



Using local knowledge to project sea level rise impacts on wave resources in California



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ARTICLE INFO

Article history:

Received 6 June 2015

Received in revised form

16 January 2017

Accepted 17 January 2017

Keywords:

Coastal management

Local knowledge

Sea level rise

Surfing

Wave resources

ABSTRACT

Sea level rise will have significant impacts on many coastal resources. Waves are an important resource in California, where they support the recreation of 1.1 million surfers who inject millions of dollars into local economies. The impacts of sea level rise on wave resource quality, however, are unknown. By examining the local knowledge of more than one thousand California surfers collected through an online survey, this study extrapolates their evaluations to estimate the susceptibility of California surf-spots to sea level rise based on the principle of tidal extrapolation. Vulnerability classifications are derived from the relationship between wave quality, tide effects, and sea floor conditions. Applying these classifications to 105 surf-spots in California evaluated by multiple respondents, we project that as a result of sea level rise by 2100: 16% of surf-spots are Endangered due to drowning; 18% are Threatened, but could adapt if natural shoreline processes are not impeded; and 5% might improve as rising sea levels increase the likelihood they will experience optimal conditions. These projections are significant not only for the many surfers who depend on surf-spots, but also for the coastal communities who rely on the availability of high quality wave resources. Results from this study also have important implications for when and how managers might take surf-spot quality and vulnerability into consideration through coastal adaptation. Lastly, this study establishes a baseline of wave resource quality in California and suggests that this baseline will shift as wave quality changes over the coming century.

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1. Introduction

Sea level rise is affecting coastal communities worldwide and the severity of these impacts is projected to increase in the coming century as the rate of sea level rise increases (Church et al., 2013; National Research Council, 2012). The results include growing threats to critical infrastructure, private property, human populations, cultural and economic resources, and entire island nations (Caldwell et al., 2013; Hanak and Moreno, 2012; Langridge et al., 2014; Marzeion and Levermann, 2014). In coastal California, dense development and a large, rapidly growing population are both susceptible to sea level rise; Heberger et al. (2009) estimate that the replacement cost of coastal property at risk from inundation by 1.4 m of sea level rise could be nearly \$100 billion. These

estimates, however, exclude the effects of impacts to the quality of breaking waves, which are valuable and potentially vulnerable resources in California. Breaking waves are a key element of California's intertidal ecosystems, are central to the viewshed and experiences of many tens of millions of people who live on and visit the California coastline each year, and enable surfing—one of the most iconic, as well as culturally and recreationally significant, activities in coastal California. Surfers rely on carefully honed knowledge of the behavior of ocean waves that informs their ability to catch and ride waves (Reineman, 2016). This study draws on an assessment of this local knowledge among California surfers to estimate how sea level rise will impact California's wave resources and discusses the implications of these impacts in the context of coastal management and climate change adaptation.

Waves drive surfing and, in turn, the character of coastal communities. In 2006, the surfing industry was valued at more than \$7.4 billion in the US alone (Lazarow et al., 2008) and is projected to reach \$13.2 billion globally by 2017 (Global Industry Analysts, 2014). The 1.1 million surfers in California, roughly one-third of

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the nation's total, contribute substantially to the estimated \$2 to \$5 billion national, annual economic impact from US surfers (Leeworthy and Wiley, 2001; Wagner et al., 2011; the number of surfers has likely increased in the 1.5 decades since these participation data were collected). The geology and bathymetry of California's active coastline (Griggs et al., 2005) lead to a high diversity of wave types, including those well suited to all surfing ability levels, from beginner to expert (Guisado and Klaas, 2005), and to a full range of oceanic swell conditions (Espejo et al., 2014). Surfers are central to California's beach image and coastal cities in California have been home to some of surfing's most seminal moments, which have in turn shaped the identities of many coastal communities (Warshaw, 2010; Westwick and Neushul, 2013). Huntington Beach, CA, for example, proclaims itself "Surf City, USA," an exclusive title for which it vied bitterly with the city Santa Cruz, CA (Carcamo, 2008).

Along these coastlines, surfers rely on specific coastal locations, "surf-spots," where depth and bottom contours interact with incoming ocean swells to produce waves that break in a way that favors riding (Butt et al., 2004). The characteristics of any surf-spot vary with the tide, swell, wind, and other conditions, as does the sensitivity of a surf-spot to changes in these conditions. For example, an ebbing tide could reduce wave quality at one surf-spot and improve it at another surf-spot, or have little effect at either depending on the size of the swell. These variations are predictable with differing levels of accuracy and precision and the general features of individual surf-spots remain fairly constant over time allowing surfers to predict with some certainty the quality of the waves at any given time. This predictive capability enables the surf forecasting industry to help surfers choose where to surf given the day's current and expected conditions (see e.g., Surfline Inc. or Magicseaweed Ltd.). While these services may offer global coverage, forecasting and daily wave quality reporting are often conducted on a surf-spot-by-surf-spot basis, which is important given the amount of potential variability between surf-spots and also given that many surfers surf both frequently and close to home (Nelsen et al., 2007; Wagner et al., 2011).

Despite the cultural and economic importance of surfing and the relative predictability of wave quality in the short term via oceanographic and meteorological forecasting, little is known about the potential long-term impacts of sea level rise on surf-spots in California, or elsewhere. Speculation within the surf media, however, is common. Surfer Magazine, for example, asks:

Sea level is expected to increase by about three feet. Many of us surfers get pretty picky about the volume of water overlaying our surfing topography. Three extra feet at any given time means that your favorite high-tide spots will be your everyday spots. You may find new high-tide favorites, but you might not see your low tide favorites... like, ever... Where are you going to surf? (Taylor, 2013)

This question as posed also emphasizes the individual nature of wave-quality preference among surfers, who develop knowledge about (Reineman, 2016) and affinities for specific surf-spots (Reineman and Ardoin, *In Review*). Thus, the focus of surfers' concerns is not only global—that is, how will ocean waves change—but highly local—how will each specific surf-spot change.

Impacts of changing global climate on the ocean's waves have been projected, primarily through numerical modeling-based approaches. Hemer et al. (2013) project ocean basin-scale changes in wave size resulting from changes to ocean water temperature and storm frequency and intensity (among other factors). Espejo et al. (2014) developed a Wave Quality Index and modeled wave quality at roughly 100 km resolution for all the world's coastlines. These

efforts, while valuable, do not address wave quality and variability at scales relevant to individual surfers or to the communities vested with coastal management authority. Other investigators have applied numerical modeling techniques at the scale of individual surf-spots (see, e.g., Feddersen, 2007; Spydell and Feddersen, 2009), but these data and computationally intense techniques are challenging to implement at the scale of entire coastlines.

The objective of this study is to fill this gap by recording the local ecological knowledge of more than 1000 California surfers via a survey-based approach and to use this knowledge to evaluate the potential impacts of sea level rise on individual surf-spots across the California coast.

2. Methods

This study primarily relies on data for conditions at California surf-spots collected through a survey of California surfers that was disseminated online in the spring of 2014. Surf-spots evaluated by respondents were verified against a dataset of surf-spot descriptions assembled and curated by a surf forecasting company. A projection of sea level rise impacts is generated based on today's tidal range through tidal extrapolation.

2.1. Tidal extrapolation

Breaking waves have very specific relationships with water depth: wave shoaling (first interaction with the seafloor) begins when the water depth is one-half of wave length and wave breaking occurs when the wave height is three fourths the water depth (Garrison, 2001). The depth over a given location on the seafloor fluctuates daily as the tide rises and falls and this has significant impacts on breaking wave quality at many surf-spots (Butt et al., 2004). Tidal extrapolation capitalizes on the overlap between current (*i.e.*, present day) tide ranges and those projected when sea level has risen (Fig. 1). Climate change-induced sea level rise is a vertical translation, not only of sea level, but also of tide range such that in the future at a given location, high tide and low tide will be higher than at present. (The mean tide range between high and low tides has increased at most West Coast tide stations over the preceding century (Flick et al., 2003), but these range changes are minor compared to projected increases in mean sea level.) Until the point when a future tide range, centered around a higher mean sea level, no longer overlaps with today's tide range, the current-day and future tide ranges will share a set of sea surface levels across those portions of their ranges that overlap (Fig. 1). Therefore, a portion of current tide levels are not merely representative of future tide conditions, but are instances when the water depth at a surf-spot is the same today as it will be in the future. The exact date of a future sea level embodied in a current-day tide level depends on a variety of factors, including tide range, isostatic adjustment, and rates of sea level rise, processes that vary locally and each change slowly and continuously. Table 1 displays current-day tide ranges and project increases in sea level for two regions of the California coast.

This study relies on a characterization of current-day conditions within the zone of overlapping depths and extrapolation outside this zone to understand how California's surf-spots will potentially behave under a higher sea level regime in the future. This approach is conceptually similar to that employed by the California Coastal Commission's "King Tides Initiative" (Papendick, 2013), which seeks to highlight future threats from sea level rise to coastal property and infrastructure by providing visual documentations of present day inundation events during extreme high tides.

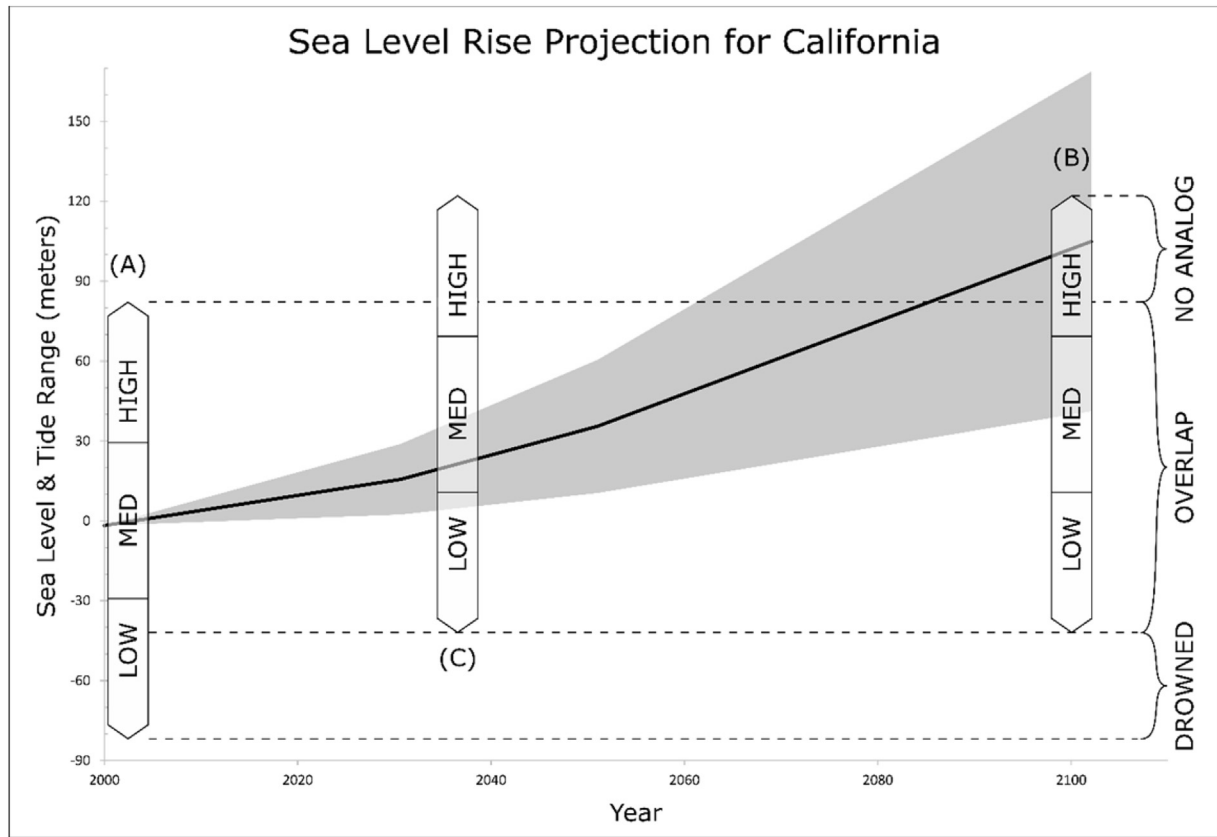


Fig. 1. Conceptual illustration of tidal extrapolation. Plot of the National Research Council sea level rise projections for the California coast (south of Point Mendocino; National Research Council, 2012) and associated tidal range. Filled grey region depicts sea level projection upper and lower ranges; solid line depicts mean of projections. (A) Represents the present day tide range above and below present day sea level (1.65 m; 0.825 m above/below mean). (B) Represents the range of year 2100 tides (1.65 m) assuming the minimum projection for sea level rise. Depicted are the associated loss (“drowned”) of the present day low tide depths, the zone where present and future tide ranges will overlap (“overlap”), and the zone above present day high tide for which there is no present day analog (“no analog”). (C) Represents those same ranges, which assuming the maximum projections for sea level rise, occur in roughly 2035. Tide range data via NOAA <http://tidesandcurrents.noaa.gov/stations.html?type=Datums> (means averaged from data for 45 available, open coast tide stations; last accessed April 20, 2015).

Table 1

Sea level rise projections and tide ranges for California. High, midpoint, and low projections for sea level rise (above year 2000 levels) via the U.S. National Research Council and current day tide ranges for two regions of the California coast. Note that Cape Mendocino marks a tectonic transition that affects the relative subsidence rates, and thus relative rates of sea level rise, to the north and south. (SLR: sea level rise.)

		South of Cape Mendocino	North of Cape Mendocino
SLR Projection: low, midpoint, high (cm) ^a	By 2030	4, 17, 30	−4, 9.5, 23
	By 2050	12, 36.5, 61	−3, 22.5, 48
	By 2100	42, 104.5, 167	10, 76.5, 143
Regional mean tide range (cm) ^b		165	213

^a SLR projection data via National Research Council Committee on Sea Level Rise in California Oregon and Washington, 2012. Available http://www.nap.edu/catalog.php?record_id=13389 (last accessed 24 May 2016).

^b Tide range data as per Fig. 1.

2.2. Wave knowledge assessment

To independently obtain surf-spot specific data for California's surf-spots, an online survey was deployed to California surfers about their knowledge of a particular surf-spot individually selected by each respondent. An opt-in, internet-based approach has previously been effective for reaching surfers: Wagner et al. (2011) successfully surveyed more 5000 surfers over a ten month period, with 98% of responses deemed useable.

2.2.1. Survey instrument

The survey instrument contained 25 to 28 questions (branching was used within the survey such that the total number of questions

for each respondent depended on their initial and subsequent responses). The instrument included a combination of multiple choice, short and free response, and multi-part questions for a total of 48–60 individual items addressing three general topics. First, respondents were queried for their general demographic information (including age, country of residence, years surfing, and surfing ability and preferences). Then, respondents were instructed to select (from their personal, unique experiences) the surf-spot they “know best” and provide general information about it (including the surf-spot's name, general location, wave type, and ocean bottom composition) as well as their familiarity with it. Lastly, respondents were asked to evaluate the interactions between the particular surf-spot they selected and the tide (including

best tide condition and wave quality at various tide levels). The survey was pilot tested via think-aloud interviews with ten surfers representing a range of ages and surfing experience levels. Although the survey's purpose was to collect data to enable projections of climate change impacts, to avoid introducing biases based on preexisting beliefs and opinions, the survey instrument framing was neutral with respect to climate change, its causes, and coastal management generally; it did not mention "sea level rise" or "climate change", either implicitly or explicitly. Due to concerns among some surfers about the secrecy of their surf-spots, careful attention was paid to issues around surf-spot location confidentiality and respondent anonymity in instrument design and throughout survey dissemination.

2.2.2. Survey dissemination

The survey was administered online using Qualtrics Survey Software (Qualtrics, LLC; <http://www.qualtrics.com>). The survey was disseminated via email to several hundred organizations, including surf retail stores, surf clubs (local and collegiate), surf industry groups, surf community websites and online publishers, surf forecasting companies, and surf-oriented environmental groups, as well as a network of colleagues within the ocean science and policy communities. Organizations were primarily, though not exclusively, located in California; recipients and respondents were asked to share the survey with their own networks. The survey was limited to adults 18 years of age or older in accordance with an approved IRB protocol. The survey opened online on March 10, 2014; this study reports on survey responses submitted before 11:59pm May 12, 2014 (a period of 9 weeks). Other than being in English, the instrument did not favor any geographic region and was available for any adult surfer to take online. This paper focuses on responses evaluating California surf-spots.

2.2.3. Data quality assessment and control

In this order, responses were eliminated that (1) were not from adults, (2) were duplicates (based on IP address and review of response variables), (3) did not proceed past the first or second preliminary questions (Age; Country of Residence), (4) did not evaluate a surf-spot in California, and (5) were incomplete, clearly erroneous, or indicative of nonresponsiveness (Gosling et al., 2000).

The survey instructed each respondent to select "the surf-spot they know best" and to answer a set of questions about that spot. The existence of each respondent's surf-spot was verified by manually matching the description of the spot's name, location, or other contextual cues, to a publically known and georeferenced surf-spot. This enabled comparability between responses. Verification was conducted against a database provided by Surfline Inc., (<http://www.surfline.com>, Huntington Beach, CA) a surf forecasting company. Surfline Inc. maintains a global database that includes comprehensive coverage of California surf-spots. Surf-spots that could not be verified against this database were researched and confirmed through other public, online surf-spot databases and published guides (see e.g., Guisado and Klaas, 2005; Surfer Magazine, 2006a, 2006b). Surf-spots that could not be linked to a known surf-spot were eliminated from individual analyses, but retained in aggregate analyses if the other variables permitted this.

Of verified surf-spots, results are only reported from those surf-spots identified and evaluated by three or more respondents; this is done, based on precedent, for two reasons. First, as Davis and Wagner (2003) stipulate when working with local knowledge: "Satisfying this standard would provide assurance that each claim is in fact an aspect of the local ecological knowledge 'system' in so far as the understandings, observations, and experiences related are demonstrably shared within the local setting" (p. 477). Second, this approach is respectful with regard to the proprietary feelings

some surfers may harbor towards "their" surf-spots (see, e.g., Mixon, 2014). In an analogous situation, the U.S. National Marine Fisheries Service follows a "rule of three" in which they aggregate fishing data from three or more vessels before releasing it, thereby protecting the privacy of fishermen and their fishing grounds.¹ Thus, only using data for surf-spots evaluated three times or more both increases the robustness of conclusions drawn from the data and also protects the privacy of respondents and surf-spots.

2.3. Surf-spot classification scheme

Surf-spots were evaluated based on their best tide for surfing and their seafloor composition; tide height influences wave quality at surf-spots (by changing depth) and the seafloor composition has ramifications for how wave quality at surf-spots changes over time (like season or year) and relates to other nearshore processes (like sediment transport and sand bar formation). For each surf-spot evaluated by 3 or more respondents, the "Best Tide" for surfing responses (very low, low, medium low, medium, medium high, high, very high tides) were converted to a continuous numerical scale (very low = 1, low = 2, ...very high = 7) and averaged; the tide's range is widely acknowledged to be a continuous (versus an ordinal) phenomenon. Surf-spots with Best Tide values below 3.5 (inclusive; i.e., for which the balance of respondents rated the best tide as very low, low, or medium low) were classified as Best at Low Tides; surf-spots with Best Tide values below 2 (inclusive) were classified as Best at Very Low Tides; surf-spots with Best Tide values above 5 (inclusive) were classified as Best at High Tides. Additionally, respondents selected the seafloor composition for the surf-spot they evaluated from a list of categories; these categories were derived from seafloor descriptions used by Surfline Inc. While agreement between different respondents for individual surf-spots was generally high, when responses varied, the surf-spot seafloor composition was classified based on the majority response. Hard Seafloors included "hard rock reef" or "sand and reef" and Soft Seafloors including "sand" or "cobbles, boulders, and loose rocks."

Surf-spot vulnerability to sea level rise is thus affected by a suite of factors including, significantly, water depth (as influenced by tide and sea level rise) and seafloor composition. These factors are combined to define surf-spots as Vulnerable to sea level rise by 2100 as follows:

Highly Endangered Surf-Spots: Currently Best at Very Low Tides and break over Hard Seafloor.

Endangered Surf-Spots: Currently Best at Low Tides and break over Hard Seafloor.

Threatened Surf-Spots: Currently Best at Low Tides and break over Soft Seafloor.

Not all surf-spots meet the criteria to be characterized as Vulnerable. Surf-spots where respondents favor high tides have the potential to improve due to sea level rise, which will result in more frequent or prolonged occurrences of optimal water depth. These surf-spots are defined as:

Improved Surf-Spots: Currently Best at High Tides.

From these two metrics, each of the surf-spots in the database was assigned a level of vulnerability or categorized as Improved.

¹ This rule is not formally codified; a description of the "Rule of 3," as practiced by the National Marine Fisheries Service, can be found in the testimony of Mark Fina before the Committee on Natural Resources of the United States House of Representatives on February 4, 2014.

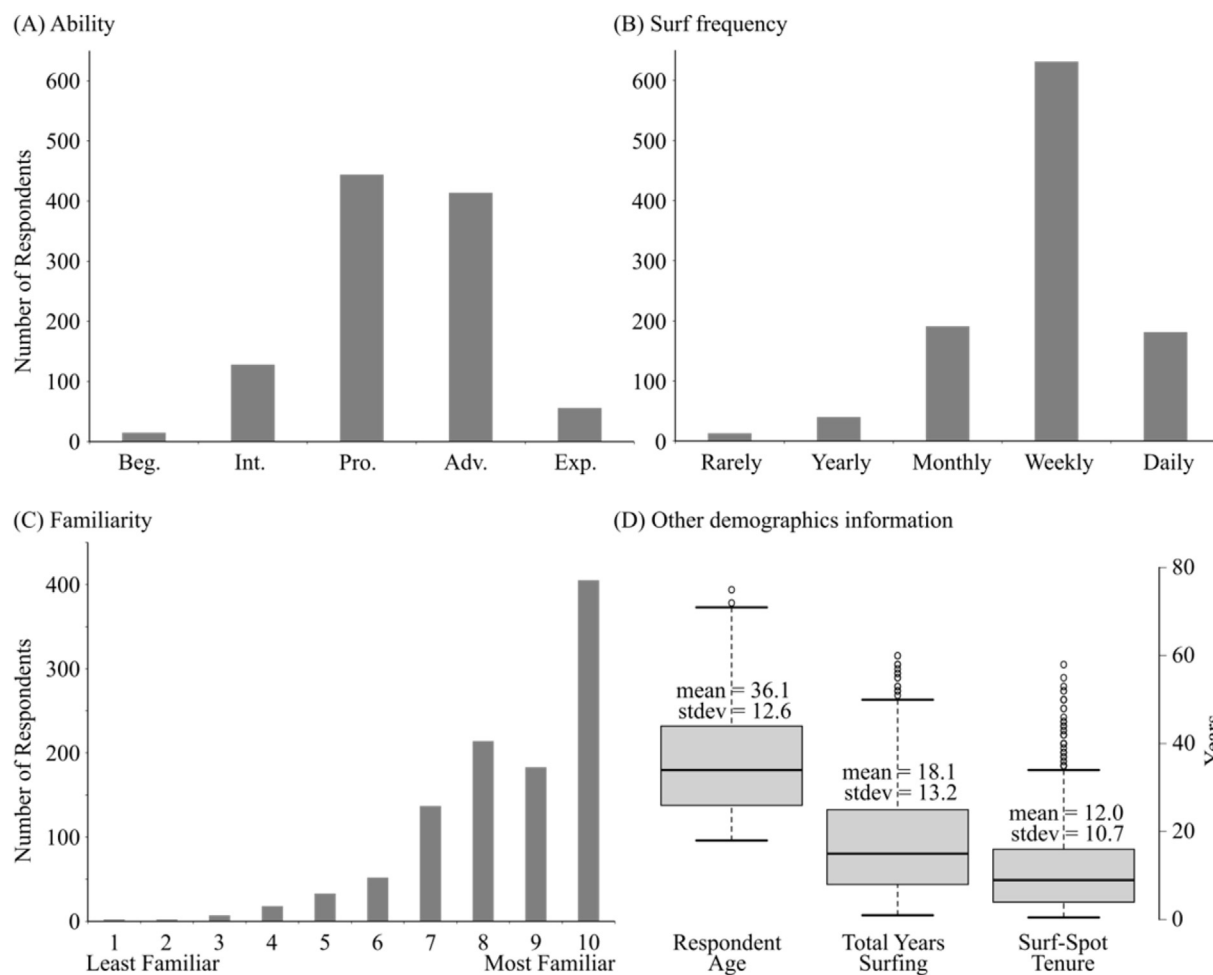


Fig. 2. Demographics of California respondents. California respondents are those who evaluated surf-spots in California in the survey: (A)–(C) are response-frequency histograms of (A) self-assessed surfing ability (Beginner, Intermediate, Proficient, Advanced, Expert); (B) frequency of surfs at their one selected surf-spot; and (C) self-assessed surf-spot familiarity. (D) Standard box plots of surfer age, years surfing, and years surfing their selected surf-spot (tenure). $n = 1057$.

Surf-spots that did not meet criteria for either were classified as “Minimally Affected,” since optimal water depths these surf-spots experience during the present day tide range will still occur during future, higher sea levels.

Shorelines in California are highly dynamic systems (Griggs

et al., 2005) and the processes that influence wave quality are complex (Butt et al., 2004; Scarfe et al., 2009). Thus, the vulnerability of a given surf-spot to impacts from sea level rise is difficult to predict. Moreover, because surf-spots themselves are also highly dynamic, there is a possibility that some could naturally adapt to

Table 2

Surf-spot response counts and verification success, by county.

County	Responses	Verified surf-spots	Unverified surf-spots	“Secret” surf-spots
Del Norte	0	0	0	0
Humboldt	8	5	0	0
Mendocino	5	3	0	1
Sonoma	3	1	0	0
Marin	18	4	0	0
San Francisco	84	4	0	0
San Mateo	38	8	1	0
Santa Cruz	137	22	2	3
Monterey	25	10	0	0
San Luis Obispo	33	13	6	1
Santa Barbara	27	13	2	1
Ventura	81	13	1	0
Los Angeles	108	26	2	0
Orange	137	32	1	0
San Diego	351	79	11	3
Unknown	2	0	2	0
Statewide Total	1057	233	28	9

maintain their quality during higher stands of sea level. For example, if natural sediment transport, sources, and sinks continue to function into the future as they do today, a sandbar on which a surf-spot currently breaks could gradually migrate inland, exactly in-step with the rate of sea level rise and thus maintain the surf-spot's quality. Currently, sea levels are rising at a higher rate than at any time in the last 27,000 years (Kopp et al., 2016). Alternatively, a surf-spot that today breaks over a hard, rocky reef unaffected by seasonal sediment availability (and thus less likely to adapt to keep pace with rising sea level) could effectively drown if it currently breaks only at low tides. Seafloor composition is a significant component of vulnerability because of the relationship between seafloor and surf-spot quality and between seafloor and coastal processes that shape it (Franklin et al., 2013). Bottom conditions (e.g., contours and composition) change over time (Butt et al., 2004) and are affected by natural phenomena like storms and currents as well as by human activities, through both terrestrial land-use and coastal management practices (Griggs et al., 2005).

3. Results

The survey was initiated 3240 times in Qualtrics; survey initiation simply indicates that respondents clicked the survey link in an email or webpage. Applying the data cleaning protocol, responses were eliminated as follows (percentages out of 3240): 44 minors (1.36%), 39 duplicate IP addresses (1.2%), 344 responses that did not proceed past the IRB and preliminary pages (10.62%), and 1542 responses that did not evaluate a surf-spot in California (47.59%); surf-spots outside of California will be the focus of a future study. These initial eliminations result in 1271 responses evaluating California surf-spots. Of these (percentages out of 1271), 197 (15.50%) were eliminated for being incomplete and 17 (1.34%) were eliminated for other reasons, leaving 1057 usable responses—hereafter “the respondents.” The survey completion rate for responses identifying and evaluating California surf-spots is thus 83.16%.

3.1. Respondents

Fig. 2 summarizes the relevant demographics of the 1057 respondents and showcases both their diversity of surfing experience and commitment to surf-spots in California. Respondent knowledge of surf-spots was assessed via several proxy indicators, which suggest that respondents possess a high level of knowledge about their surf-spots. 517 (48.91%) respondents have been surfing at their spot for 10 years or longer, 802 (75.88%) respondents rate themselves 8 or higher on a 10 point scale of familiarity with their spot, and 812 (76.82%) respondents surf at their spot 52 times per year or more (Fig. 2).

3.2. Surf-spots

After cleaning and verification, a total of 233 unique surf-spots were identified; this total includes surf-spots from each of California's Pacific Coast counties, except for Del Norte County; Table 2 summarizes the response rates and surf-spot counts from each county. In addition to the 233 identified surf-spots, nine respondents stipulated that their surf-spot was “secret” and did not provide its name. A further 28 surf-spots were not verifiable with any known surf-spot. This is not evidence that these surf-spots do not exist; rather it suggests that these surf-spots are insufficiently documented to be found via the verification process described in Section 2.3.3. 127 surf-spots were evaluated one or two times; 37 responses evaluated secret or unverifiable surf-spots; 105 surf-spots were evaluated three or more times and thus examined in

subsequent analyses. The location of all but two of the secret and unverifiable surf-spots could still be verified to the county level.

3.3. Best tide evaluations and wave quality

At a state-wide, aggregate level, the plurality of respondents rate surf-spots as experiencing their “Best Conditions” below mean (medium) tide (Fig. 3 A): 422 (41.37%) rate best conditions at below medium tide and 313 (30.69%) rate best conditions at medium tide. Only 232 (22.75%) rate best conditions above medium tide. These ratings are corroborated by a separate metric in which respondents evaluated wave quality at different tide-levels: Fig. 3 B shows that the plurality of respondents rate best conditions at medium tides and that more rate best conditions at low tide than at high or very high tides. These responses substantiate the assertion that tides are influential on surf-spot quality and therefore that the water depth (which will eventually be increased by sea level rise) also has significant implications for a surf-spot's quality.

3.4. Wave resources vulnerability

Tidal extrapolation (see Section 3.3.1, above) implies that depths of portions of the tide range during today's current sea level will overlap with depths of portions of the tide range in the future when sea level has risen; see Fig. 1. This overlap presents an opportunity to gain insight into how current-day surf-spots will behave under a regime of higher sea level and is thus suggestive—and qualitatively predictive—of how rising sea level will impact surf-spots in the future. The timing of these impacts is highly dependent on a variety of physical forcing processes, from local (sediment erosion or

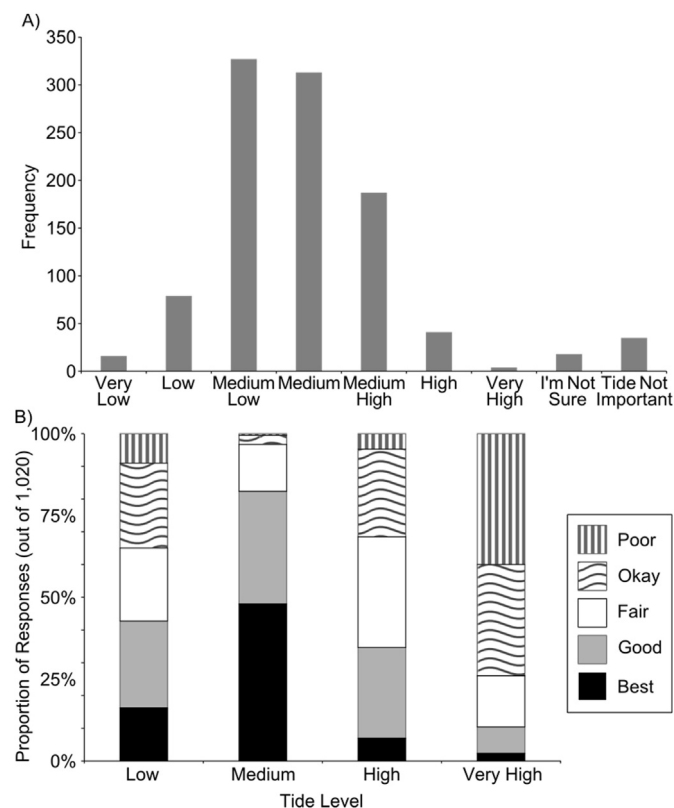


Fig. 3. Surf-spot quality results. Statewide, aggregate data for (A) the number of respondents rating the tide level at which their surf-spot experiences its “Best Condition.” The plurality of respondents favor tides below medium versus above medium tide. And (B) wave-quality evaluations for different tide levels. (n = 1020).

deposition) to regional (isostatic adjustment post glaciation and climate change-induced modifications to the ocean circulation), to global (climate change-induced sea level rise). The timing and magnitude of impacts are also highly correlated with aspects of individual surf-spots, namely the tides—and associated depths—at which surf-spots exhibit their optimal conditions. As sea level rises locally, surf-spots that break at low tide, or medium tide, or high-tide will be increasingly and sequentially inundated: the water will simply be too deep for them to experience their best conditions. In California south of Cape Mendocino (located in Humboldt County; see map in Fig. 4) where the majority of surf-spots evaluated in this study are located, the low-end projection of 0.42 m of sea level rise by 2100 is roughly one-third of the average tide range (1.596 m) for the same region (Table 1). Thus, a conservative tidal extrapolation implies that by 2100 on this stretch of coast: current-day low tide conditions will vanish, current-day medium tide levels will become future low tides, current-day high tide levels will become future medium tides, and in the future, a new high-tide not experienced in the current-day will appear above current-day high tide levels (“no analog” in Fig. 1).

According to this minimum sea level rise scenario, by 2100 the

best conditions experienced by more than 40% of respondents today (Fig. 3 A) will no longer occur. Similarly, more than 40% of respondents will lose access to the Best and Good conditions they currently experience during low tide (Fig. 3 B). Furthermore the surf-spot quality data depicted in Fig. 3 B shows that in general, surf-spot quality degrades with higher tides: by 2100, Poor, Okay, and Fair conditions will predominate over Best and Good conditions—a significant net loss in surf-spot quality. Applying the surf-spot classification scheme defined in Section 3.3.3 individually to the 105 surf-spots evaluated by three or more respondents in this study, five (4.8%) might improve and 64 (61%) will likely see minimal effects due to the lowest sea level rise projections for 2100 (Fig. 4). However, more than one-third are vulnerable to impacts from sea level rise: 19 (18.1%) are Threatened and 17 (16.2%) are Endangered; no surf-spots meet the definition for Highly Endangered. Fig. 4 also presents the vulnerability disaggregated to a per county basis: surf-spot vulnerability is clearly not distributed evenly along the coast. San Francisco, Santa Cruz, Ventura, and San Diego counties in particular each have very high proportions of vulnerable surf-spots. By contrast, San Luis Obispo County could experience improvement at one-half of its evaluated surf-spots. All

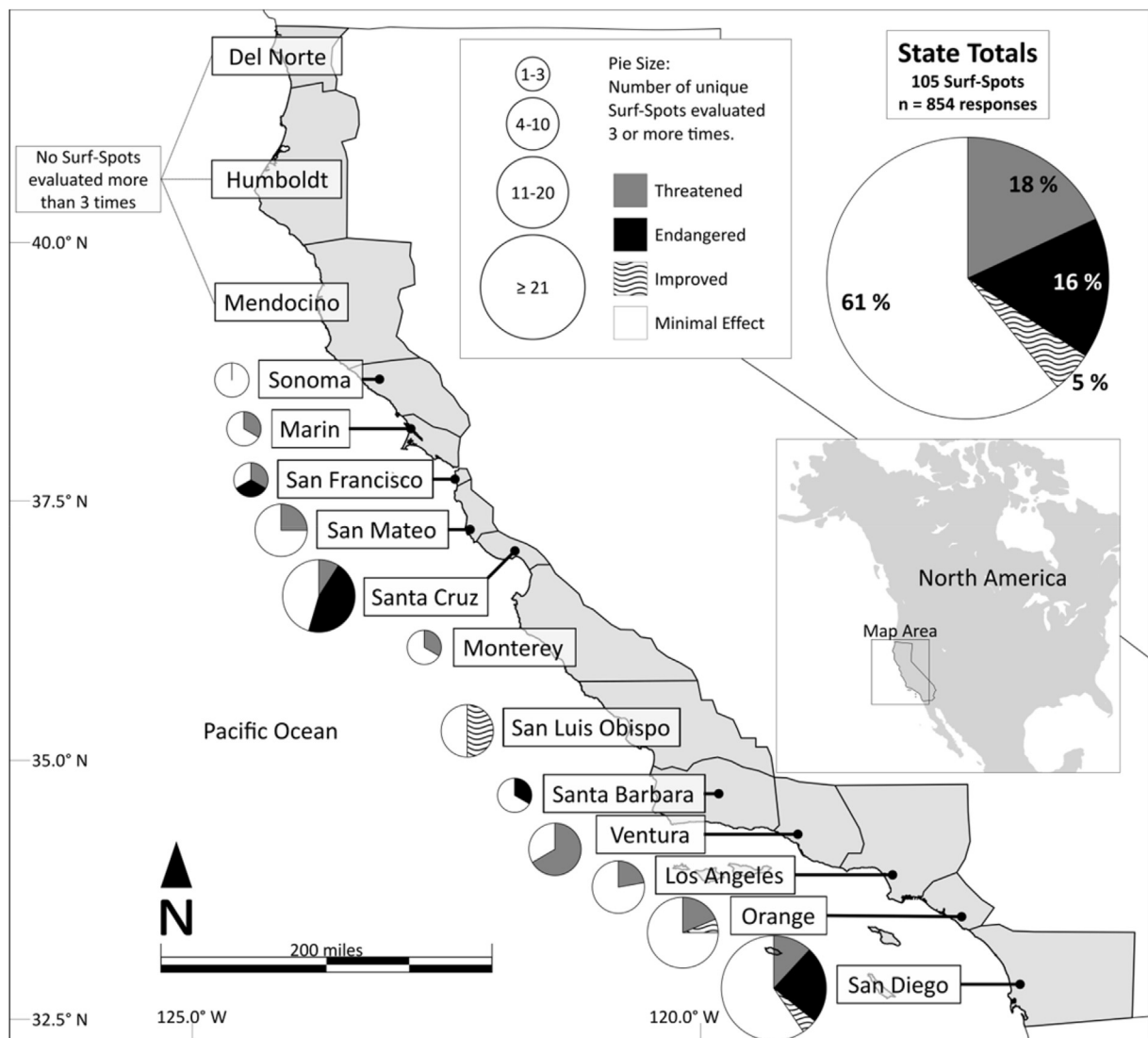


Fig. 4. Map of California surf-spot vulnerability. Map depicts proportion of Threatened, Endangered, Improved, and Minimally Affected surf-spots per county. Response frequencies per county are displayed in Table 2. Statewide, aggregate results are presented in the large pie chart in the upper right.

of these projections for surf-spot quality change are predicated on the assumption that the coastline is allowed to adapt according to natural processes that are not interrupted by human activities.

4. Discussion

By collecting the local wave knowledge of more than 1000 California surfers and extrapolating from this knowledge based on the principles underpinning ocean wave physics and sea level rise, this study projects a substantial decrease in the quality of surf that will be experienced by future surfers in California: the best conditions experienced today by 40% of respondents are likely to disappear due to sea level rise by 2100 (Fig. 3 A). More concerning still, these data suggest that of the 105 surf-spots (evaluated by 3 or more respondents) in this study, 16.2% are Endangered and a further 18.1% of surf-spots are Threatened as a result of sea level rise (Fig. 4). Endangered surf-spots will drown and cease to exist as they do now; Threatened surf-spots could adapt, but may still drown. Fig. 5 illustrates conceptually the relationship between sea level rise, bottom composition, and shoreline management and how they relate to vulnerable surf-spots. Fully one-third of surf-spots in this study are vulnerable to impacts from sea level rise; very few will likely improve. While it is possible that as yet undiscovered surf-spots may emerge as a result of rising sea level, this study only evaluates extant surf-spots and does not incorporate a mechanism to detect surf-spots where they do not already exist.

These results are important for several reasons. First, surf-spots are vital coastal resources in California. They support the regular and frequent recreation of more than one million surfers, define the identities of individuals and coastal communities, and drive a recreation and tourism industry worth many millions of dollars (Leeworthy and Wiley, 2001; Nelsen et al., 2007; Wagner et al., 2011). Given this importance and other changes, both ongoing and projected, for our coasts (Caldwell et al., 2013; National Research Council, 2012), it is no surprise that surfers have wondered about the future of surf-spots (e.g., Taylor, 2013). But despite this importance, this study is the first regional-scale projection of surf-spot vulnerability to sea level rise impacts on surf-spot-by-surf-spot and county-by-county basis. This study also provides a typology for classifying vulnerability based on the physical characteristics of surf-spots and proposes a method for determining those characteristics.

The 105 surf-spots included in these results represent less than one-half of the more than 230 unique surf-spots in California identified in the survey and only a tiny fraction of surf-spots worldwide. While it is not appropriate to extrapolate the results of this sample to the total population of surf-spots, a cursory examination of Surfline Inc.'s global surf-spot database, with surf-spot "best conditions" defined and coded as per Section 3.3.3, shows that of 2204 surf-spots globally, 30% are best below medium tide and therefore are also potentially vulnerable (Threatened or Endangered) to sea level rise. Of the 179 California surf-spots in Surfline's database, 46% (79) are potentially vulnerable to sea level rise. This estimate is slightly higher than the 34% arrived at in this study; the difference could imply that the methodology this study relies on is more conservative or that the 74 additional spots included in the Surfline database (but not included in these analyses, as per Section 3.3.2.3) are generally more susceptible to sea level rise.

4.1. Shifting baselines

The impacts from sea level rise projected here (based on the low-end scenario for sea level rise) will not occur instantaneously, but will accumulate slowly over the coming decades. Where surf-

spots are Endangered, sea level rise will force an equally slow degradation in surf-spot quality; under the high-end sea level rise projections, these impacts will occur more quickly. This study thus presents a conservative projection of surf-spot vulnerability. Few of the surfers surveyed in this study, however, will be alive in the year 2100 and unless they continue surfing for many decades and maintain an accurate, comparative frame of reference for wave quality, they will not likely perceive such gradual changes in quality.² By contrast, future generations of surfers are not likely to have this historical frame of reference; they will not realize that their surf-spots are inferior in quality compared with the past and, thus, further degradation of quality will be measured against this already diminished baseline. This is an example of "shifting baseline syndrome" as identified by Pauly (1995) to describe generational differences in the baseline quality of fishery stocks that result in "gradual accommodation of the creeping disappearance of resource species, and inappropriate reference points for evaluating economic losses resulting from overfishing, or for identifying targets for rehabilitation measures" (p. 430). These results suggest that there will also be a shifting baseline in wave quality with as yet unknown implications for individuals, communities, economies, and future coastal management decision-making. Popular media sources (Taylor, 2013) and anecdotal evidence suggest that crowding is an increasingly problematic factor in the surfing experience leading to the possibility of a shifting baseline in the social quality of surf-spots in addition to the physical resource quality.

Understanding these changes and the vulnerability of resources to global and local drivers of change is essential for effectively managing them into the future. For coastal resources like waves, it is important to note that while the 85 year timeframe discussed here is long in terms of the typical resource user, it is commensurate with the timeframe of infrastructure and other development projects in the coastal zone (Melius and Caldwell, 2015). Coastal development has a high potential and a historic record of influencing surf-spot quality in California.³ It is largely through development—and its lasting impacts—that surf-spot quality has been altered previously (Corne, 2009). Efforts to adapt to rising sea levels will likely include shoreline-modifying development. This study establishes baseline data for surf-spot quality that will be useful in subsequent efforts to assess impacts from future development as well as from sea level rise directly. Without information about surf-spot vulnerability, it is not possible to consider the quality and future of wave resources and to incorporate them into long-term adaptation planning.

4.2. Connection to coastal management

Climate change and associated sea level rise will likely accelerate the use of coastal management practices that can disrupt surf-spots and in particular could disrupt the ability of Threatened surf-spots to adapt to rising sea level. As of 2001, roughly 10% of

² While several dozen surfers in this study indicated they have been surfing the same surf-spot for more than four decades, the survey instrument did not query whether they have observed changes in surf-spot quality in that time.

³ Direct impacts result in the elimination of a surf-spot by, for example, the construction of a breakwater that changes the bottom contours or prevents swells from reaching a surf-spot (as occurred at Dana Point, CA in 1966; see Westwick and Neushul, 2013). Impacts can also be indirect by altering a coastal process that subsequently changes the quality of a surf-spot, for example a jetty that prevents sediment transport and alters sandbar formation at a surf-spot. Impacts on surf-spots can also be both negative and positive (i.e., they can improve surf-spot quality; Corne, 2009) and while they are generally unintentional, they can be intentionally designed to improve surf-spot quality, as is the case with artificial surfing reefs (Scarfe et al., 2009).

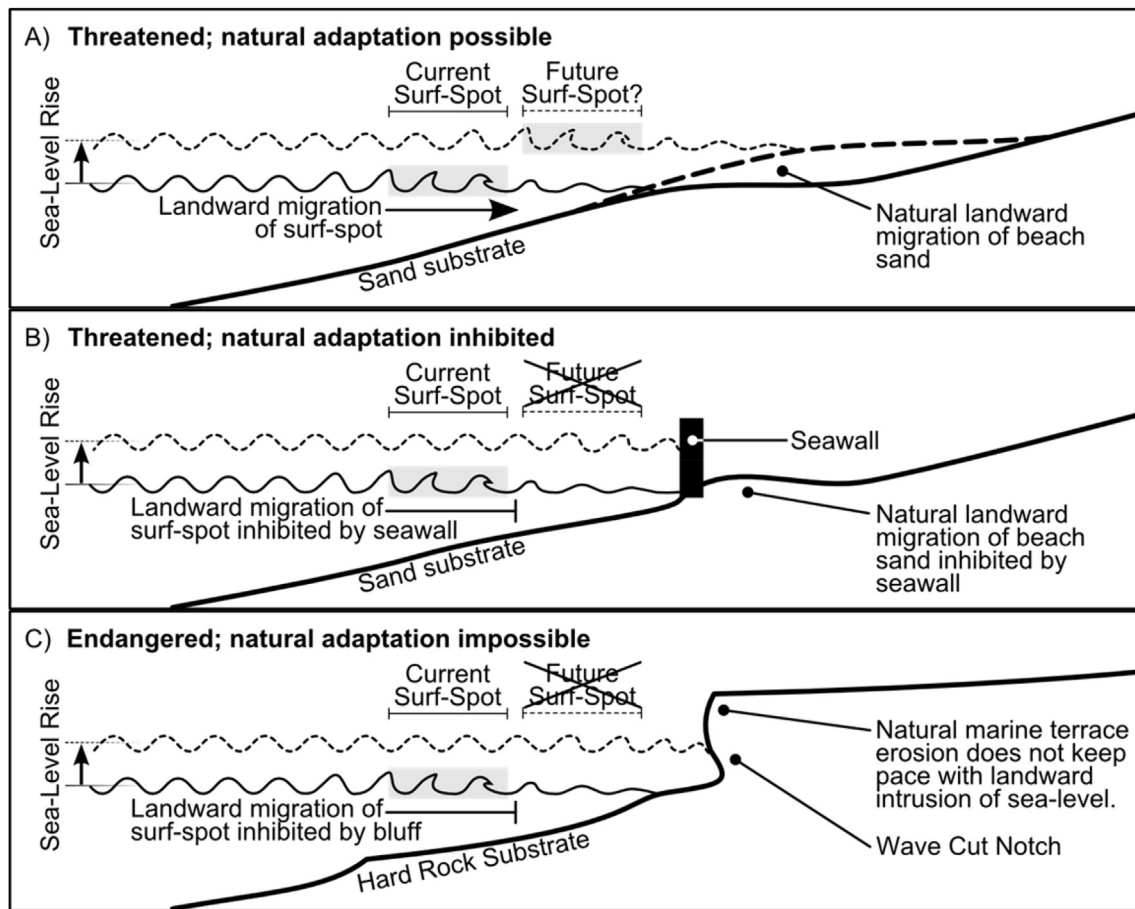


Fig. 5. Factors influencing surf-spot vulnerability. This conceptual diagram depicts relationships between sea level rise, seafloor composition, and surf-spot location and vulnerability in three scenarios for low-tide surf-spots. (A) Threatened surf-spot: surf-spot breaks over natural, sandy (“soft”) substrate that could adapt to sea level rise and maintain surf-spot quality and character; (B) Threatened surf-spot: surf-spot breaks over natural, sandy substrate, but the beach is modified with an armoring structure (seawall) that prevents natural adaptation of the beach and by extension, the surf-spot; (C) Endangered surf-spot: surf-spot breaks over rock ledge (“hard”) substrate that will not naturally adapt in pace with sea level rise.

California's 1100 mile coastline has been hardened (“armored”) to protect (usually from erosion) or enable coastal development (Griggs et al., 2005; Melius and Caldwell, 2015; Runyan and Griggs, 2003). Armoring results in loss of beach area seaward of the hardened structure and disrupts sediment flow on its periphery. It also prevents natural erosion processes from widening the beach at its landward end (where the armoring structure is situated) and prevents the introduction of sediment into the coastal environment (Pilkey and Wright, 1988), though the latter processes is likely an insignificant source of sediment (Runyan and Griggs, 2003). Human interference with both of these natural processes will likely prevent surf-spots from migrating landward with rising sea levels, as compared in Fig. 5 A and B. This interference will also prevent beaches from migrating landward to keep pace with sea level rise: these beaches will drown as they back up against bluffs (Fig. 5 C) or shoreline armoring (Fig. 5 B) protecting private property or public infrastructure (Garfin et al., 2013).

Coastal armoring, littoral cell disruption (e.g., by jetties), and entrapment of sediment in California's heavily impacted upstream watersheds (e.g., through surface hardening and dam construction), have also resulted in the need to replenish sand (“beach nourishment”) at many important and heavily visited beaches (Griggs et al., 2005). The estimated cost of this nourishment is \$120 million in one-time costs and \$27 million annually statewide (California Department of Boating and Waterways and California State

Coastal Conservancy, 2002). Artificial replenishment of beach sand could mitigate impacts to Threatened surf-spots, though the financial costs are very high. The direct impacts of sea level rise over the coming century and the use of armoring and beach nourishment to adapt to those impacts (and to other changing coastal conditions brought about by climate change and sea level rise) necessitate that surfers will have to adapt. Surfers will adapt by slowly and steadily (over lifetimes and generations) changing their behavior by accepting different quality conditions, surfing different surf-spots, riding different equipment, and as a result of shifting baseline syndrome, unknowingly altering their preferences. Armoring and beach nourishment efforts to mitigate sea level rise impacts on infrastructure and beaches, respectively, could result in fundamental changes to the coastal conditions that create and shape wave resources, up to and including the complete disappearance of surf-spots, and will force surfers to undertake more significant or immediate adaptations.

This study both records and relies on the knowledge of surfers—wave resource users—to project impacts to resource quality resulting from climate change-driven phenomena. Increasingly, knowledge possessed by resource users, despite having its origins outside contemporary resource management paradigms, is recognized as a valuable source of data for understanding how to manage resources, such as fisheries, in the best interests of both the human and the natural system (Berkes, 2003; Davis and Wagner, 2003;

Gilchrist et al., 2005; Huntington, 2000; Shackeroff and Campbell, 2007). Surfers' knowledge of wave resources can be considered a form of local knowledge because it "constitutes a 'body' and a 'system' of understandings and know-how that arise through time from a variety of individual and shared experiences and observations, mediated by culture, with regard to environmental factors, behavioral attributes, and ecological dynamics" (Davis and Wagner, 2003; Reineman, 2016). In the case of wave resources, because their quality and characteristics are locally and individually unique and because their primary users' preferences are also unique, relying on the specific local knowledge of those users is especially advantageous. Individual differences can be mitigated, and confidential locations protected, by following the Rule of Three (Davis and Wagner, 2003; see also fn 1). The utility of the vulnerability assessment approach used here is that it could be easily and affordably deployed at much smaller, community-level scales, for example, to provide coastal planners with highly context and location specific information to aid with decision-making that could affect wave resources.

4.3. Limitations

Important caveats to these results should be addressed. One strength of this approach is that individual evaluations of wave "quality" reflect the subjective nature of wave resource quality; the resulting projections of surf-spot vulnerability, however, are thus descriptive rather than deterministic. In the case of surfing, there is no absolute standard of quality. Absolute measures like significant wave height and wave period do exist (for review, see Scarfe et al., 2009) and are also projected to change as a result of climate change (Dowdy et al., 2014; Hemer et al., 2013); these projections are important for advancing understanding of large scale oceanographic change that might impact waves. Wave preferences among surfers, however, are unique and individual, reflecting each surfer's ability, preference, and mood. By characterizing these results in terms of quality as assessed by individuals, the projections better represent the needs of resource users; future vulnerability assessment efforts might combine both approaches. Other studies have used numerical modeling approaches to describe coastal processes, like sediment transport (Bonaldo et al., 2013) or erosion (Dickson et al., 2013). Studies within the surf zone, however, become highly computationally demanding due to the non-linearity inherent in breaking waves coupled with nearshore sediment transport processes (Ruessink et al., 2012). Given the complexity of oceanographic processes involved and the individualistic nature of quality, it is arguably more straightforward to rely on the local ecological knowledge of seasoned resource users rather than the output of numerical models when attempting to project changes in resource quality. Though respondents were drawn exclusively from surfers with access to the Internet who voluntarily chose to complete the survey, this method has previously been found effective for reaching large numbers of surfers (Wagner et al., 2011). If this design introduces any biases, they will likely favor more accurate and precise results because of the inherent interest in wave conditions that might prompt surfers to use online forecasting services in the first place.

The external validity of these results depends on assumptions underlying tidal extrapolation, in particular that other conditions remain unchanged (lest they have a confounding effect), but this is optimistic. It is possible that seafloor and other conditions may naturally adapt such that during future, higher sea levels, the same wave quality will persist over the tide's range. However, given the accelerated rate of sea level rise projected in the coming century (Church and White, 2006; Church et al., 2013; Kopp et al., 2016) combined with the great extent to which the natural coastal

environment has been and will continue to be modified (e.g., through coastal sediment management and erosion control and watershed management upstream preventing normal sediment loading of the coastal environment; Griggs et al., 2005), it seems unlikely that all surf-spots will naturally adapt to rising sea levels, though surely some will. Surf-spots with hard bottoms (e.g., rock or coral reef) are especially unlikely to adapt; spots with soft (e.g., sand or cobble) bottoms may adapt with sea level rise such that the robustness of tidal extrapolation is weakened. Warmer temperatures, more (or less) frequent, powerful storms, larger or smaller waves, and altered El Niño cycles will also diversely affect wave resources, as will changes in tidal range (though these changes in range are second order compared to sea level rise projections). These issues, combined with current, typical management responses to shoreline protection in California, like seawalls, underscore the significance of recent calls for coastal adaptation programs that will allow natural shoreline processes to continue naturally despite rising sea level (Caldwell and Segall, 2007; Caldwell et al., 2013; Hanak and Moreno, 2012; Melius and Caldwell, 2015). Heeding these calls will also likely mitigate sea level rise impacts on Threatened surf-spots.

Regardless, it is likely that surfers will have to adapt to continued changing conditions on the California coast. While the projections about surf-spots made here are not absolute, the evidence, including physical changes on the coast due to sea level rise and extant shoreline modifications undertaken in response to those changes, the limited portfolio of options to mitigate or adapt to future changes, and the local knowledge of these coastal systems held by users, suggest with a high degree of certainty that today's "wavescape" will change. Surf-able waves are a limited resource; there is an inverse relationship between the number of surfers in the water at a surf-spot and the waves available per surfer. The combined result of potential wave loss and increased crowding of waves implies changes in meaningful access to a resource of significant value to the surfing community (Reineman and Ardoin, *In Review*); the influence of the social carrying capacity of recreational resources has been extensively explored in other settings (see e.g., Schreyer and Roggenbuck, 1978; Stankey and McCool, 1984; Tarrant et al., 1997). These changes will have ramifications in the lives and experiences of surfers as well as on the communities and industries that have grown up around them. More research is necessary to increase understanding of the determinants of surf-spot vulnerability, to improve capacity to project changes to wave-resources, and to understand and plan for their sustainability in coastal communities.

4.4. Conclusions

By engaging directly with the surfing-community to better understand the vulnerability of an important coastal resources to global change, this study provides a path to better informed, engaged management of wave resources. In so doing, it determines that: (1) Sea level rise will likely impact the quality of surf-spots; in California that impact will be a net reduction in overall wave quality at current surf-spots. (2) Vulnerability of surf-spots to sea level rise varies geographically, with some surf-spots and some regions experiencing more significant reductions in wave quality; due to sea level rise, roughly 18% of surf-spots evaluated here are Threatened by drowning and 16% are Endangered; 5% could improve. And (3) that surfers' local ecological knowledge of waves constitutes a measureable source of data about environmental condition and variation. Given the vast economic and cultural importance of surfing, these conclusions suggest that coastal managers should not only give credence to the wave knowledge of surfers, but also take wave quality and vulnerability into

consideration, especially when planning coastal armoring, beach nourishment, or other developments, whose impacts to natural coastal processes could affect waves.

Acknowledgements

The authors wish to acknowledge the thousands of surfers who shared their time and knowledge to make this study possible. Gratitude is also due to Surfline Inc. (Jonno Wells & Dr. Graeme Rae) for access to their surf-spot database, as well as to Leif Thomas, Ben Reineman, and Austin Becker for their substantive comments early in the development of this research. The first author was supported by a Goldman Fellowship from the Woods Institute for the Environment at Stanford University.

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