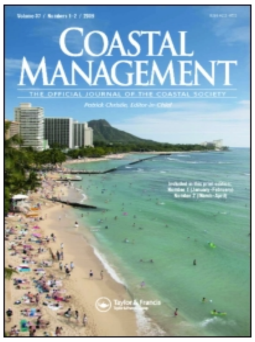

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Capturing Energy from the Motion of the Ocean in a Crowded Sea

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ABSTRACT
Conversion to renewable energy sources is a logical response to the increasing pressure to reduce greenhouse gas emissions. Ocean wave energy is the least developed renewable energy source, despite having the highest energy per unit area. While many hurdles remain in developing wave energy, assessing potential conflicts and evaluating tradeoffs with the existing uses is essential. Marine planning encompasses a broad array of activities that take place in and affect large marine ecosystems, making it an ideal tool for evaluating wave energy resource use conflicts. In this study, we used a spatially explicit, open source decision support tool to evaluate wave energy facility development off the U.S. west coast. We then used this output to identify potential conflicts between wave energy facilities and the existing marine uses in the context of marine planning. We found that regions with the highest wave energy potential were distant from major cities and that infrastructure limitations (cable landing sites) restrict integration with the existing power grids. We also identified multiple potential conflicts, including commercial fishing, shipping and transportation, and marine conservation areas. While wave energy generation facilities may be economically viable, we must also incorporate costs associated with conflicts that arise with the existing marine uses.

KEYWORDS
conservation areas; economics; marine planning; renewable energy; resource conflicts; wave energy

Introduction

Global climate change is arguably the most pressing and urgent environmental problem in existence. Under the current range of representative concentration pathways (RCPs), global mean temperature is projected to increase anywhere from 0.3 to 4.8°C by the year 2100 (Intergovernmental Panel on Climate Change 2014). The low end is bracketed by an optimistic assumption (RCP 2.6) that global annual greenhouse gas emissions peak between 2010 and 2020, and decline "substantially" thereafter. The worst-case scenario (RCP 8.5), assumes greenhouse gas emissions continue to rise throughout the 21st century. Regardless of which IPCC RCP is used, greenhouse gas emission must be decreased substantially in

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order to avoid dramatic changes in sea level, temperature, and severe weather events (Intergovernmental Panel on Climate Change 2014).

The greatest single (25%) contributor to these greenhouse gas emissions is electricity and heat production (Intergovernmental Panel on Climate Change 2014), the majority of which is derived from burning fossil fuels. Subsequently, developing and expanding renewable energy sources for electricity is critical if we wish to significantly reduce greenhouse gas emissions.

Fortunately, we already have the capability to substantially reduce greenhouse gas emissions over the next 50 years (Pacala and Socolow 2004) by modifying and substantially expanding existing technology. Further, it is conceivable that renewable wind, water (hydroelectric, wave energy, and tidal turbines), and solar power sources could provide all of the planet's electricity needs, assuming substantial expansion of these existing energy sources (Delucchi and Jacobson 2011; Jacobson and Delucchi 2011). Wave energy capture (WEC) devices are the least developed of all the renewable energy sources, despite having the greatest energy density (Clément et al. 2002), which suggests they have enormous untapped potential for reducing greenhouse gas emissions. However, installing WEC devices in coastal marine regions has ecological, sociological, and economic consequences, which require coordinated and integrated planning. For example, each WEC device used in this study is a 700-ton, 150-m-long, 3.5-m-diameter, semi-submerged structure composed of four 37-m-long sections linked by articulating joints, and is moored to the bottom with cables. The devices would be deployed in arrays at densities over $10/km^2$, which would pose a significant conflict with the existing marine uses.

The economic value of marine-based resources in the United States is vast: the estimated contribution in 2007 to the Gross Domestic Product (GDP) from coastal counties (including the Great Lakes) was nearly 8 trillion USD (Joint Ocean Commission Initiative 2011). Major sources of goods and services in this revenue stream include tourism and recreation, shipping and transportation, commercial and recreational fishing, and coastal energy exploration and production. On the west coast of the United States, the total value of foreign maritime import and export trade was over $600 billion in 2014 (U.S. Census Bureau 2014) and the combined total landed value of commercial fishing was over $774 million in 2014 [National Oceanic and Atmospheric Administration (NOAA) 2015]. Coordinating such a vast array of competing ocean uses occurring over such enormous areas requires considerable effort and requires reliable socioeconomic and ecological information.

The process of marine planning provides an ideal framework for such coordination, as it encompasses a broad array of activities that can take place in and affect large marine ecosystems (Crowder and Norse 2008; Katsanevakis et al. 2011). Assessing potential conflicts and evaluating tradeoffs among the activities is an important part of marine planning (Douvere and Ehler 2011; White, Halpern, and Kappel 2012). For example, the new U.S. Ocean Policy includes a mandate for marine planning to "reduce conflicts among uses and between using and preserving the environment to sustain critical ecological, economic, and cultural services for this and future generations" (White House Council on Environmental Quality 2010). The first step in this marine planning process is to catalog current uses and consider overlap with areas of potential new uses.

In this paper, we focus on one activity—the generation of wave energy—and how it might conflict with other existing activities in the context of marine planning, on the west coast of the United States. Wave energy has the potential to generate substantial amounts of renewable electricity and provides relatively continuous and predictable power, which is advantageous for electrical grid operation. Although the technology has yet to be fully developed and put into mass production, wave energy generation costs are likely to fall over time as the underlying technologies develop and the industry expands (Astariz and Iglesias 2015). Although much uncertainty exists (Farrell, O'donoghue, and Morrissey 2015; Guanche et al. 2014), wave energy may become economically feasible in the near future if fossil fuel energy costs continue to increase.

While waves can provide a source of clean and renewable energy, the facilities for capturing wave energy and producing electricity have a substantial footprint in the marine environment. For this reason, they might conflict with the existing ocean uses or conservation strategies for protecting marine species and habitats. Wave energy facilities could hinder fishing opportunities, supplant recreational activities, diminish aesthetic views, and create navigational hazards. The existence and extent of these potential impacts are, of course, site-specific, and so analyzing the possibilities in a framework such as marine planning is desirable.

Evaluating a site's capacity for wave energy depends on various factors, including wave power resources; the characteristics and costs of wave energy conversion devices; demand and pricing for electricity; availability of transmission networks; constraints on siting of energy conversion facilities; and compatibility with other uses or ecosystem attributes. Cost-benefit analysis of harvestable wave energy facilitates the evaluation of tradeoffs between the benefits of placing a wave energy facility in a particular location and the costs of installing, maintaining, and operating the facility at that location. Our intent is to find the best locations for wave energy facilities, given certain assumptions about the economic parameters that affect those locations. These locations are then compared to the spatial distribution of the existing marine uses, which enables us to identify areas where potential conflicts exist.

Methods and data

Our analysis of wave energy production focused on the U.S. west coast, in an area bounded by the U.S. border to the north and south, and an east and west boundary defined by water depth (40 and 200 m, respectively). The choice of water depths roughly bounds the range in which the wave energy device we chose (Pelamis) can operate (Pelamis Wave Power Ltd. 2010). We selected the Pelamis over other wave energy conversion (WEC) devices because it was considered the most "maturely developed" oscillating body device available (Farrell et al. 2015; Lewis et al. 2011; O'Connor, Lewis, and Dalton 2013) and had the best performance and economic information available.

Wave energy model

We used an existing geographic information system (GIS)-based decision-support tool to provide spatially explicit information for evaluating wave energy conversion facilities and possible conflicts with other marine uses (Guerry et al. 2012). The tool is the Wave Energy Model (WEM) of the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST, v. 3.1.3) toolkit (Sharp et al. 2014). Previous studies have utilized InVEST for characterizing wave energy potential off the coast of southwest Vancouver Island, BC, and for identifying resource conflicts (Kim et al. 2012), but similar efforts have never been done for the U.S. west coast. The wave energy model consists of three parts: (1) assessment of potential wave power based on wave conditions; (2) quantification of harvestable energy using technology specific information about a wave energy conversion device; and (3) assessment of the economic value of a wave energy conversion facility over its life span as a capital investment.

The WEM tool uses wave and water depth information to assess the potential energy that can be captured by wave energy devices. By choosing a particular device (Pelamis), the WEM tool can then quantify the captured wave energy and electricity production over the entire study area on a 3 × 3 km regular grid. The economic value of energy production is estimated based on the economic costs (capital, operating, and maintenance) of the device and the transmission of the power. WEM grid cells with positive net present value (NPV) have maximum net economic value and were used to prioritize wave energy facility siting in this study. This prioritization criterion was somewhat arbitrary; since there is a great deal of uncertainty surrounding the economic inputs to the WEM, the NPV calculations should only be used as a reference, rather than an absolute value.

Specifically, the WEM tool uses the following input data: water depth; wave height and power; performance and costs of specific wave energy conversion devices; electricity prices and discount rate; transmission line landing and power grid connection points; and project life span (see Tables 1 and 2 for types and sources of data used by the WEM tool). Of these, we modified the area of interest and landing and power grid connection points to match our west coast study area. We set the number of devices at 90, which correspond to a density (10 devices/km^2) recommended in the literature (Previsic 2004b). Table 2 lists the data inputs that were fed into the economic portion of the model. Of these, we input the cost of underwater and overland transmission line, the price of electricity, and the discount rate, which reflected the best available information for the west coast, as of 2010. Given the cost of overland transmission lines was based on 2003 data, we applied an inflation adjustment to approximate 2010 costs (BLS 2015). The price of electricity was set at $0.235/kWh, which is considered a reasonable rate for a renewable energy source such as wave energy (Dalton et al. 2010). We set the discount rate at a relatively high 11.6%, which is considered a reasonable value for "first-of-a-kind" offshore wind power projects (Levitt et al. 2011). It is

Table 1. InVEST wave energy model (WEM) data inputs.

Category	Item	Source
Number of devices	90	Previsic et al. (2004b)
Water depth	Water depth (m)	Amante and Eakins (2009)
Wave power	Wave height (m) Peak wave period (s)	NOAA (2011b)
Wave energy device performance	Captured wave energy for a given seastate condition defined by wave height and wave period (kW) Upper limit of wave height for device operation (m) Upper limit of wave period for device operation (s)	Previsic et al. (2004a)
Area of interest	North and south boundaries defined by U.S. Exclusive Economic Zone on the U.S. west coast. East and west boundaries determined by water depth, 40 and 200 m, respectively	VLIZ (2014) and NOAA (2003)
Landing and power grid connection	Existing power grid connection points (and the corresponding landing points). Assumed local infrastructure would accommodate wave energy production	HSIP (2013)

Table 2. InVEST wave energy model (WEM) economic inputs.

WEM input	Value	Source
Maximum capacity of device	750 kW	Previsic et al. (2004a)
Capital cost per installed	$3671/kW	Dunnett and Wallace (2009)
Cost of mooring lines	$20/m	Dunnett and Wallace (2009)
Cost of underwater transmission line	$631,501/km	National Grid (2010)
Cost of overland transmission line	$287,187/km	American Transmission Company (2003)
Operating and maintenance cost	$0.042/kWh	Dunnett and Wallace (2009)
Price of electricity	$0.235/kWh	Kim et al. (2012); Dalton et al. (2015)
Discount rate	11.6%	Levitt et al. (2011)
Project life span	25 years	Kim et al. (2012)

reasonable to also consider wave energy projects as "first-of-a-kind," given the higher risks associated with financing an initial project and the need to attract project investors (Levitt et al. 2011). The remaining values were defaults for the WEM.

Obtaining accurate input data and parameters for the economic valuation portion of the model is a significant challenge because there have been no commercial-scale wave energy facilities implemented to date. These economic parameters determine whether a wave energy facility will be economically viable—that is, whether the net present value of its construction, operation, and maintenance will be greater than zero. In order to get a sense of how the model responded to changes in the various economic inputs, we ran a sensitivity analysis where we varied the economic inputs by ±10% (see supplementary material).

Existing marine uses

We considered three general categories of existing marine uses and examined how they might conflict spatially with the optimal locations of the wave energy facilities. The three existing marine use categories were (1) commercial fishing; (2) maritime transportation; and (3) marine conservation areas (Table 3). We used Esri ArcGIS (v. 10.1) for all of the spatial overlays and comparisons made between the WEM output and the existing marine resource use.

Commercial fishing

We used two geospatially explicit sources of commercial fishing effort data to generate indices of effort for each of the WEM 3 × 3 km grid cells: direct observer and vessel

Table 3. List of existing marine uses considered in overlap analysis with potential wave energy facilities.

Marine use	Description	Source
Commercial fishing	Effort (towlines) measured directly using observer data	NOAA (2010, 2011a); see Table 4
	Effort and general activity based on Vessel Monitoring System (VMS) data	NOAA (2014); see Table 5
Maritime transportation	Individual track lines of cargo, pleasure, passenger, tanker, and tug and towing vessels in 2011, based on Automatic Identification System (AIS) data	NOAA (2014b)
Conservation areas	Green sturgeon critical habitat	NOAA (2009)
	Pacific groundfish Essential Fish Habitat (EFH) conservation areas	NOAA (2006)

Table 4. Description of observer-based groundfish fishery fleets, fishery, and gear types used to quantify commercial fishing effort in overlay analysis.

Fleet	Fishery	Gear	Source
Bottom trawl	Various groundfish	Bottom trawl	West Coast Groundfish Observer Program (WCGOP); NOAA (2010)
At-Sea Pacific hake midwater	Pacific whiting (*Merluccius productus*)	Midwater trawl	NOAA (2011a)
Fixed gear (line)	CA nearshore, CA open access fixed gear, limited entry sablefish, limited entry zero tier, OR blue/black rockfish nearshore, WC open access fixed gear	Historic longline, pots and traps, longline (fixed hooks), longline (snap-on hooks)	West Coast Groundfish Observer Program (WCGOP); NOAA (2010)
Fixed gear (point)	CA nearshore, CA open access fixed gear, limited entry sablefish, limited entry zero tier, OR blue/black rockfish nearshore, WC open access fixed gear	Vertical hook and line, rod and reel, other hook and line, pots and traps, troll gear	West Coast Groundfish Observer Program (WCGOP); NOAA (2010)

monitoring system (VMS). We chose these two measures of fishing effort because they are the best available, spatially explicit, direct measures of the locations of fishing vessels while they are actively fishing or transiting to fishing grounds.

Observer-based data. We used observer-based fishing effort data (2002–2010) for three different commercial fleets: bottom trawl (herein trawl), at-sea Pacific hake (*Merluccius productus*) midwater trawl (herein hake), and fixed gear (herein fixed). Data were collected as individual vessel towlines, represented by a vector connecting the gear-in and gear-out location for each individual fishing set. Certain types of fixed gear data (see Table 4) were also reported as individual point locations where these specific gear types were deployed. All observer-based data were provided by the At-sea Hake Observer Program (A-SHOP) and the West Coast Groundfish Observer Program (WCGOP) under NOAA's Northwest Fisheries Science Center, Fishery Resource Analysis and Monitoring (FRAM) Division (Table 4).

For the trawl, hake, and line-based fixed (reported by specific gear type, see Table 4) data, we used the GIS software to intersect the individual towlines (line drawn from the start to end location of a gear tow or set) with the 3 × 3 km WEM grid cells and calculated cumulative fishing effort (total duration that gear was deployed in the water) per grid cell. Since most individual towlines spanned multiple WEM grid cells, we calculated the proportion of each towline that fell within a given WEM grid cell and multiplied that by the duration reported for the entire towline. Certain fixed gear (reported by specific gear type, see Table 4) data were also reported as points with corresponding durations, so we summed the total number of points and their associated duration for each WEM grid cell.

For the hake and trawl fleets, the data represent total fishing effort (100%). Previous studies using fixed gear fleet observer data, spanning similar time frames, reported approximately 18% coverage of fishing effort (Feist et al. 2015). Therefore, fishing effort for the fixed fleet is largely underestimated. This deficiency was unavoidable since only about 18% of the fixed gear vessels have observers on board.

The observer-based data are the most direct measure of where fishing occurs for the fleets that are observed, since each gear deployment is marked by a georeferenced start and end point, clearly delineating the beginning and ending of any given fishing set. The greatest

Table 5. Description of vessel monitoring system (VMS)-based data used to quantify commercial fishing activity in overlay analysis (NOAA 2014).

Code	Description
210*	Limited entry fixed gear, not including shorebased IFQ
211	Limited entry groundfish non−trawl, shorebased IFQ
220	Limited entry midwater trawl gear, non−whiting shorebased IFQ
221	Limited entry midwater trawl, Pacific whiting shorebased IFQ
222†	Limited entry midwater trawl, Pacific whiting catcher/processor sector
223†	Limited entry midwater trawl, Pacific whiting mothership sector (catcher vessel or mothership)
230§	Limited entry bottom trawl, shorebased IFQ, not including demersal trawl
231	Limited entry demersal trawl, shorebased IFQ
233*	Open access longline gear for groundfish
234*	Open access groundfish trap or pot gear
235*	Open access line gear for groundfish
240	Non−groundfish trawl gear for ridgeback prawn
241	Non−groundfish trawl gear for pink shrimp
242	Non−groundfish trawl gear for California halibut
243	Non−groundfish trawl gear for sea cucumber
260	Open access prawn trap or pot gear,
261	Open access Dungeness crab trap or pot gear
262	Open access Pacific Halibut longline gear
263	Open access salmon troll gear
264	Open access California halibut line gear
266	Open access highly migratory species line gear
267	Open access coastal pelagic species net gear
268	Open access California gillnet complex gear
269 to 999	Unknown, unclassified, not listed, or exempt

Notes. *Overlaps with fixed gear fleet observer-based data, not included for resource conflict scoring.
†Overlaps with at-sea hake fleet observer-based data, not included for resource conflict scoring.
§Overlaps with bottom trawl fleet observer-based data, not included for resource conflict scoring.

limitation of these data is the lack of comprehensiveness—observers do not monitor all of the fishing gear types and fleets.

VMS-based data. To address lack of comprehensiveness in the observer-based data, we also used vessel monitoring system (VMS) data. VMS is used by enforcement agencies to track the locations of fishing vessels in real time to determine if they are fishing in closed areas. This source differs from observer-based data in that vessels are monitored continuously, regardless of whether or not they are actively fishing. Consequently, the VMS gives a general picture of where fishing vessels are, and by association, which areas off the coast are most heavily accessed. Vessel positions are transmitted every hour to remote monitoring stations on land, so the data are point locations. One advantage of the VMS over direct observation data is that the VMS is used for a far greater variety of gear types and species targets (Table 5). The greatest limitation is that the raw point data do not characterize when and where vessels are actively fishing. Others (see Hiddink et al. 2011; Hintzen et al. 2012) have developed methods to infer locations of active fishing by calculating velocity between any given pair of sequential points. When velocity falls within a defined interval for a given gear type, active fishing is assumed. The complexity of applying these methods to 1.8 million VMS data points and for each of the 24 different gear types and associated species targets was beyond the scope of this research. We used data from January 2013 through July 2014 (NOAA 2014a). We measured the relative intensity of fishing vessel use in each WEM grid cell by spatially overlaying the VMS points and counting how many fell within any given WEM grid cell for each VMS fishing vessel category.

Maritime transportation

For maritime transportation, we used the U.S Coast Guard vessel traffic data, or Automatic Identification System (AIS) for the year 2011. The AIS is used to monitor the location and characteristics of large vessels in U.S. and international waters in real time. Vessel categories include cargo, fishing, pleasure, passenger, tanker, or tug and towing (NOAA 2014b). We excluded the fishing category since we had more direct and comprehensive measures of fishing effort, as described in the previous section. Ship tracks are represented as vector lines, similar to the observer-based fishing effort data, which do not begin and end exactly within each 3 × 3 km WEM grid cell. In order to calculate the total distance traversed by each vessel type for each grid cell, we used ArcGIS to intersect the ship tracks with the WEM grid and summed the total distance traversed over each of the WEM grid cells for each ship category.

Marine conservation areas

We considered two types of marine conservation areas: (1) critical habitat designated under the Endangered Species Act (ESA) and (2) essential fish habitat conservation areas designated under the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). For critical habitat, designation of an area requires federal agencies or other parties with federal permits or licenses to avoid adversely modifying that habitat. Agencies that have activities or that issue such permits or licenses are required to consult with the National Marine Fisheries Service to ensure that these actions do not have adverse effects. We used green sturgeon (*Acipenser medirostris*) critical habitat designations that occur off the Oregon, Washington and California coasts (CH Marine Coastal Zones only) for our analysis (NOAA 2009, http://www.nmfs.noaa.gov/gis/data/critical.htm). The total area affected by this designation is about 33,000 km^2. For essential fish habitat conservation areas, we used regions designated for Pacific groundfish along the west coast. These areas have restrictions for several types of fishing gear and impose various types of constraints. For our analysis, we used only those areas where fishing with bottom trawl gear was prohibited, affecting a total area of about 35,000 km^2 (NOAA 2006, http://www.westcoast.fisheries.noaa.gov/fisheries/management/groundfish_closures/essential_fish.html).

Spatial conflict with existing marine uses

We used the results from our overlay analyses to assess potential conflicts of the existing marine resource use with wave farm development. We examined potential conflict of wave farm development with the existing marine uses from two perspectives: generally, across the total space utilized by each marine use category and specifically, within each of the WEM 3 × 3 km grid cells. The general overlap analysis provided insight on the overall potential conflict of wave farm placement with each resource use type, and the specific overlap resource conflict model identified exactly where the conflict would occur as well as its magnitude.

General patterns of marine use overlap potential wave energy development

The WEM was restricted to depths between 40 and 200 m, but the marine resource uses we analyzed were not limited to the region defined by this depth range. In order to calculate the overall proportion of any given marine use that overlapped with optimal wave farm locations, we calculated the cumulative amount of each marine use that occurred within positive NPV WEM grid cells and the cumulative amount that occurred outside of these grid cells, out to a maximum depth of 1,200 m (NOAA 2003).

Resource conflict model

For simplicity, we only generated conflict scores for positive NPV WEM grid cells, but it is important to note that the accuracy of the NPV of any given grid cell is unknown, given the uncertainty surrounding the economic inputs. We merely used NPV as a reference or cutoff to simplify the analyses.

First, we generated cumulative use values on each of the WEM grid cells for three of the five resource use categories: observer-based fishing effort (cumulative hours fished per grid cell for all three fleet types); VMS-based fishing activity (cumulative number of VMS observations per grid cell for all gear categories); and maritime vessel traffic (cumulative distance traversed per grid cell for all five vessel categories). Given the three observer-based fleets are also monitored by VMS, we excluded the corresponding VMS data on these fleets (codes 210, 222, 223, 230, 233, 234, and 235, see Table 5).

Second, considering each positive NPV WEM grid cell as a sample, we calculated the median value across all grid cells for observer-based fishing effort, VMS-based fishing activity, and maritime vessel traffic. Given the patchy nature (and negative exponential distribution) of these marine activities, 95.1%, 79.5%, and 92.0% of the cumulative activity in observer-based fishing effort, VMS-based fishing activity, and maritime vessel traffic, respectively, were represented by the population of grid cells with values greater than the median. We assigned a score of 1 to grid cells with a value greater than the median for their corresponding marine use type, and grid cells with a value less than the median were given a score of 0.

Finally, for the marine conservation areas, WEM grid cells that had more than 25% of their area covered by a given conservation area type (green sturgeon critical habitat and essential fish habitat conservation areas) received a score of 1 and those less than 25% covered were classified as a 0. This scoring system resulted in grid cells that could have a final composite conflict score anywhere from 0 to 5, with a five representing overlap with all five possible resource use types.

Economic tradeoff case study

We used the limited entry bottom trawl data to provide an economic comparison case study. These were the only fishing effort or activity data that we were able to gather accurate economic information at the scale of our 3 × 3 km WEM grid cells. We used commercial landings data and associated gross revenue information to calculate the value of each individual fishing vessel towline for 2011 and 2012. To convert these gross revenue values to net profit per towline, we multiplied them with a correction factor of 0.43. We calculated the correction using the variable cost net revenue value of the bottom trawl fleet in 2011 and 2012 (Steiner et al. 2015), which is a reasonable proxy for net profit margin in the bottom trawl fleet. We overlaid the towline vector representations with the WEM grid and calculated the proportion of each towline that fell within each WEM grid cell. We then multiplied that proportion by the value of the corresponding towline and summed all of these values for each WEM grid cell.

To compare annual bottom trawl net revenue for each WEM grid cell with the predicted NPV for wave energy facilities, we converted to an annualized net value (ANV) using the following equation:

$$\mathrm{ANV} = \mathrm{NPV}\frac{i(1+i)^{T}}{(1+i)^{(T+1)}-1}$$

where i is the discount rate (0.116) and T is the duration over which NPV was originally calculated (25 years). Converting to ANV yields "the amount one would have to pay at the end of each time period t so that the sum of all payments *in present value terms* equals the original stream of values" (U.S. EPA 2014). Finally, we divided the wave energy model ANV by the bottom trawl net profit margin for each WEM grid cell in order to examine the tradeoffs between cessation of bottom trawl-based commercial fishing in favor of wave energy development.

Results

Wave energy model

There were 5,901 3 × 3 km grid cells in the WEM output spanning the 40–200 m depth range. The cumulative NPV over the modeled 25-year project life span in the 2,053 positive NPV WEM grid cells was $33.2 billion. The cumulative potential wave power was 58,134 kW/m in the positive NPV grid cells and the annual cumulative captured wave energy was 382,100 GWh/y. By comparison, the total annual energy output in the U.S. from all sources in 2014 was about 4.1 million GWh/y, and 539,800 GWh/y from all renewables, combined (U.S. EIA 2015).

Wave power and energy generally increased with depth off the coast, approaching maxima of 35 kW/m and 207 GWh/y, respectively (Figures 1 and 2). There were strong latitudinal gradients in both wave power and energy. Wave power and energy were greatest off the coasts of WA and OR (Figures 1A and B, and 2A and B), but diminished greatly with latitude in CA (Figures 1C and D, and 2C and D). However, there were a couple of power and energy "hotspots" off the coast of CA, specifically Cape Mendocino and Point Reyes (Figures 1B and C, and 2B and C).

NPV was highest off the WA and OR coasts and lowest off most of the CA coast (Figure 3). Long stretches of the WA and northern CA coasts with high energy wave potential had negative NPV, due to a lack of existing power landing connection points (Figure 3). With the exception of Cape Mendocino and Point Reyes, CA did not have any positive NPV grid cells (Figure 3).

Sensitivity analyses indicate that WEM output was most sensitive to the price of electricity, discount rate, and capital cost per installed and the least sensitive to mooring lines cost and overland transmission line cost (see supplementary material).

Existing marine uses

Activity levels in the WEM grid cells varied widely across the various resource use categories. The amount of overlap relative to all activities occurring in water depths shallower than

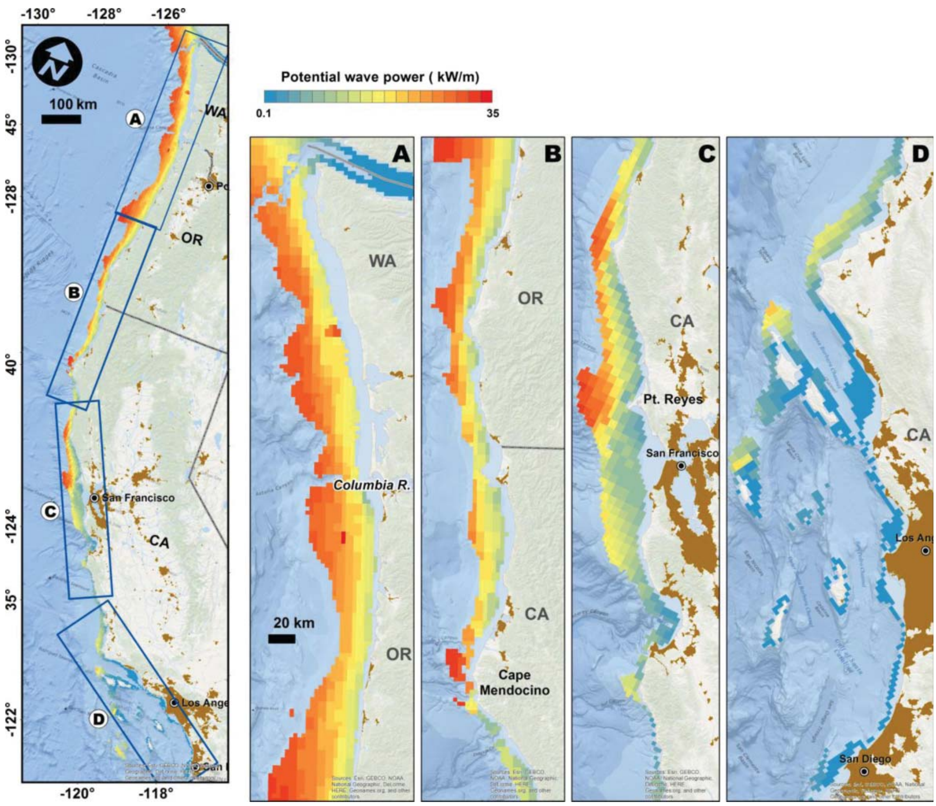

Figure 1. Maps of InVEST predicted wave power potential (kWh/m) in the 40-200 m depth range along the west coast of the United States. Brown regions on land indicate urban areas with population density > 1,000/km^2 (U.S. Census Bureau 2012).

1,200 m was relatively low (generally less than 15% of all activity in this region overlapped with positive NPV WEM grid cells), but the intensity of actual use for any given WEM grid cell could be extremely high.

Observer-based fishing data

From 2002 to 2010, there were 1,054,888 total hours that fishing gear was deployed across the 3 fishing fleets we measured. 99.64% of the fishing towlines occurred in water depths shallower than 1,200 m. Only 108,595 (10.29%) of those hours occurred within positive NPV grid cells. Of the 3 fleets, trawl had the highest total effort (689,931 h) and the highest percentage (14.15%, 97,611 h) of effort overlap with positive NPV grid cells (Figure 4). The total duration for the hake and fixed fleets were 46,030 and 318,928 h, respectively, with 3,738 (8.12%) and 7,246 (2.27%) h occurring within positive NPV grid cells (Figure 4).

VMS-based fishing data

From January 2013 to July 2014, there were nearly 1.8 million VMS-based vessel location observations occurring at depths shallower than 1,200 m. Nearly 14% (247,515) of all those observations

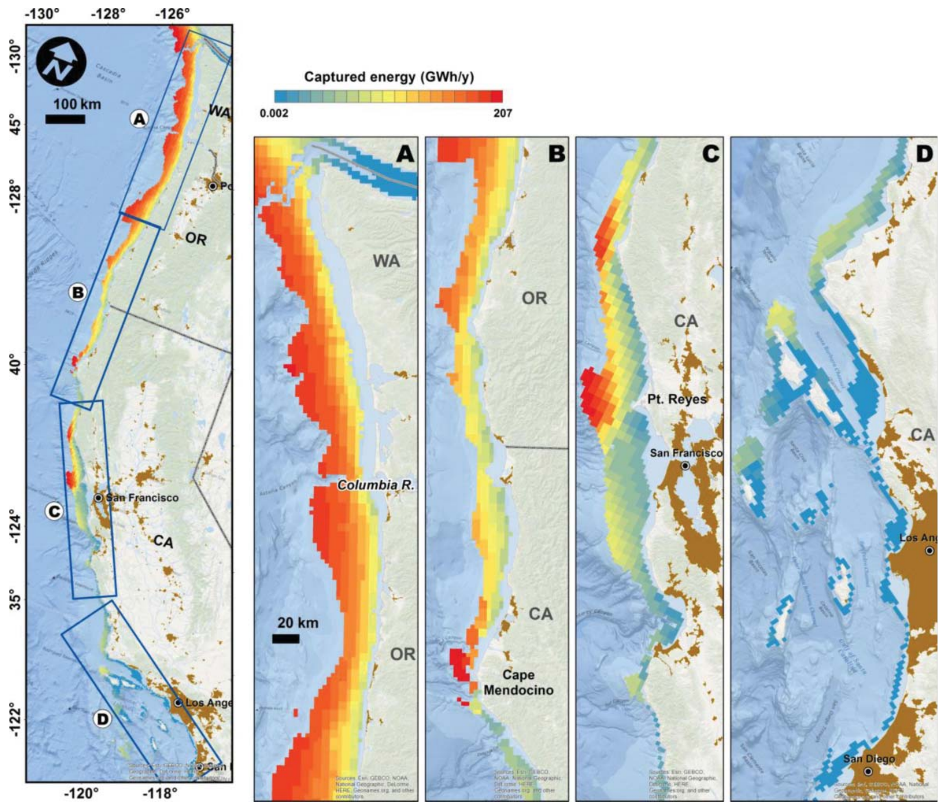

Figure 2. Maps of InVEST predicted captured wave energy (GWh/y) per Pelamis wave energy conversion device in the 40-200 m depth range along the west coast of the United States. Brown regions on land indicate urban areas with population density > 1,000/km^2 (U.S. Census Bureau 2012)

occurred within positive NPV WEM grid cells. VMS observations per positive NPV WEM grid cell had a mean of 121, with a range of 0–971. Nearly 90% of all VMS-based observations falling within positive NPV WEM grid cells were represented by 7 of the 24 declaration types: pink shrimp (74,823), open access (OA) salmon (34,392), other (31,280), OA highly migratory spp. (25,319), limited entry (LE) midwater hake shorebased (SB) IFQ (21,870), LE bottom SB IFQ (19,301), and OA Dungeness (14,931, Figure 5). The remaining 17 VMS declarations represented less than 10% of all observations falling within positive NPV WEM grid cells. Based on economic data reported for pink shrimp and salmon commercial harvest, the total landed value of these species in 2013 was $34 and $77 million, respectively (NOAA 2015).

Maritime transportation

In 2011, there were about 6.2 million km of maritime vessel traffic in water depths shallower than 1,200 m. About 0.5 million km (8.9%) overlapped with positive NPV WEM grid cells, with a mean of 269 km traversed and 106 unique vessel tracks/grid cell. The per grid cell range was 0–13,471 km traversed and 0–3,942 tracks. Cargo ships represented the majority (344,464 km) of vessel traffic falling in positive NPV WEM grid cells, with tug and towing about 1/3 of that (121,640 km) and tanker lower still (55,932 km, Figure 6). Only about 5%

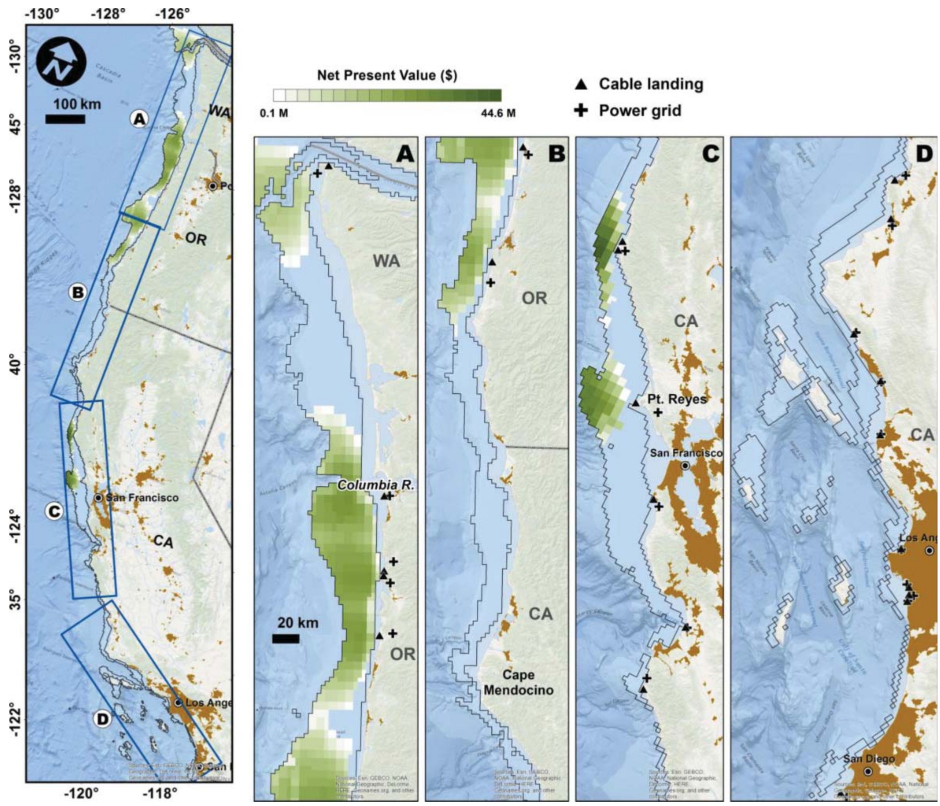

Figure 3. Maps of InVEST predicted net present value (million of dollars) per 3 x 3 km grid cell over the 25-year wave farm lifespan in the 40-200 m depth range along the west coast of the United States. Triangles mark existing submarine cable landing sites used by the wave energy model to calculate the cost of running power cable from proposed wave farm facilities to shore. Plus symbols mark the locations of existing power grid substations used by the wave energy model to calculate the cost of running power cables from landing sites. Brown regions on land indicate urban areas with population density > 1,000/km^2 (U.S. Census Bureau 2012).

of all reported vessel traffic overlapping with positive NPV WEM grid cells were categorized as passenger (16,313 km) or pleasure (13,195 km, Figure 7).

Marine conservation areas

There was a substantial overlap between positive WEM NPV grid cells and green sturgeon critical habitat. About 50% (1,032) of the grid cells had some degree of overlap and 659 of those had 100% overlap. The decrease in total NPV of the study area if green sturgeon critical habitat was completely avoided would be about $12.3 billion (37.0%). There was relatively minor overlap between positive NPV WEM grid cells and essential fish habitat. 1,770 (86.2%) of all positive WEM NPV grid cells had no overlap at all, with 88 having 100% overlap. The cumulative NPV of all grid cells with non-zero overlap was $3.5 billion (10.5%).

Resource conflict model

Across the entire study area, 96% (1,969) of all positive NPV WEM grid cells had a resource conflict score above 0. There were a few resource conflict hotspots within the study area,

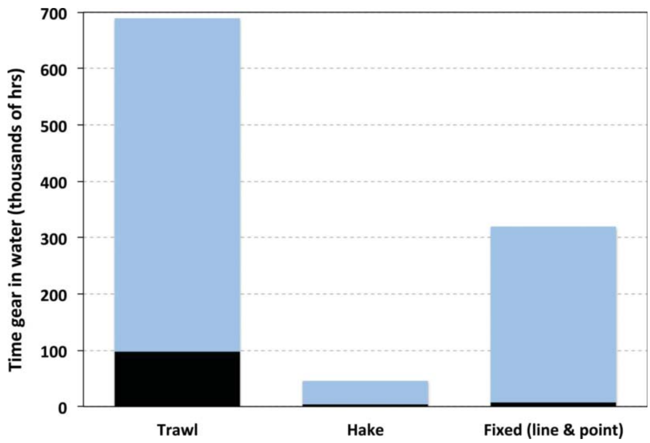

Figure 4. Bar chart of the total duration (thousands of h) fishing gear was deployed from 2002–2010 for the trawl, hake and fixed fleets. Black portion of bar corresponds to positive net present value InVEST WEM grid cells only and blue portion is the all other grid cells plus fishing fleet data out to the 1,200 m isobath.

particularly off the mouth of the Columbia River at the border or OR and WA, and just off Point Reyes, CA (Figure 7). Patches where there was a conflict score of 0 occurred off the northern WA coast, off the central coast of OR and just north of Cape Mendocino, CA (Figure 7). Most of the positive NPV value grid cells had a conflict score of 2 (862 grid cells with a total NPV of $13.9 billion), but only 84 had a conflict score of 0 (total NPV of about

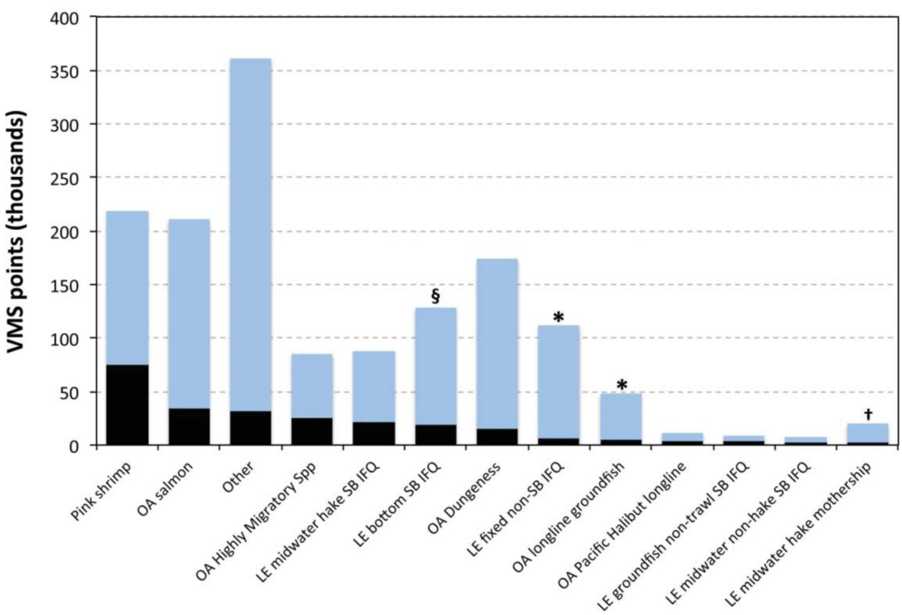

Figure 5. Bar chart of total number of VMS observations (thousands), by declaration, from January 2013 through July 2014. Black portion of bar corresponds to positive net present value InVEST WEM grid cells only (criteria for rank order) and blue portion is all other WEM grid cells plus VMS data out to the 1,200 m isobath. *Overlaps with fixed gear fleet observer based data. †Overlaps with At-sea hake fleet observer based data. §Overlaps with bottom trawl fleet observer based data.

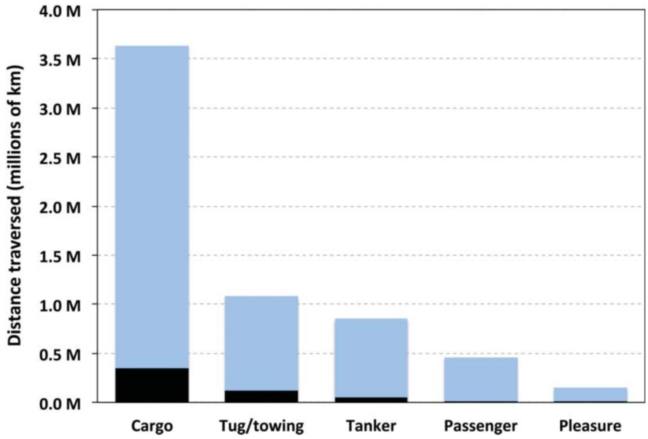

Figure 6. Bar chart of total distance traversed (millions of km), by vessel class, of maritime vessels in 2011. Black portion of bar corresponds to positive net present value InVEST WEM grid cells only and blue portion is all other grid cells plus maritime vessel traffic data out to the 1,200 m isobath.

$1.2 billion, Figure 7E). Mean NPV increased as a function of conflict score, with a range from $15 million to $18 million (Figure 7E regression line), suggesting that the more optimal wave farms sites tended to occur in areas with more marine uses.

Economic tradeoff case study

The ANV of potential wave farms was orders of magnitude greater than the value of bottom trawl-based commercial fishing. In positive NPV WEM grid cells where there was overlap with the bottom trawl fleet, the mean total annual net value of fishing was about $1.5 million, whereas the annualized net value for potential wave farm development was nearly 3 orders of magnitude more valuable at $1.4 billion. Only 1 of the 728 positive NPV WEM grid cells that overlapped with bottom trawl fishing had an ANV less than the mean value of bottom trawl fishing from 2011 to 2012, and the ratio was nearly 1:1 (0.94). Of the remaining grid cells, the maximum ratio was about 80 million to 1 with a mean of 216,380 to 1 (Standard error (SE) = 67,495, Figure 8).

Discussion

The renewable energy potential of ocean waves is vast: an estimated 2.11 TW of power per year is available along the world's coasts (Gunn and Stock-Williams 2012). To place this in perspective, the United States consumes around 0.44 TW of power per year (Central Intelligence Agency 2013). Clearly, the power of ocean waves holds great potential as a renewable energy source. The Pelamis devices modeled in this paper, if fully developed in all of the positive NPV grid cells in the modeled domain, could potentially harness approximately 0.08 TW of electrical power, which is about 10% of the total United States consumption.

Wave energy potential varies widely around the globe, with higher latitudes often experiencing greater energy (Gunn and Stock-Williams 2012). However, human population density is greatest at lower latitudes (Sale et al. 2014), creating a mismatch between wave

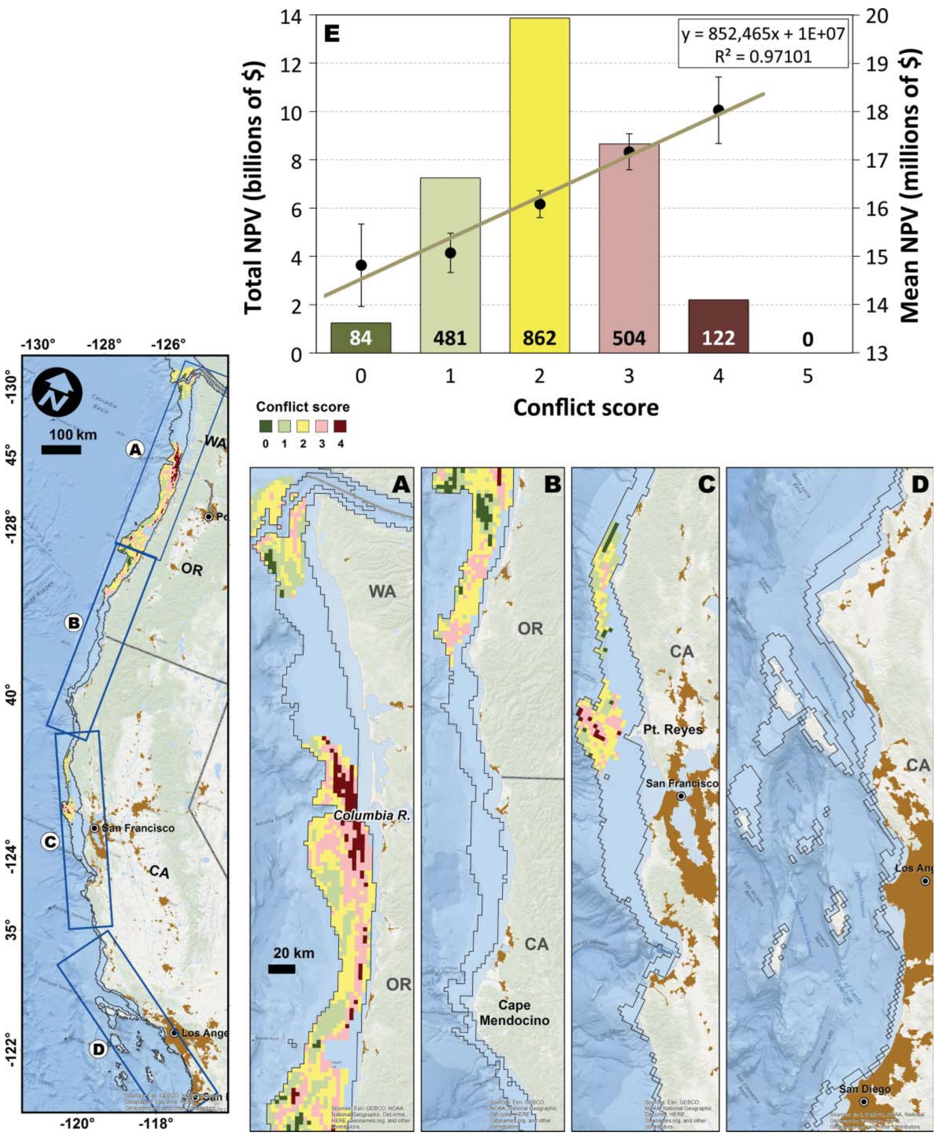

Figure 7. Maps of resource conflict scores between all resource uses and positive net present value InVEST WEM grid cells in the 40-200 m depth range along the west coast of the United States. Inset: bar chart of total summed value (NPV in billions of dollars) of grid cells for each resource conflict score. Numbers within each bar represent the number of grid cells with the corresponding conflict score. Right y-axis and associated regression line depict relationship between conflict score and mean NPV of grid cells. Bars indicate standard error of the mean.

energy potential and human populations. This certainly was the case in our study, where southern California had the lowest wave energy potential, despite having adequate infrastructure for receiving wave farm electricity. The greater demand for electricity in California is exemplified by its population size alone (39 million), which is more than 3.5 times the population of Oregon and Washington combined (U.S. Census Bureau 2015). Further, Washington has nearly twice the population size of Oregon (U.S. Census Bureau

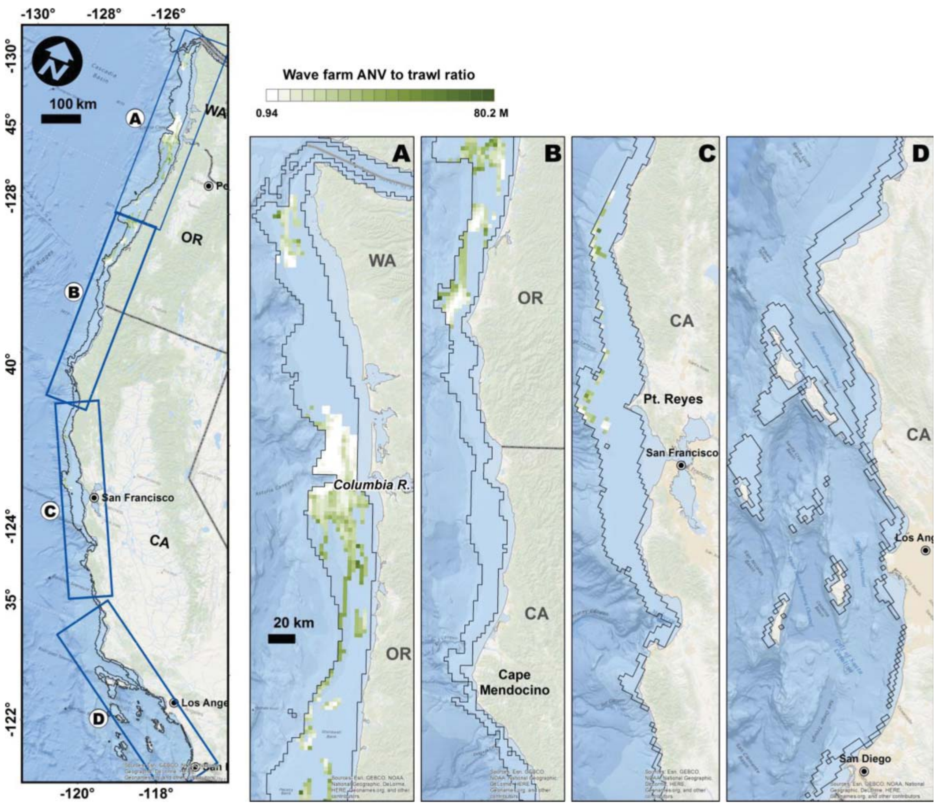

Figure 8. Maps of the ratio of annualized net value of wave energy generation to bottom trawl mean net profits in 2011and 2012 for positive net present value InVEST WEM grid cells in the 40-200 m depth range along the west coast of the United States.

2015), but lacks the infrastructure (submarine cable landing sites) to receive wave farm-based electricity. Given the high wave power and energy potential off the Washington, southern Oregon, and northern California coast, the NPV potential of this region could be improved with the addition of only a few submarine cable-landing sites. While the WEM tool could be used for this purpose to create potential NPV maps based on hypothetical additional landing sites in the aforementioned deficient locations, the feasibility and cost of installing new submarine cable landing sites is beyond the scope of this paper (see Evans and Page 2014).

The reality and potential consequences of GCC makes development of wave energy, as well as other renewable energy sources, worth pursuing. The United States produces about 1.5 billion metric tons of carbon a year (from fossil-fuel burning, cement production, and gas flaring), which is about 17% of the global total, second only to China (Boden, Marland, and Andres 2013). Electricity production accounts for 31% of greenhouse gas emissions in the United States, and 67% of this electricity is generated from the combustion of fossil fuels, primarily coal and natural gas (U.S. EPA 2015). Given the electricity production potential afforded by full development of the Pelamis WEC devices used in this study, if the existing fossil fuel-based electricity generation was converted to wave energy, greenhouse gas emissions from electric power generation (U.S. EIA 2015) in the United States could be reduced by nearly 14% a year. The United States is potentially targeting a 17% drop in CO_2 emissions by the year 2020, relative to 2005 levels, dropping by 83% by the year 2050 (UNFCCC 2015). While levels in 2012 had dropped 11% relative to 2005 (Boden et al. 2013), reaching a total decrease of 83% by 2050 will require numerous changes in industrial, transportation, and agricultural practices, including development and expansion of renewable energy sources (Pacala and Socolow 2004; UNFCCC 2015). Finally, wave farm development need not occur in isolation or independent of other renewable energy sources. For example, combining offshore wind and wave farms reduces periods of zero power output, provides more consistent power output, and improves economic efficiency (Stoutenburg et al. 2011).

Using an existing GIS-based tool for evaluating potential locations of wave energy facilities, we have characterized the wave energy generating potential of the U.S. west coast and demonstrated how potential conflicts with the existing marine uses can be identified. The variety of methods used by various data sources to measure the intensity and value of these uses makes a comparison across uses or an aggregation of the conflicts problematic. Nevertheless, the simple set of spatial representations we have generated can present planners with a screening tool, identifying areas where a more refined investigation is worthwhile.

The InVEST WEM tool has the capability of quantifying the consequences, in terms of captured wave energy and economic value, of placing wave energy facilities in various locations, changing cable landing and power grid connection points, and using different types of WEC devices. Coupled with similar quantitative measures of the change in a facility's impact on existing marine uses, this capability would allow for an extended assessment of the potential tradeoffs between wave energy production and those other uses. This would provide important information to aid marine planning decisions related to WEC device placement.

Several deficits prevent us from exploring this issue, however. As noted above, the data sources for the existing marine uses are limited in how they spatially measure the intensity and value of those uses. We were only able to assess a subset of one of the existing uses (bottom trawl fishing) in terms of economic value, and wave farm development was clearly a better option, economically. However, our sensitivity analysis of the economic inputs clearly indicates that the economic outputs are very sensitive to the price of electricity, discount rate and capital cost to install wave farms. Therefore, we approach economic comparisons with caution, given the uncertainty associated with many of the economic inputs. While some conclusions can be drawn for a particular use that certain locations are likely to create "more" or "less" of a conflict, little more than that can be said. Second, for some uses, a conflict or lack of one is inferred from the presence or absence of that use in a particular location. Much more must be understood about the real nature of conflicts and the ability of various uses, including wave energy production, to coexist spatially before a viable tradeoff analysis could be conducted. For example, with regard to conservation habitats considered in this analysis, overlap with sturgeon critical habitat could trigger requirements for federal agencies such as the Federal Energy Regulatory Commission to consult with NOAA Fisheries before licensing a wave energy facility. This adds to the uncertainty associated with this overlap analysis, which is not easily addressed. Finally, many of the other uses can choose alternate locations in response to a spatial conflict. For example, maritime vessel traffic could conceivably navigate around a wave farm, were the farm to be placed directly in a shipping lane. The economic cost would then be a function of extra fuel and time used in avoiding a wave farm and not one of complete economic loss for maritime traffic. An understanding of how such choices are made and the availability and value of alternate locations would be needed, again, for a robust tradeoff analysis.

We did not consider the physical, ecological, or sociological effects of wave farms in our analyses, but it is important to note that there are likely consequences from installing such facilities in marine coastal areas. One of the most obvious physical impacts of wave farm development would be wave attenuation. In a study looking at the device we modeled in our analyses (Pelamis), Rusu and Soares (2013) observed wave attenuation immediately down wave of a prototype, but this effect was not evident at the coastline. However, at the surf zone level, longshore current was decreased, which has implications for sediment transport and other shoreline dynamics (Rusu and Soares 2013). Similar patterns of localized wave attenuation and decreased shoreline current velocities have been observed in other WEC devices (Diaconu and Rusu 2013). Since there are no wave farms currently in existence, there are no studies that have directly looked at their ecological impacts. However, the list of potential ecological consequences of wave farm development is long, including alterations to community structure, foodweb dynamics, direct mortality, electromagnetic fields, and entanglement risk to marine mammals (Boehlert, McMurray, and Tortorici 2008; Boehlert and Gill 2010). Finally, in addition to the physical and ecological impacts of wave farm development, there are clear social impacts, and engaging stakeholders and the public during wave farm development is critical (Bonar, Bryden, and Borthwick 2015; Dalton et al. 2015).

If we wish to reduce our annual greenhouse gas emissions by increasing the level of renewable energy resources off the nation's coasts, we must carefully integrate economics, resource conflicts, and physical, ecological, and sociological impacts of renewable energy development. In this paper, we have made inroads to the economics and resource conflicts surrounding wave energy development on the west coast of the United States. Much more work still needs to be done before we can move forward, and marine planning is a powerful tool for addressing such complex demands in an integrated fashion.

Acknowledgments

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