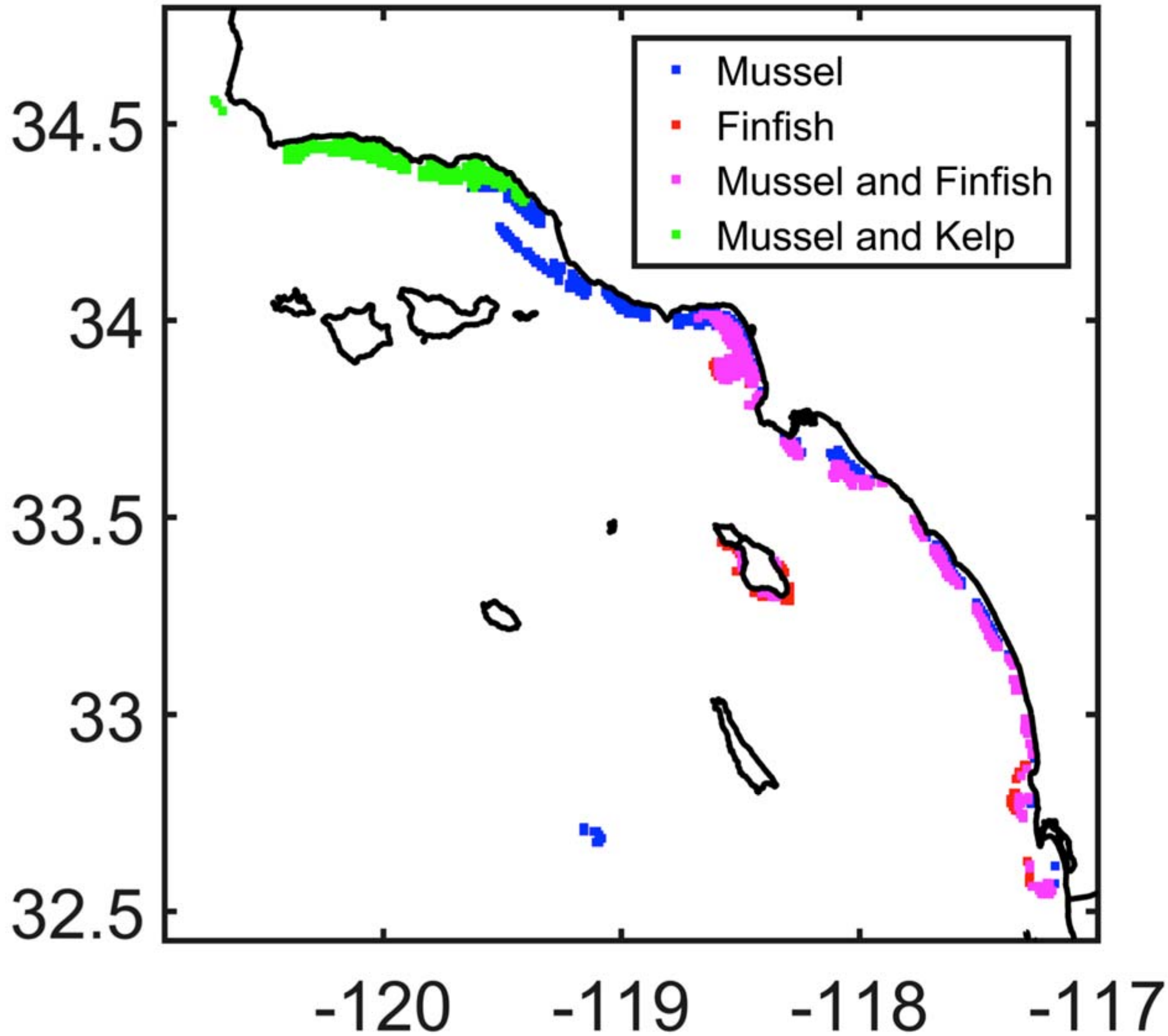
where x is the eigenvector of a given site i in the disease adjacency matrix, A, with an eigenvalue, λ. As explained by the Perron–Frobenius theorem, λ is the largest eigenvalue and x the corresponding eigenvector[96] for a given site. Thus, the value λ represents the degree of centrality for a given site, which we used to represent the disease response to finfish aquaculture at that site. For a given spatial plan of aquaculture development, total risk of disease spread of the entire plan was calculated as the sum of the eigenvector centrality values of the developed sites (Supplementary Fig. 6d).

Supplementary Table 1: Steps for implementing the full MSP analytical model.

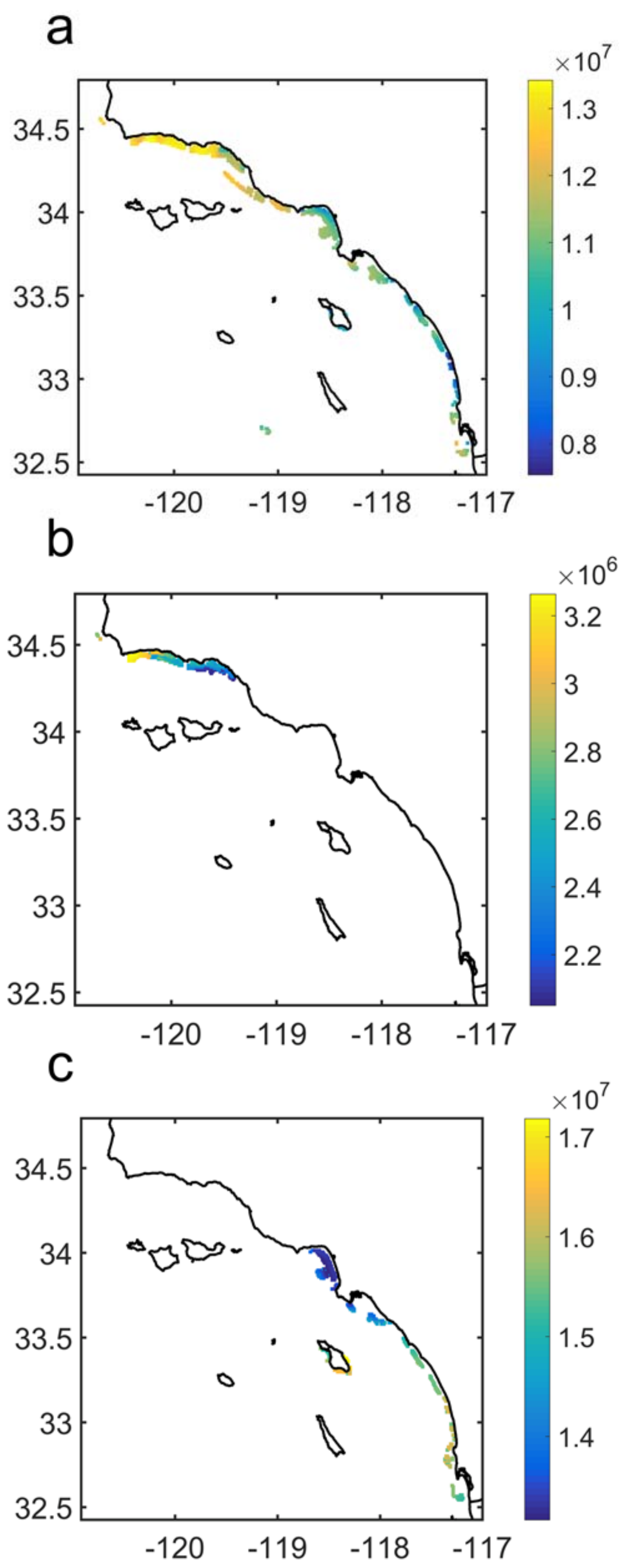
Step	Significance	Case study description
• Specify study domain • Identify emerging sectors and key existing sectors of concern in relation to emerging sector development	• Delineates the spatial planning problem • Acknowledges environmental impacts and socioeconomic conflicts that may be generated by emerging sectors	• Study domain: Southern California Bight • Emerging sectors: mussel, finfish and kelp aquaculture • Impacts and existing sectors: halibut fishery, benthic health, viewshed quality, risk of disease outbreak
• Identify and delineate potential development locations for emerging sectors	• Constrains spatial planning problem to feasible sites for development	• Aquaculture development restricted from fixed sites: military areas, shipping lanes, protected areas, rocky substrate, minimum and maximum depth zones, and areas around sewage outfalls and major river mouths • Identified 1,061 feasible sites for at least one type of aquaculture
• Generate spatial models of the existing and emerging sectors and their interactions	• Explicitly characterize interactions between existing and emerging sectors	• Spatially-explicit biological and socio-economic models of the three emerging and four existing sectors, modelled across all feasible sites
• Apply all potential policy options to the sector models across all feasible sites	• Quantifies site-specific sector responses to the alternative policy options • Sector responses can represent values or impacts, and can be in different units	• Model response of each sector to each of four policy options at each site: no development, or development of mussel, finfish or kelp aquaculture • Aquaculture and halibut fishery sector responses represent value (in economic annuity) • Benthic health, viewshed quality and risk of disease outbreak sector response represent impact (in various units)
• Convert impacts into values • Estimate the value to each sector for each policy option at each site	• Aligns sector valuations, such that, for all sectors, higher numbers are more beneficial to the sector	• For benthic health, viewshed quality and risk of disease outbreak sectors, value for a policy option at a site calculated as the maximum response by the sector across all sites and policy options minus the sector's modelled response to the policy option at the site

		• For aquaculture and halibut fishery sectors, value is equal to the sector's modelled response
• Transform all sector values to a common, unitless scale (i.e., where the value equals the proportional contribution of each policy option at each site to each sector's total potential value)	• Transforms sector values into comparable units	• For each sector, its scaled value is the value of the sector at a given site, under a given policy option, divided by the maximum total potential value (i.e., the summed value if the ideal policy option for that sector was selected at every site)
• Apply weighting factors to each sector's scaled values	• Accounts for different relative socio-political preferences for each sector • Different combinations of preference weights can be used to evaluate different priorities, or when priorities are uncertain or unspecified	• All combinations of six weights $\{\alpha_n = 0, 0.2, 0.4, \ldots 1\}$ were applied across the seven sectors, generating $6^7 = 279{,}936$ results indicating the weighted value to a sector at a site from implementing one of the policy options
• For a particular set of preference weights, generate a marine spatial plan solution by selecting the policy option at each site that maximizes the sum of weighted sector values • Calculate the domain-wide outcome of that plan for each sector	• Indicates an optimal spatial plan, and associated sector impact and/or value, in relation to specified priorities across sectors (i.e., preference weights)	• The marine spatial planning solution illustrates the optimal policy option (i.e., aquaculture development option) for each of the 1,061 sites, where, for each site the selected option best maximizes the sum of the seven weighted sector values • Outcome indicates how the plan will affect each sector in terms of its response and/or proportional change in impact or value
• Replicate the above step for each set of sector-specific weights	• Identifies the set of spatial plans that delineate the efficiency frontier of marine spatial plan solutions that optimally balance the tradeoff in values and impacts among the interacting sectors	• A seven-dimensional, 279,936-point efficiency frontier of marine spatial plan solutions of optimal aquaculture development in relation to the values of the three aquaculture and four existing sectors and their interactions

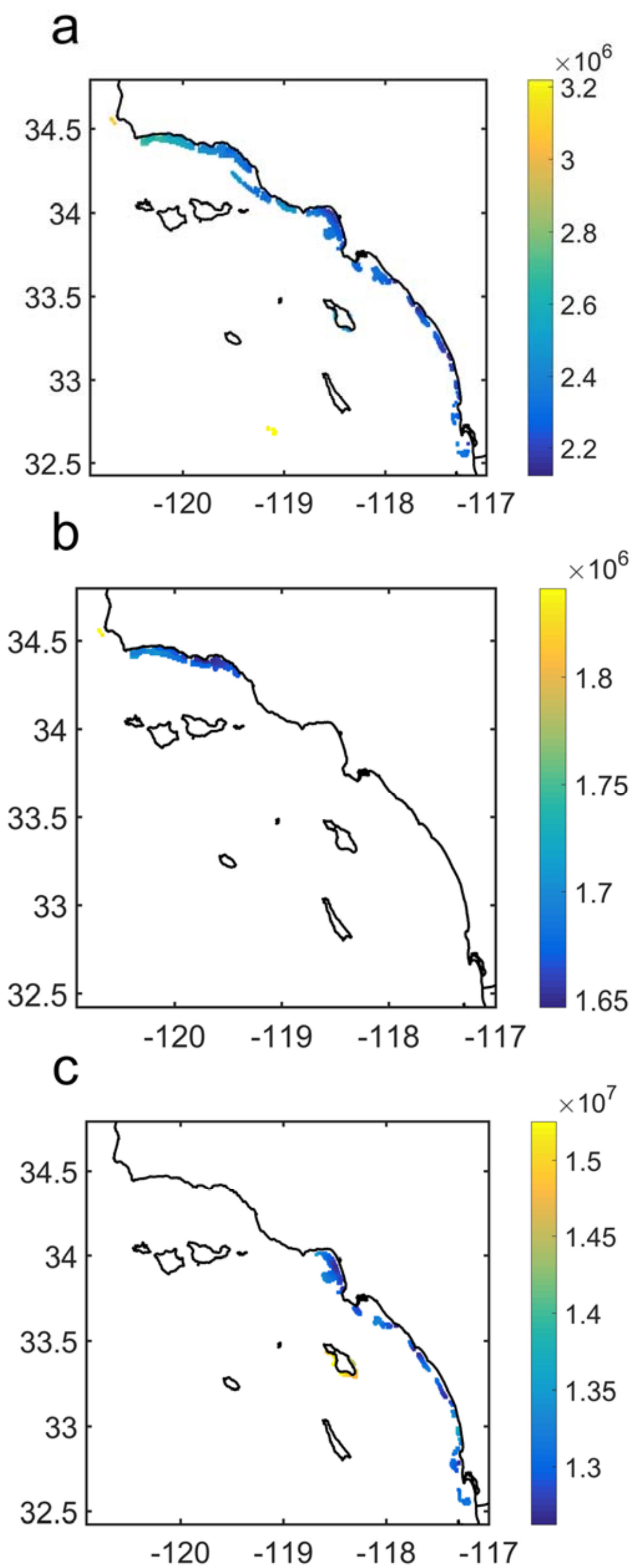
Supplementary Figures



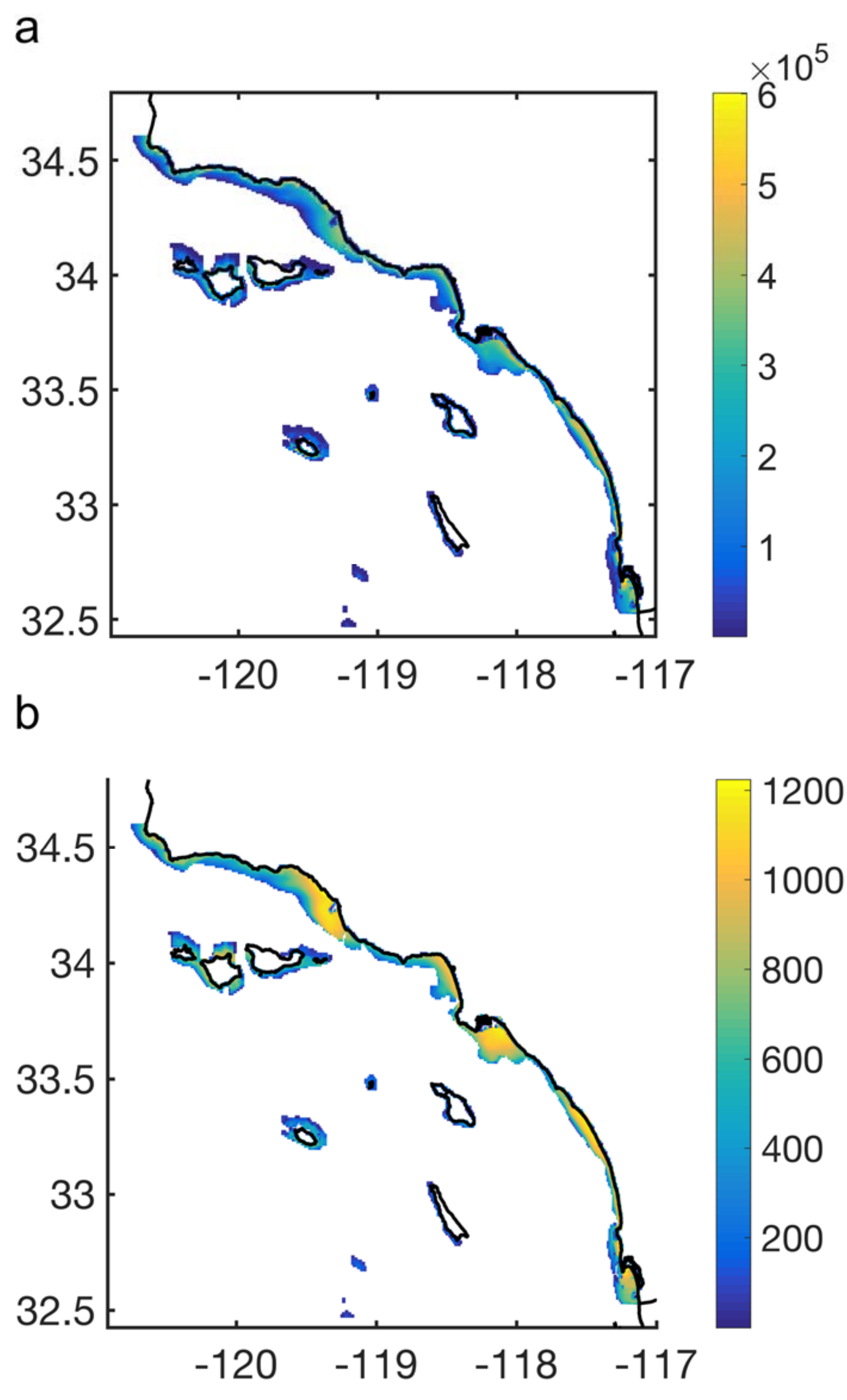
Supplementary Figure 1: Development domains of the three forms of aquaculture, given the imposed logistical, sociopolitical, and economic constraints.



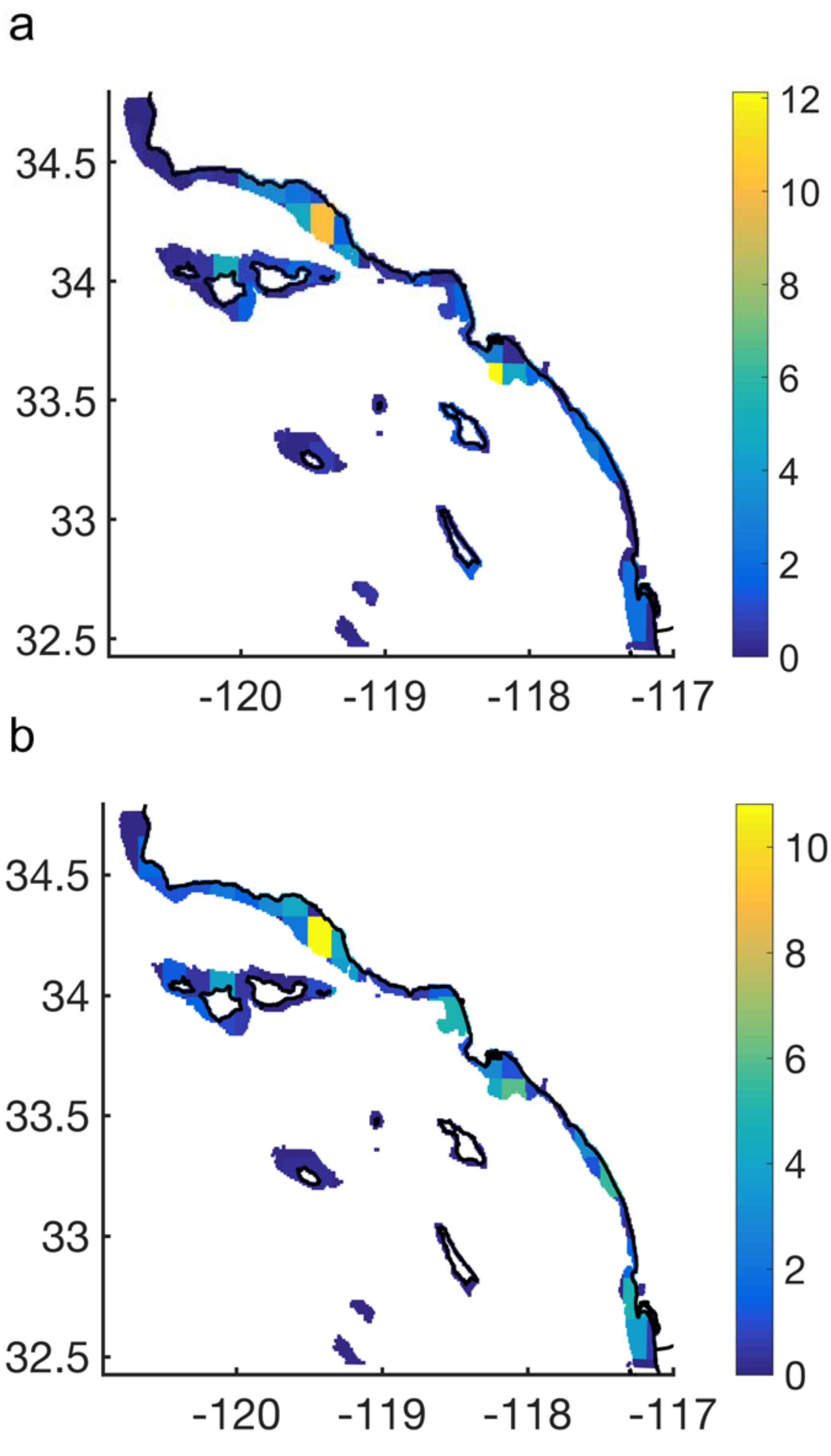
Supplementary Figure 2: Modelled annual revenue of (a) mussel, (b) kelp, and (c) finfish aquaculture for each site, in US dollars.



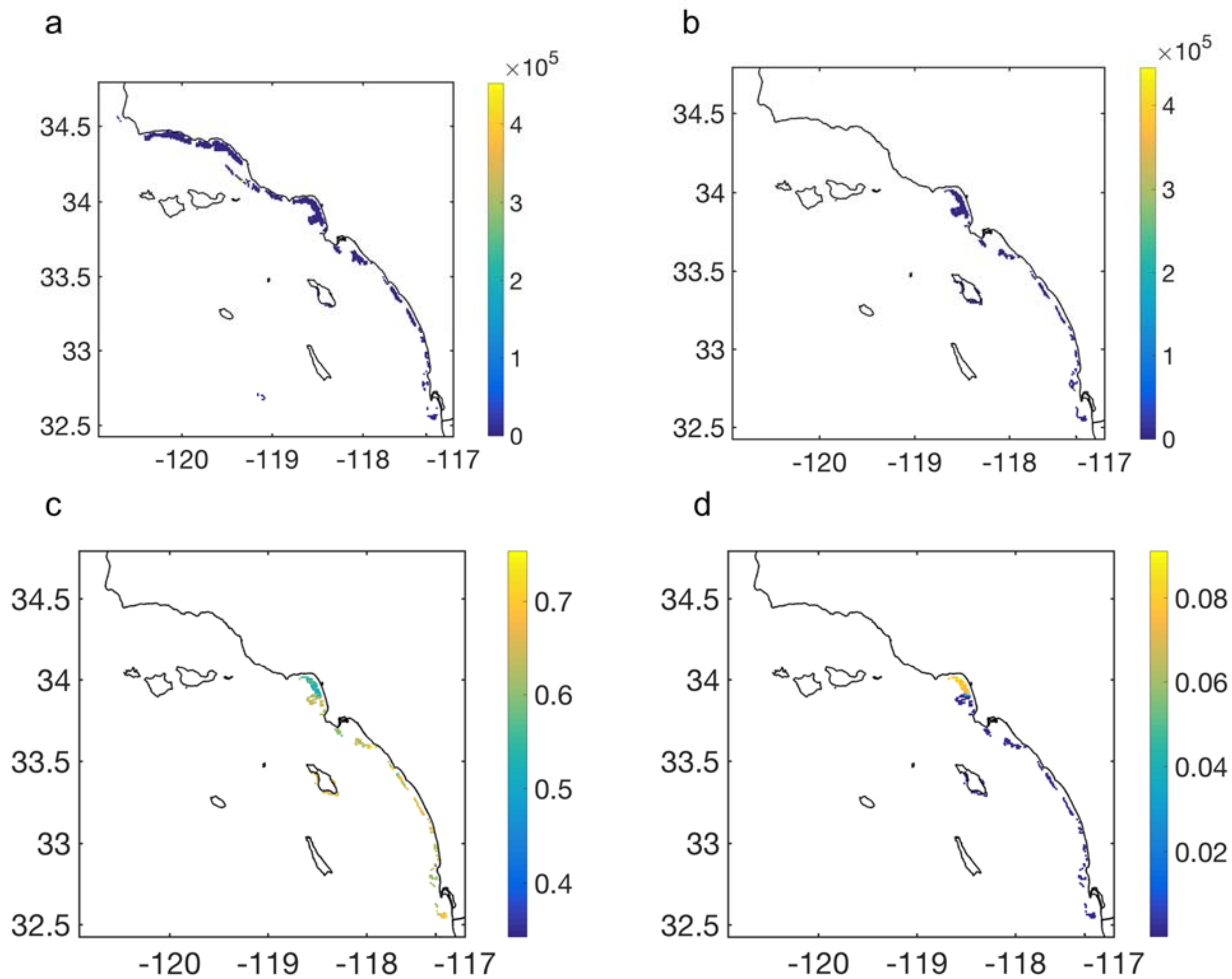
Supplementary Figure 3: Potential annual costs of (a) mussel, (b) kelp, and (c) finfish aquaculture for each site, in US dollars.



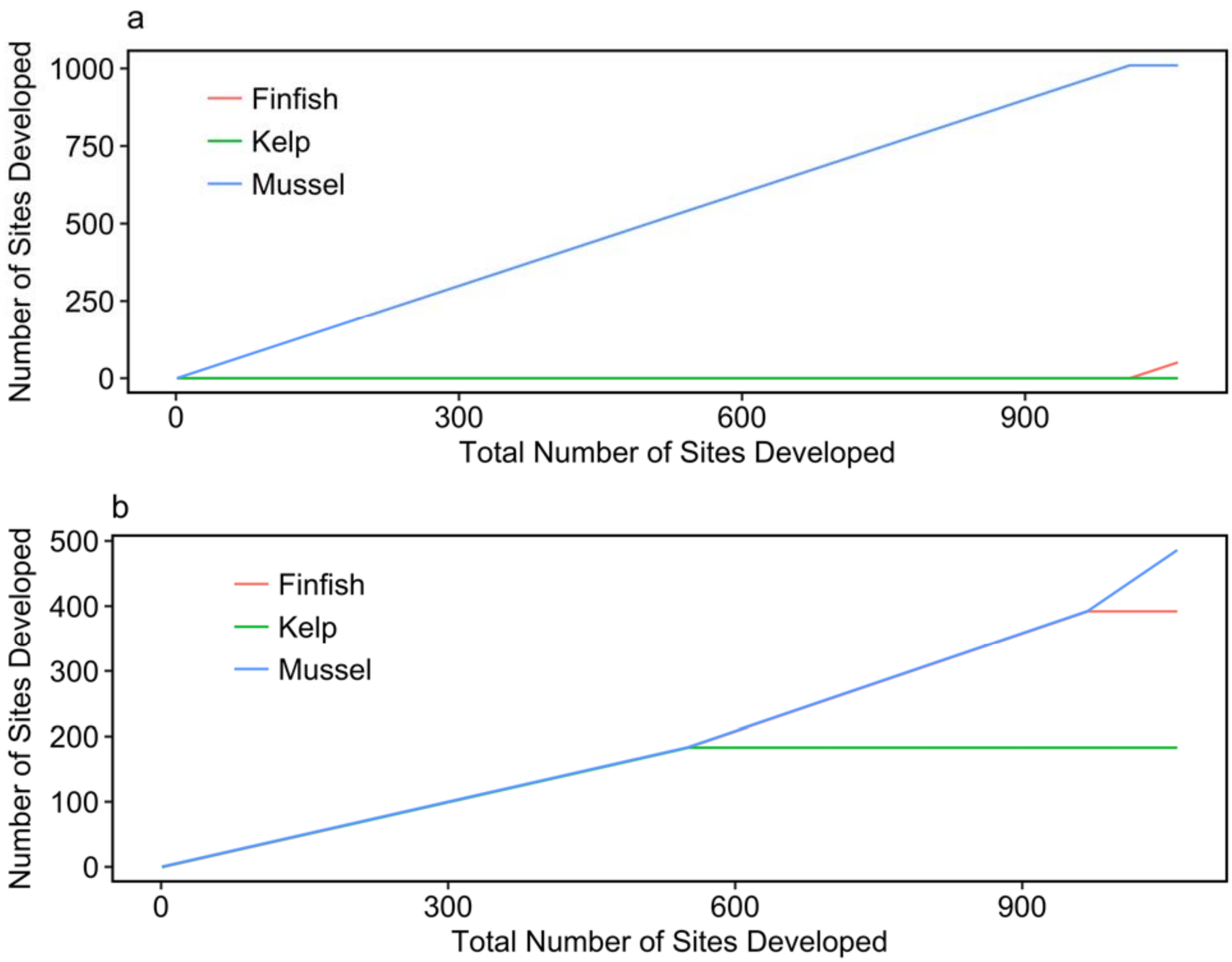
Supplementary Figure 4: (a) Halibut habitat index, used for characterizing relative availability of suitable habitat in each site. The index was calculated for each site as the logarithmic function derived from the Haugen[43] data and evaluated at the site's depth, multiplied by the area soft and mixed-sediment habitat in the site. (b) Model estimate of halibut spawning stock biomass density (kg per km^2) in a world without fishing.



Supplementary Figure 5: (a) Empirical data of the proportion of total halibut fishery landings in each California Department of Fish and Wildlife reporting block. (b) Model estimate of halibut fishery landings (kg per km^2).



Supplementary Figure 6: Coastal viewshed impact (number of impacted people by a farm) of mussel and kelp farms (a) and finfish farms (b) at each site. (c) Benthic impact (TOC flux) for each developable finish site. (d) Potential disease risk (in terms of eigenvector centrality) for each developable finfish site.



Supplementary Figure 7: Number of sites developed by each aquaculture type, given unconstrained (a) and constrained (b) approaches to conventional planning.

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Description of Additional Supplementary Files

File Name: Supplementary Data 1
Description: **Spatial data layers.** Source, year and weblink for spatial data layers used in analyses and by component models.

File Name: Supplementary Data 2
Description: **Model parameters and variables**. Model parameters and other variables used in component models, including values and supporting references.

Supplementary Data 1. Spatial data layers				
Analysis Component	**Layer**	**Source**	**Year**	**URL**
Base layers	Coastline at mean high tide (Coastn83)	California Department of Fish and Wildlife, Marine Region GIS Lab	unk.	ftp://ftp.dfg.ca.gov/R7_MR/BASE/
Habitat mapping	California Geology Series - Continental Margin (GMA_#_HAB, where # is 1-7)	ref. 106; California Seafloor Mapping Lab	1987	http://arcims.csumb.edu/DATA_DOWNLOAD/CAGeologySeries.zip
Habitat mapping	Predicted substrate (central and south)	California Department of Fish and Wildlife, Marine Region GIS Lab	unk.	ftp://ftp.dfg.ca.gov/R7_MR/HABITAT/
Habitat mapping	10m bathymetry for Southern California Bight	California Seafloor Mapping Program; California State University Monterey Bay (CSUMB) Seafloor Mapping Lab	2014	http://seafloor.otterlabs.org/SFMLwebDATA_CSMP_SouthernCal.htm
Habitat mapping	Hillshade from 10m bathymetry	California Seafloor Mapping Program; CSUMB Seafloor Mapping Lab	2014	http://seafloor.otterlabs.org/SFMLwebDATA_CSMP_SouthernCal.htm
Habitat mapping	Vector Ruggedness Measure from 10m bathymetry	California Seafloor Mapping Program; CSUMB Seafloor Mapping Lab	2014	http://seafloor.otterlabs.org/SFMLwebDATA_CSMP_SouthernCal.htm
Constraint mapping	California State Marine Protected Areas (MPA_CA_Existing_130101)	California Department of Fish and Wildlife, Marine Region GIS Lab	2012	https://www.wildlife.ca.gov/Conservation/Marine/GIS/Downloads
Constraint mapping	De Facto Marine Protected Areas in U.S. Waters	National Marine Protected Areas Center	2005	http://marineprotectedareas.noaa.gov/dataanalysis/defacto/
Constraint mapping	Channel Islands National Marine Sanctuary (cinms_py)	NOAA, National Marine Sanctuaries Program	2008	http://sanctuaries.noaa.gov/library/imast/cinms_py2.zip
Constraint mapping	Wastewater outfall locations	ref. 107; Heal the Ocean	2010	http://healtheocean.org/research/detail/california_ocean_wastewater_inventory
Constraint mapping	Major river mouth locations	ref. 108	2011	n/a
Viewshed model inputs	Southern California Coastal Relief Model, v.1	National Geophysical Data Center, 2003. U.S. Coastal Relief Model - Southern California. National Geophysical Data Center, NOAA. doi:10.7289/V500001J. NOAA National Centers for Environmental Information	2003	http://www.ngdc.noaa.gov/mgg/coastal/grddas06/grddas06.htm
Viewshed model inputs	California Coastal Access Points	California Department of Fish and Wildlife, Marine Region GIS Lab, based on California Coastal Access Guide	unk.	ftp://ftp.dfg.ca.gov/R7_MR/CULTURAL/
Viewshed model inputs	Terrestrial Managed Areas	California Resources Agency Project and The Nature Conservancy; California Department of Fish and Wildlife	unk.	n/a
Viewshed model inputs	Human Population Density	ref. 86; Natural Capital Project	2013	n/a
Halibut model inputs	Halibut trawl grounds (MAN_SCSR_HalibutTrawlGrounds)	California Department of Fish and Wildlife, Marine Region GIS Lab	2003	ftp://ftp.dfg.ca.gov/R7_MR/MANAGEMENT/
Halibut model inputs	Port locations	this study, digitized in Google Earth	2014	n/a

Supplementary Data 2. Model parameters and variables					
Model	**Description**	**Inputs**	**Parameter**	**Value**	**Source (see Supplementary references)**
Mussel	Growth Model Parameters	Energy conductance	v_{ref}	0.01359 cm d-1	ref. 11
Mussel	Growth Model Parameters	Maintenance rate coefficient	kM_{ref}	0.00447539 d-1	ref. 11
Mussel	Growth Model Parameters	Maintenance ratio	$Maint_{ratio}$	0.446888	ref. 11
Mussel	Growth Model Parameters	Yield of reserves from food	y_{EX}	0.696818 mol mol-1	ref. 11
Mussel	Growth Model Parameters	Yield of structure from reserves	y_{VE}	0.878007 mol mol-1	ref. 11
Mussel	Growth Model Parameters	Aspect ratio	d_m	0.1989	ref. 11
Mussel	Growth Model Parameters	Fraction of reserves committed to growth +	K	0.9283	ref. 11
Mussel	Growth Model Parameters	Conversion efficiency of reserves to gonad	k_r	0.95	ref. 11
Mussel	Growth Model Parameters	Density of structure	$Mv_{density}$	0.0041841 mol cm-3	ref. 11
Mussel	Growth Model Parameters	Maturity at puberty	Ehp	97.41 J	ref. 11
Mussel	Growth Model Parameters	Chemical potential of reserves	m_e	550000 J mol-1	ref. 11
Mussel	Growth Model Parameters	Structural length at puberty	L_p	0.753047 cm	ref. 11
Mussel	Growth Model Parameters	Max specific feeding rate	Jx_{max}	0.0000783383 mol C d-1 cm-2	ref. 11
Mussel	Growth Model Parameters	Arrhenius temperature	T_a	3243 K	ref. 11
Mussel	Growth Model Parameters	Reference body temperature	T_{ref}	293 K	ref. 11
Mussel	Growth Model Parameters	Half saturation constant	Fh	0.0000000121 mol C m-3	ref. 11
Mussel	Growth Model Parameters	Carbon content	$C_{content}$	0.034	ref. 97
Mussel	Growth Model Parameters	Initial length	Lw_{init}	0.03 cm	ref. 6
Mussel	Growth Model Parameters	Reserve carbon: Structural carbon	mE_{init}	1.3168	ref. 6
Mussel	Growth Model Parameters	Gonad carbon	M_{init}	0 C mol	ref. 6
Mussel	Growth Model Parameters	Initial mussels	n_{init}	130000000	ref. 6
Mussel	Growth Model Parameters	Temperature	$Temp$	K	OCM
Mussel	Growth Model Parameters	Current speed	V	cm d-1	OCM
Mussel	Growth Model Parameters	Mixed layer depth	Mld	M	OCM
Mussel	Growth Model Parameters	Particulate organic carbon	X_e	mol C cm-3	ref. 15
Mussel	Economic Parameters	Mussel market price	P	$3.3 per kg	See supplementary notes
Mussel	Cost Model Parameters	Number of trips to a mussel farm in a year	T	2080	See supplementary notes
Mussel	Cost Model Parameters	Distance from port to farm	D_{port}	Variable	Calculated in this study
Mussel	Cost Model Parameters	Average boat speed	S	8 miles per hour	See supplementary notes
Mussel	Cost Model Parameters	Boat fuel consumption	F_e	16 gallons/hour	See supplementary notes
Mussel	Cost Model Parameters	Diesel cost	P_f	$4.10/gallon	Market price
Mussel	Cost Model Parameters	Labor costs	L_c	$11 per hour	See supplementary notes
Mussel	Cost Model Parameters	Labor hours	L_t	8 hours plus transport time	See supplementary notes
Mussel	Cost Model Parameters	Starting costs	CS	$3,941,300	See supplementary notes
Mussel	Cost Model Parameters	Fixed annual operating costs	FC	$1,719,604	See supplementary notes
Mussel	Cost Model Parameters	Variable annual operating costs	VC	Determined by cost model	Calculated in this study
Kelp	Kelp Production Model Parameters	Frond area	A_o	6 dm^2	ref. 23
Kelp	Kelp Production Model Parameters	Photosynthetic efficiency	a_e	3.75 e-5 g C dm-2 h-1	ref. 23
Kelp	Kelp Production Model Parameters	Minimal carbon reserve	C_{min}	0.01 g C g sw-1	ref. 23
Kelp	Kelp Production Model Parameters	Carbon per dry weight structural mass	C_{struct}	0.2 g C g sw-1	ref. 23
Kelp	Kelp Production Model Parameters	Exudation	g	0.5 g C g sw-1	ref. 23
Kelp	Kelp Production Model Parameters	Frond erosion	e	0.22 A-1	ref. 23
Kelp	Kelp Production Model Parameters	Irradiance for max photosynthesis	I_{sat}	200 umol photons m-2 s-1	ref. 23
Kelp	Kelp Production Model Parameters	Max nitrate uptake rate	J_{max}	1.4 e-4 g N dm-2 h-1	ref. 23
Kelp	Kelp Production Model Parameters	Structural dry weight per area	k_A	0.6 g dm-2	ref. 23
Kelp	Kelp Production Model Parameters	Dry weight to wet weight ratio	k_{dw}	0.0785	ref. 23
Kelp	Kelp Production Model Parameters	Mass of carbon reserves to gram carbon	k_C	2.1213 g (gC)-1	ref. 23
Kelp	Kelp Production Model Parameters	Mass of nitrogen reserves to gram nitrogen	k_N	2.72 g(gN)-1	ref. 23
Kelp	Kelp Production Model Parameters	Growth rate adjustment parameter	$m1$	0.1085	ref. 23
Kelp	Kelp Production Model Parameters	Growth rate adjustment parameter	$m2$	0.03	ref. 23
Kelp	Kelp Production Model Parameters	Max area specific growth ratio	μ_{max}	0.18 day -1	ref. 23
Kelp	Kelp Production Model Parameters	Min nitrogen reserve	N_{min}	0.01g N(g sw)-1	ref. 23
Kelp	Kelp Production Model Parameters	Max nitrogen reserve	N_{max}	0.22 g N(g sw)-1	ref. 23
Kelp	Kelp Production Model Parameters	Amount of nitrogen per unit dry weight	N_{struct}	0.01g N(g sw)-1	ref. 23
Kelp	Kelp Production Model Parameters	Max photosynthetic rate at T=TP1K	$P1$	1.22 e-3 g C dm-2 h-1	ref. 23
Kelp	Kelp Production Model Parameters	Max photosynthetic rate at T=TP2K	$P2$	1.44 e-3 g C dm-2 h-1	ref. 23
Kelp	Kelp Production Model Parameters	Photoperiod parameter	$a1$	0.85	ref. 23
Kelp	Kelp Production Model Parameters	Photoperiod parameter	$a2$	0.3	ref. 23
Kelp	Kelp Production Model Parameters	Respiration rate at T = T R1	$R1$	2.785 e-4 g C dm-2 h-1	ref. 23
Kelp	Kelp Production Model Parameters	Respiration rate at T = T R2	$R2$	5.429 e-4 g C dm-2 h-1	ref. 23
Kelp	Kelp Production Model Parameters	Reference temperature for respiration	T_{R1}	285 K	ref. 23
Kelp	Kelp Production Model Parameters	Reference temperature for respiration	T_{R2}	290 K	ref. 23
Kelp	Kelp Production Model Parameters	Arrhenius temperature for photosynthesis	T_{AP}	1,694.4 K	ref. 23
Kelp	Kelp Production Model Parameters	Arrhenius temperature for photosynthesis at high end of range	T_{APH}	25,924 K	ref. 23
Kelp	Kelp Production Model Parameters	Arrhenius temperature for photosynthesis at low end of range	T_{APL}	27,774 K	ref. 23
Kelp	Kelp Production Model Parameters	Arrhenius temperature for respiration	T_{AR}	11,033 K	ref. 23
Kelp	Kelp Production Model Parameters	Current speed at which J = 0.65*Jmax	$U_{0.65}$	0.03 m s-1	ref. 23
Kelp	Kelp Production Model Parameters	Nitrate uptake half saturation constant	K_X	4 umol L-1	ref. 23
Kelp	Kelp Production Model Parameters	Irradiance	I	umol photons m-2 s-1	ref. 98
Kelp	Kelp Production Model Parameters	Water temperature	T	C	OCM
Kelp	Kelp Production Model Parameters	Current speed	U	m s-1	OCM
Kelp	Kelp Production Model Parameters	Nitrate concentration	X	mmol L-1	OCM, ref. 36
Kelp	Economic Parameters	Kelp market price	p	$3/kg	See supplementary notes
Kelp	Cost Model Parameters	Number of trips to a kelp farm in a year	T	Variable based on harvests	Calculated in this study
Kelp	Cost Model Parameters	Distance from port to farm	D_{port}	Variable	Calculated in this study
Kelp	Cost Model Parameters	Average boat speed	S	8 miles per hour	Based on mussel model
Kelp	Cost Model Parameters	Labor days for seeding		14	ref. 20
Kelp	Cost Model Parameters	Labor days for mid-season maintenance		1/week	ref. 20

Kelp	Cost Model Parameters	Labor days for harvest		Total production (tons)/4	ref. 20
Kelp	Cost Model Parameters	Labor cost	L_c	$11/hour	Based on mussel model
Kelp	Cost Model Parameters	Starting costs	*SC*	$2,978,250	Adjusted from mussel model; refs. 20 and 99
Kelp	Cost Model Parameters	Fixed annual operating costs	*FC*	$1,542,608	Adjusted from mussel model; refs. 20 and 99
Kelp	Cost Model Parameters	Variable annual operating costs	*VC*	Determined by cost model	Calculated in this study
Finfish	Production Model Parameters	Surface temperature	T_s	C	OCM
Finfish	Production Model Parameters	Bottom temperature	T_b	C	OCM
Finfish	Production Model Parameters	Mixed layer depth	*mld*	M	OCM
Finfish	Production Model Parameters	Inorganic nitrate concentration	*X*	mmol L-1	Calculated based on temperature; ref. 36
Finfish	Production Model Parameters	3D continuous current fields	*Gij*	Determined by ROMS	OCM
Finfish	Production Model Parameters	Bathymetry	*d*	M	OCM
Finfish	Production Model Parameters	Cage stock density	*D*	0.2 kg fish per m3 cage volume	ref. 34
Finfish	Biomass linear model coefficients	Intercept		-2446040	Calculated in this study (regression model)
Finfish	Biomass linear model coefficients	Mean summer surface current		-9521	Calculated in this study (regression model)
Finfish	Biomass linear model coefficients	Mean summer surface temperature		303743	Calculated in this study (regression model)
Finfish	Biomass linear model coefficients	Mean winter mixed layer depth		6552	Calculated in this study (regression model)
Finfish	Biomass linear model coefficients	Inorganic nitrate		-107107	Calculated in this study (regression model)
Finfish	Cost Model Parameters	Fixed annual operating expenses	*FC*	$12,665,661	See supplementary notes
Finfish	Cost Model Parameters	Fuel cost per meter from port		$15	See supplementary notes
Finfish	Cost Model Parameters	Additional labor cost per meter from port		$25.48	See supplementary notes
Finfish	Economic Parameters	Finfish market price	*p*	$8/kg	ref. 38
Halibut fishery	Individual Growth	Maximum length	L_∞	126.25 cm	ref. 41
Halibut fishery	Individual Growth	Growth rate	*k*	0.1035 year-1	ref. 41
Halibut fishery	Individual Growth	Age at size zero (theoretical)	t_0	0.57 year	ref. 41
Halibut fishery	Individual Growth	Multiplicative effect	*a*	0.000008495	ref. 41
Halibut fishery	Individual Growth	Exponential effect	*b*	3.03305	ref. 41
Halibut fishery	Individual Growth	3D continuous current fields	*Gij*	Determined by ROMS	OCM
Halibut fishery	Life History	Max age		27 years	ref. 16
Halibut fishery	Life History	Age of maturity		4 years	ref. 16
Halibut fishery	Life History	Legal fishing age		5 years	ref. 16
Halibut fishery	Life History	Age at which individuals can move from settled site (not including larval dispersal stage)		5 years	ref. 16
Halibut fishery	Life History	Compensation ratio: Ratio between maximum possible larval survival and larval survival in an unfished site	*CR*	16	ref. 41
Halibut fishery	Life History	Steepness parameter	*h*	0.8	ref. 41
Halibut fishery	Life History	Total equilibrium annual yield without aquaculture development	*TAC*	177,779 kg/year	ref. 41
Halibut fishery	Life History	Site-specific fishing effort	E_i	Determined by fleet in relation to *TAC* and fishing closures	ref. 41
Halibut fishery	Life History	Natural mortality	*M*	0.25 year -1	ref. 41
Halibut fishery	Economic Parameters	Price	*p*	$10.67/kg	ref. 41
Viewshed		Height of viewer (average height of U.S. adult)	*h*	1.7 m	https://www.cdc.gov/nchs/fastats/body-measurements.htm
Viewshed		Visibility radius for mussel and kelp farms	V_{mk}	3 km	ref. 73
Viewshed		Visibility radius for finfish	V_f	8 km	ref. 75
Viewshed		Curvature correction factor and a refractivity coefficient		0.13	ArcGIS 10.2 Viewshed tool default
Benthic impact		Surface temperature	T_s	C	OCM
Benthic impact		3D continuous current fields	*Gij*	Determined by ROMS	OCM
Benthic impact	TOC linear model coefficients	Intercept		-1.24	Calculated in this study (regression model)
Benthic impact	TOC linear model coefficients	Average summer surface temperature		0.107	Calculated in this study (regression model)
Benthic impact	TOC linear model coefficients	Average winter bottom temperature		0.0241	Calculated in this study (regression model)
Benthic impact	TOC linear model coefficients	Surface current		-0.00331	Calculated in this study (regression model)
Benthic impact	TOC linear model coefficients	Depth		-0.00123	Calculated in this study (regression model)
Benthic impact	TOC linear model coefficients	Average summer mixed layer depth		0.0102	Calculated in this study (regression model)