Valuing beach ecosystems in an age of retreat

By

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ABSTRACT

California's coast is eroding, along with its iconic sandy beaches. As a result, the pressure for already extensive coastal armoring of these dynamic shorelines is increasing. Beach loss will accelerate with sea level rise, as will the rate of armoring, unless checked by major public policy initiatives. To conserve functional beach ecosystems for the public good, adaptation strategies need to include preservation of shorelines without armoring and the restoration of natural coastal processes. As in many other ecosystems, investigations of the full value of ecosystem services of intact dune-beach-surf zone systems and the development of protocols for robust measurement of indicators of those services are incomplete. Consequently, valuation of the ecological functions and services (except for storm buffering and recreation) of beaches are rarely applied to mitigate for armoring projects. To move forward in *developing* a viable approach for mitigating the increasing losses to sandy beach ecosystems associated with the multitude of coastal armoring projects on open coast sandy shorelines, we considered several economic valuation methods and suggest that ecosystem replacement cost should be considered as part of any mitigation strategy. Using this framework, we propose a mitigation system for shoreline armoring projects that is: 1) intended to minimize long term loss of the resources and services of intact beach ecosystems, 2) based on simple metrics, 3) easy to interpret and apply, and 4) capable of being used in conjunction with a mitigation banking system.

ADDITIONAL KEYWORDS: Beach, ecosystem services, coastal armoring, replacement cost, offsets, mitigation, sea level rise, erosion, restoration, coastal processes, non-market valuation, ecological economics.

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Perched on the edge of land and sea, sandy beaches are widely recognized as important economic and recreational assets that provide billions of dollars in revenue and are economic drivers for coastal tourism and real estate values worldwide (e.g. see King 1999; King and Symes 2004). Beaches are beloved by residents and tourists for the many cultural, aesthetic, and leisure experiences they offer, but the ecological values of these unique coastal ecosystems have received far less recognition (Defeo *et al.* 2009).

Sandy beach ecosystems are highly dynamic, with the sand moving constantly as a result of tides, waves, storms, and other processes (McLachlan and Brown 2006). Sandy beaches come in all shapes and sizes, and all types naturally widen and narrow due to seasonal cycles of deposition and erosion and in response to storms, oceanographic conditions, and watershed processes. Natural geologic processes on sandy beaches can be accelerated or altered by human activities, such as coastal development and dam building. These characteristic dynamics and landscape scale impacts have important implications for the conservation and management of beaches as intact functional ecosystems.

Beaches provide an array of important ecological functions and services that are not provided by any other ecosystem (Schlacher *et al.* 2007). The unique biodiversity and ecological functions and resources supported by sandy beach ecosystems are often under-appreciated compared to their socioeconomic, recreational, and cultural values (Schlacher *et al.* 2007, 2014). However, the biodiversity and the intrinsic ecological roles and functions of sandy beach ecosystems are not provided by any other coastal ecosystem. These vital roles and functions include rich invertebrate communities and food webs that are prey for birds and fish; buffering and absorption of wave energy by stored sand; filtration of large volumes of seawater; detrital and wrack processing and nutrient recycling; and the provision of critical habitat and resources for declining and endangered wildlife, such as shorebirds and pinnipeds (McLachlan and Brown 2006; Hubbard and Dugan 2003; Schlacher *et al.* 2014, Harris *et al.* 2014).

Because of the visual appeal, many coastlines have been developed for residential or commercial purposes. To protect coastal development from waves and erosion, the shoreline is often armored with hard structures, such as seawalls and revetments (Gittman *et al.* 2015). For example, in southern California, about a third of the coastline has been armored (Griggs *et al.* 2005). However, seawalls, revetments, and other armoring structures have caused significant loss of beach ecosystems in the state. By fixing the shoreline, armoring traps beaches between land and sea creating a classic example of coastal squeeze. The rigid line in the sand created by armoring severely limits the ability of beach ecosystems to adjust to changing conditions, accumulate sand, provide recreation and support intertidal biodiversity and wildlife (Dugan *et al.* 2018, Melius and Caldwell 2015).

The disappearance of sandy beaches following placement of coastal armoring is a significant loss for both recreation and ecosystem function. Economists have developed a fairly wide array of techniques for valuing recreation on the coast. Since beaches in California are free by law, economists estimate the value of a beach visit as equivalent to the "willing-

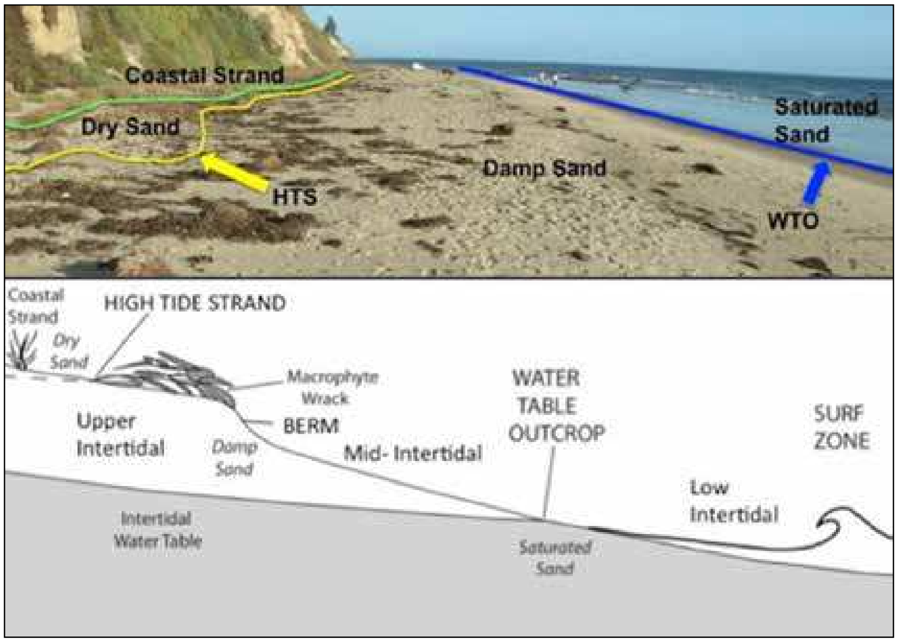

Figure 1. Illustration of the major beach zones and dynamic ecological features of sandy beaches on a bluff-backed beach (Arroyo Burro County Beach, Santa Barbara, California) Photo: Jenny Dugan). (HTS= High Tide Strand, WTO = Water Table Outcrop).

ness to pay" for the visit. However, many policy-makers have struggled with how to value the wide array of *other* ecosystem services and functions. To conserve fully functioning and self-sustaining beach ecosystems for the public good, adaptation strategies need to incorporate preservation of shores without armoring and the restoration of natural coastal processes. As in many other ecosystems, investigations of the full value of ecosystem services of intact dune-beach-surf zone systems and the development of protocols for robust measurement of indicators of those services are incomplete. As a consequence, mitigation for coastal armoring is likely to understate or underestimate the full ecological functions and services of beach ecosystems.

The value of intact functional ecosystems is much greater than the sum of the parts. For this reason, adaptation strategies should seek to conserve entire coastal ecosystems as much as possible. Projected losses of sandy beaches in California are substantial (Vitousek *et al.* 2017), creating an urgent need to develop ecologically sound and sustainable policies for mitigation and restoration to conserve sandy beaches as intact ecosystems. To make progress in mitigating the increasing losses to sandy beach ecosystems associated with coastal armoring projects we describe a case study for California that developed a metric for mitigation that provides for preservation and restoration of intact beach ecosystems as well as recreation. We propose a mitigation system for armoring projects intended to result in no net loss of beach ecosystem resources and services, based on simple metrics, easy to interpret and apply, and capable of being used in conjunction with a mitigation bank.

RATIONALE

Beach ecosystems and economics

California's beaches support some of the highest intertidal biodiversity, productivity, abundance and biomass ever reported for beach ecosystems globally (Dugan *et al.* 2003). This biodiversity includes numerous endemic species of plants and animals, species of special significance, marine mammals, migratory birds, and endangered species that depend on sandy beaches as critical habitat (Dugan *et al.* 2003; Hubbard and Dugan 2003; Schlacher *et al.* 2014; Martin 2015; Schooler *et al.* 2017; Dugan and Hubbard 2016), for reproduction, foraging, and resting. All of these biota and functions can be significantly impacted by shoreline armoring (Dugan *et al.* 2018). Despite the fact that the adverse effects of shoreline armoring on the beach animals, plants, food webs, and habitats have been reported for California beaches and elsewhere (e.g. Dugan *et al.* 2008; Jaramillo *et al.* 2012), these ecological impacts have never previously been monetarily valued.

Fundamentally, the ecological components (habitats, communities, individual species) and functions of sandy beach ecosystems are unique and irreplaceable (Schlacher *et al.* 2007; Dugan *et al.* 2010). These components are not found in or provided by any other coastal ecosystem. Characterized by unconsolidated sand, a lack of attached intertidal plant life, and highly mobile animals, sandy beaches represent an unusually dynamic coastal habitat. The distinctive mobility of the intertidal animals and of the sand itself mean that concepts of intertidal zonation commonly applied to other more stable shore types cannot be applied to sandy beaches (Dugan *et al.* 2013). On beaches intertidal animals have to move (swim, crawl, run, hop, or surf), then burrow rapidly, to adjust to ever-changing conditions of waves and tides and shifting beach profiles. The high mobility of beaches and their endemic intertidal animals creates challenges for rapidly characterizing the biota and habitat conditions. However, the different habitat zones of beaches are used by characteristic mobile biota, with numerous species adapted to this dynamic sandy environment, including mole crabs and clams in the wave wash, polychaetes and isopods in the mid-beach and direct-developing invertebrates on the upper dryer beach near the high tide line, with a zone of pioneering coastal strand vegetation above that (Figure 1). Many shorebirds forage along the high tide line, in stranded macrophyte wrack, and in the wave wash along with roosting on the upper beach. A variety of surf zone fish, (surfperches, corbina, sharks and rays) use sandy intertidal invertebrates as prey (Dugan and Hubbard 2016). Birds, such as the threatened Western Snowy Plover and endangered California Least Tern, nest and raise their chicks on open coast beaches. Beaches are also extensively used as haul out areas and rookeries by marine mammals, and beach-nesting fish, such as the California Grunion lay their eggs in nests in the warm damp sands of the upper beach (Martin 2015; Roberts *et al.* 2007; Johnson *et al.* 2009; Martin *et al.* 2013).

Here we outline an approach that could be used to address the mitigation of adverse ecological effects caused by shoreline armoring on sandy beach ecosystems using California as a case study (CCC 2015). As defined by the California Environmental Quality Act

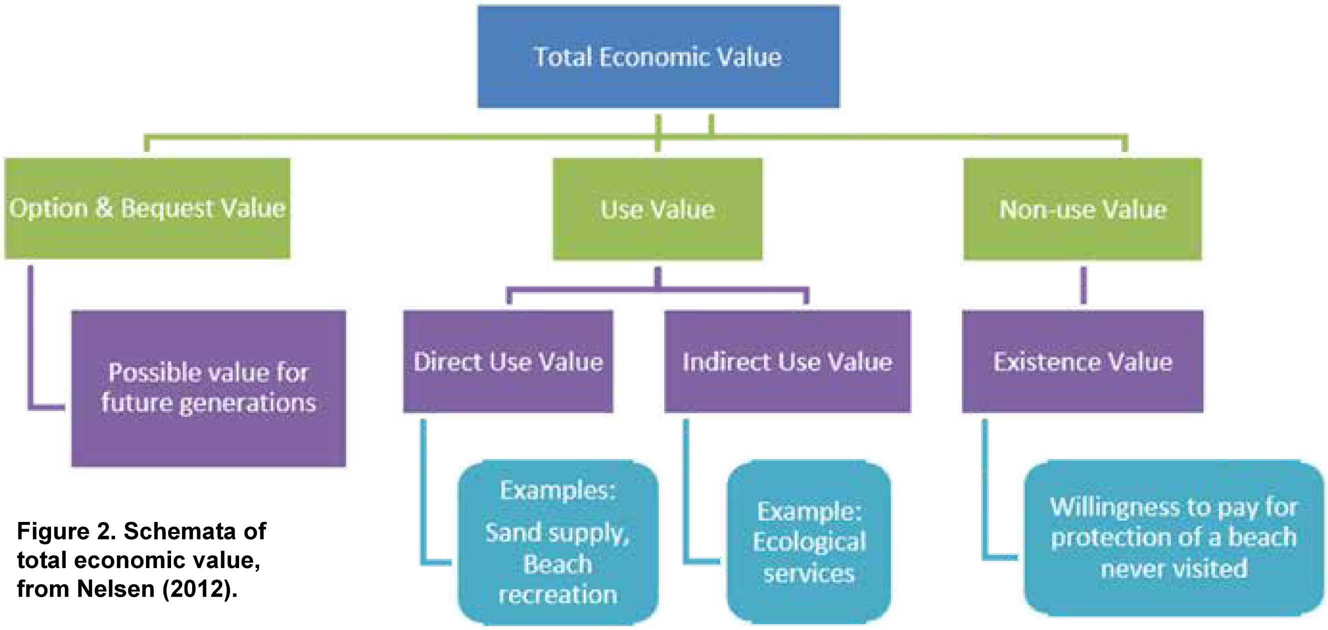

Figure 2. Schemata of total economic value, from Nelsen (2012).

(CEQA) guidelines Section 15370, "mitigation may take the following forms:

1) Avoid the impact altogether by not taking an action;

2) Minimize the impact by limiting the degree or magnitude of the action or its implementation;

3) Rectify the impact by repairing, rehabilitating, or restoring the impacted environment;

4) Reduce or eliminate the impact over time by preservation and maintenance operations during the life of the action;

5) Compensate for the impact by replacing or providing substitute resources or environments."

As a practical matter, even with efforts to minimize armoring and its ecological impacts, sea level rise and coastal erosion are likely to increase efforts to armor more of California's coastline, requiring mitigation step #5 above. Consequently, this paper focused on developing a rationale and a framework for use in the mitigation of impacts of shoreline armoring through the restoration of sandy beach ecosystems either at the project site or within the same littoral cell. The under-appreciation of beaches as ecosystems is also reflected in much of the economic research on beaches, which, not surprisingly, focuses on the recreational value of beaches. Figure 2 presents a standard diagram of the different economic benefits/values provided by natural ecosystems such as beaches. Beach recreation is only one type of ecosystem service provided by beaches, albeit an extremely important one for many beaches.

Economists have developed a number of widely-accepted standard techniques for valuing recreation at beaches and public places (e.g. see Haab and McConnell 2002; Parsons 2017). Recent advances in geospatial modeling and dataset availability now allow economists and others to estimate the storm damage prevention benefits of beaches with reasonable accuracy and reasonable cost (e.g. see The Nature Conservancy 2016).

Other ecosystem services

Defeo *et al.* (2009) list 14 different types of ecosystem functions, goods, and services (EFGS) generated by beaches (Table 1). However, most studies of the economic benefits of beaches only consider and estimate the first three out of these 14 benefits, and two of those (wave dissipation and response to sea level rise) are similar. De Groot *et al.* (2002) provide one of the most widely cited discussions of ecosystem valuation which encompasses many different types of habitat, including beaches. He specifically discusses potential economic methods for valuing ecosystems and endorses the standard metrics for recreation, as well as valuing some flows (e.g. waste treatment) by comparing these services to the cost of providing them by other means (e.g. sewage treatment plants). However, in order for this method to work, ecologists must be able to confidently measure these benefits. Moreover, even if this approach is technically feasible it may not be cost-effective since the biological, ecological and economic studies necessary to conduct such an analysis are likely to be expensive, particularly for smaller site studies, such as for a seawall application.

In addition, De Groot *et al.* (2002) list a number of ecological services that cannot be valued by standard methods or by pricing equivalent services, specifically the following as suitable for a replacement cost method: disturbance regulation, water supply, soil retention and formation, nutrient cycling, waste treatment, pollination, and biological control. Many of these categories closely match the ecological services listed in Table 1. For maintenance of biodiversity and genetic resources, and refugia and sanctuary functions, De Groot *et al.* (2002) recommend direct market prices. That approach assumes that economists can measure the value of genetic and biological diversity; however, this facet of ecological economics is still young with few, if any established methods and protocols. Although this approach might be appropriate for commercial fishing, it is not easy to apply to beaches. It is difficult to identify the precise contribution beaches make to fish habitat, in order to estimate the contribution to fisheries production.

Estimating the market value of the loss of a particular species or habitat is difficult for a variety of reasons. First, there typically is no market value for many

Table 1.
Sandy beach ecosystems services by use value type, from (Defeo *et al.* 2009).

Sandy beach ecosystem services	Direct use value	Indirect use value
Sediment storage and transport;	X	
Wave dissipation and associated buffering against extreme events (storms, tsunamis);		X
Dynamic response to sea level rise (within limits);		X
Breakdown of organic materials and pollutants;		X
Water filtration and purification;		X
Nutrient mineralization and recycling;		X
Water storage in dune aquifers and seawater discharge through beaches — beaches with dunes only		X
Maintenance of biodiversity and genetic resources;	X	
Nursery areas for juvenile fishes;	X	
Nesting sites for turtles and shorebirds, and rookeries for pinnipeds;	X	
Prey resources for birds, fishes, and terrestrial wildlife;	X	
Scenic vistas and recreational opportunities;	X	
Bait and food organisms;	X	
Functional links between terrestrial and marine environments in the coastal zone.	X	

common and important beach species (e.g. shorebirds, sand crabs, etc.). Second, the relationship between the quality and size of beach habitat and the abundance of these species is highly variable due to ecosystem dynamism. Quantification would require quite extensive and expensive biological/ecological study. Consequently, many of the ecological services provided by beaches are not valued and in practice, economic analyses of beaches often focus exclusively on recreation or storm damage prevention.

When weighing options for adaptation to sea level rise, however, these seldom valued considerations may be important. In these analyses, beaches are typically compared to seawalls or other coastal armoring structures. The benefits of a beach are often measured in terms of gains in beach recreation with beach filling with imported sand, whereas the loss is measured as loss of beach recreation if and when the beach erodes to the point where recreation is diminished. However, seawalls and other coastal armoring structures significantly diminish the habitat quality, biodiversity and ecological functioning of beaches in many important ways, and economists have not previously developed a robust and applicable method to estimate the losses in ecological functions involved.

Barbier *et al.* (2011) also examined a variety of ecosystem services for estuarine and coastal habitats, including beaches. They point out that our current knowledge of ecosystem services is quite limited. They also indicate that although many studies value small changes in specific components of ecosystems, one cannot necessarily extrapolate from those changes to a larger scale.

Defining EFGS in spatial terms

Another potential way to value ecosystem functions and services from beaches and other habitat is to assign values by area or other geospatial metrics as per Costanza *et al.* (2006). Using an analysis of 94 peer-reviewed papers and six other studies to estimate the economic values of seven types of biomes including beaches and the cumulative ecosystem services in New Jersey, he estimated that New Jersey's beaches deliver $42,147 per acre per year in economic/ecological services. However, it should be emphasized that, once again, Costanza's estimates only consider two ecological goods: beach recreation and storm-damage prevention. While these types of studies can be useful in the aggregate, these metrics do not necessarily provide managers with a framework for use in preserving key habitats, biodiversity or ecological functions of a specific beach or ecosystem. Also, as discussed below, the use of area is also an imperfect metric to estimate the functioning of a beach ecosystem.

Offsets

Offsets are commonly used to mitigate for the loss of ecosystem services provided by wetlands and other ecosystems (Table 2). Briefly, offsets create or restore a similar type of ecosystem to compensate for the loss of habitat. For example, if an area of wetlands is lost due to human development, often the proposed mitigation involves creating a new wetland or restoring or improving another existing wetland. Often, these offsets include ratios to determine a ratio of equivalency. For example, if one were devising an offset for the loss of a highly functioning 10-acre wetland, the offset would likely require a much larger newly created wetland. For wetland restoration, it is common to use a 3:1 or 4:1 ratio of equivalency, at least in part because a newly formed wetland often has lower ecological function than a well-established wetland. The process involved in determining offsets is presented schematically in Figure 3.

Quetier and Lavorel (2011) provide a comprehensive overview of the use of offsets when mitigating for projects that impair ecosystem function and discuss specific mechanisms used to evaluate an ecosystem and ecosystem service losses. For example, species richness or some other measure of biodiversity is often used for offsets but this often does not capture the complexities of biodiversity and community composition. Table 3 provides an analysis of a number of specific offset systems used by government agencies from many different countries and jurisdictions. Although the techniques vary, some general trends can be identified. First, most of these mechanisms require that an ecosystem be replaced by a (roughly) similar ecosystem, e.g. wetlands should be replaced by other wetlands. In addition, some of these mechanisms require explicit outcomes, in terms of predefined criteria, specific benchmarks, and allowances for time.

In the U.S., Habitat Equivalency Analysis (HEA) provides a methodology designed to estimate offsets to ecosystem damages from human activity. HEA has been applied to damages to beach ecosystems from oil spills and, in principle, could be applied to mitigation for shoreline armoring. However, HEA, as currently applied has a few shortcomings. First, it is often quite expensive since HEA is typically applied in cases that are litigated heavily. Second, in some cases, HEA allows damages to be remediated with different in-kind (out of kind?) services if beach restoration is deemed not feasible. For example, mitigation

Table 2.
Offset mechanism for ecosystems currently in place.

	A: Target components of biodiversity		B: Indicators				C: Temporal dynamics		D: Uncertainties
	Measure of losses and gains	Out-of-kind offsets possible?	Predefined	One or several	Bench-marks	Landscape component	Baseline	Delays	
Wetland mitigation methods (USA)	Wetlands (area x score)	N	Y	Several	Y	Y	Current	N	N
UMAM (USA)	Wetlands (area x score)	N	Y	Several	Y	Y	Current	Y	Y
HEA/REA (USA)	DSAYs	Y	N	Single	Y	N	Projected	Y	N
Conservation/ bio-banking (USA & Australia)	Protected species (credits)	N	N	Single	Y/N	Y/N	Current	N	N
Habitat Hectares (Australia)	Native vegetation (area x score)	N	Y	Several	Y	Y	Current	N	N
Ausgleich (Germany)	Protected species and habitats (area x habitat type)	N	N	Several	N	Y/N	Current	Y	Y
Biotopwertverfahren (Germany)	Undeveloped land (area x score)	Y	Y	Single	Y	N	Current	N	N
Natura 2000 (EU)	Integrity of the Natura 2000 network	N	N	Several	N	Y	Current	N	N
Offset ratios (France)	Protected species and habitats (area x habitat type)	N	Y	Single	N	N	Current	N	N

for a loss in beach ecology may be replaced by an increase in coastal zone camping availability or playgrounds. This provision brings one right back to the problem that ecological components of sandy beach ecosystems are not valued in and of themselves.

In addition, the use of HEA or other offset mechanisms for beach ecosystem services is often limited by a lack of baseline information. Sandy beach ecosystem functions, goods and services do not usually meet all of the four basic requirements to conduct HEA: 1) that the primary services are not necessarily biological; 2) that one can quantify in some way the lost EFGS; 3) one can estimate the recovery rate (e.g. post sand replenishment); and 4) a suitable site for restoration exists.

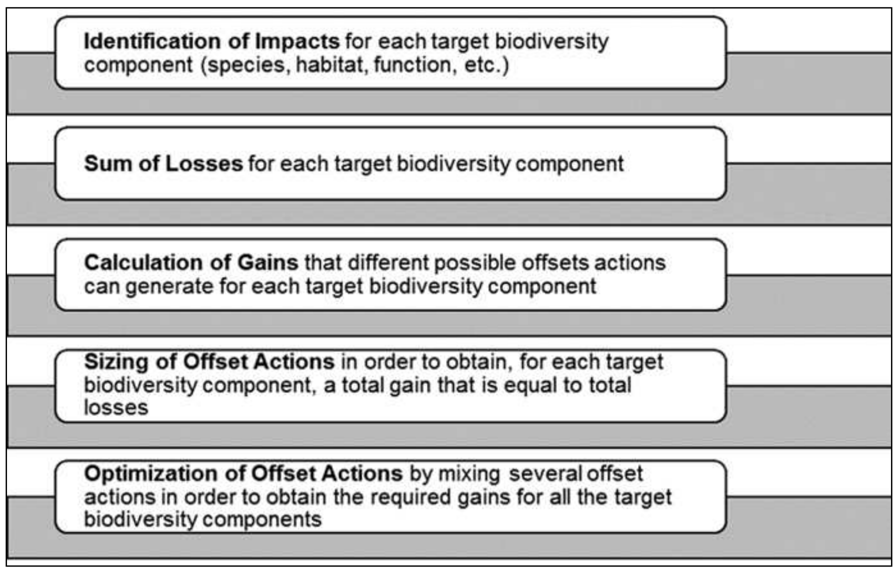

Figure 3. Methodology for creating offsets (Quetier and Lavorel 2011) provides a schematic depicting the process involved in determining offsets currently in use for other environmental mitigation.

The impacts to sandy beaches can be broken down into several components: (a) the area lost by the armoring structure (often referred to as "placement loss"); (b) the consequent narrowing of the beach in front of the armoring structures; and (c) the reduction in sand supply from the armored backshore. If beach nourishment, or the addition of groins or other ancillary structures is involved, then the losses to be mitigated should include both short-term habitat loss (e.g. from burial) as well as any long-term habitat alteration (Peterson and Bishop 2005; Peterson *et al.* 2006, 2014) and any other negative effects from common beach maintenance activities (Dugan *et al.* 2003; Martin *et al.* 2006; Schooler *et al.* 2017).

The inherent high variability of many beach ecosystem features and current lack of robust estimates of the ecological services of the majority of beaches precludes selecting or quantifying a single measure of ecological services lost provided or recovery rates from impacts with any confidence. Suitable sites for restoration of beach ecosystem services could include the beach that is being adversely affected, or nearby beaches, ideally located in the same littoral cell.

The offset approach and recreational value

Any offset approach must also account for the recreational value of beaches. For example, the California Coastal Com-

Table 3.
Summary of the strengths and weaknesses of various offset approaches in current use (Quetier and Lavorel 2011).

Approach	Opportunities	Constraints	Possible uses
Circumstantial reasoning	Specificity to the local ecological context (problem-solving approach)	Harder to process for environmental authorities	Impacts on nature conservation priorities such as rare or endangered species, priority habitat types, etc.
• Freedom to develop or use appropriate indicators and scoring methods	Heterogeneous data sources can be used	Less transparent and harder to communicate to stakeholders	Particular natural or use contexts where standardized methods are not applicable
• The complete reasoning must be presented and justified (e.g. references and benchmarks, model parameters, field data)	Local expertise can compensate for a lack of quantitative or measurable data	Requires methodological developments with corresponding time and budget, as well as additional data	Early stages in the development of standardized methods
	Makes innovative actions easier	Not easily comparable between projects	Examples include German Ausgleich and Natura 2000 procedures in Europe or Habitat banking in the USA
		Not transferable between projects (hence no accumulation of know-how) and thus less predictability of offset requirements for developers	
Standardized scoring method	Ease of use and transparency	Requires consensual references and guidelines that are common across projects (for a given target component of biodiversity)	Habitat types, species' habitats and ecosystem properties or functions for which suffer from recurring impacts (e.g. wetlands) and for which a scoring system has been agreed upon by environmental authorities
• Indicators and scoring methods are predefined, for impacts on a given target species, habitat type, ecosystem function, etc.	Comparability between projects, which makes cumulative effects easier to assess	Limited choice of indicators (off-the-shelf) that may or may not be appropriate to the local ecological context of a project impact	When applied to broadly defined target component of biodiversity (e.g. grasslands), the approach can be considered as allowing like-for-similar offsetting (see third approach below)
• Validity and reproducibility of indicators and scoring methods must be tested	Lower legal risks	Options for modulating offset size according to local context must be anticipated and justified	Examples include several wetland mitigation scoring methods in the USA or the habitat-hectares approach developed in Australia
• It remains essential that offset size can be modulated according to local context (uncertainties, cumulative impacts, etc.) cumulative impacts, etc.)	Depending on the selection of indicators and scoring methods, offset requirements can be easier to predict in early project phases		
• Standardized scoring method and like-for-similar correspondence	Same advantages as the standardized point-based systems above, with also:	Requires an accepted correspondence scale between target species, habitat types, ecosystem functions, etc., and hence an established hierarchy of nature conservation priorities that does not vary between projects	Species, habitat types or ecosystem functions that have low priority status but for which offsets are nevertheless required
• Indicators and scoring methods are predefined, for impacts on a given target species, habitat type, ecosystem function, etc.	Allows like-for-similar offsetting and trading-up, which gives authorities and developers more flexibility in designing offsets	The local ecological context might only be taken into account superficially	Species or habitat types for which trading-up is an appropriate source of conservation action (in addition to other means already targeting these species or habitat types)
• Scores for different targets are made comparable using a common correspondence scale			Examples include the German Biotopwertverfahren
• It remains essential that offset size can be modulated according to local context (uncertainties, cumulative impacts etc.)			

mission recognizes that loss of recreational value due to armoring must be mitigated.[1] One possible criticism of the approach suggested in this paper is that if recreation, or any other impact (e.g., sand supply) is mitigated in addition to replacement cost, then policy makers are overstating the actual loss. This over-estimation is often referred to as double-counting. Fu *et. al.* (2010) address this issue specifically and make a number of suggestions to minimize the issue of double counting. In particular, they call for establishing consistent classification systems for ecological functions, goods, and services. One possible approach to the issue of double counting is to assign a fixed percentage (0%-100%) of the EFGS, and apply this same percentage to the restoration costs, The Nature Conservancy (2016) employed this approach in assessing the ecological value of beaches in southern Monterey Bay.[2] If a specific project is proposed as mitigation, policy makers could also use potential recreational offsets as well in the project. However, we believe that any policy regime mitigating for coastal armoring should consider recreation and the other EFGS separately.

APPROACH

Ecological valuation method

In this section, we articulate a conceptual rationale for and initiate the development of an ecological valuation method by applying a case study of recent restoration projects in California beaches. The goal is to develop a method to estimate the value of the ecological components and functions of a beach ecosystem that are impacted or lost due to specific changes to the beach and coastal processes resulting from the installation of shoreline armoring. Our analysis was an interdisciplinary effort between ecologists and economists, assisted by engineers experienced in coastal processes and projects, and represents the first steps in establishing a conceptual framework that will allow valuation of the ecological losses to beaches resulting from coastal armoring. This framework is intended to provide a starting place for improving ecological valuation of beaches.

Table 4.
Predicted ecological effects of shore-parallel armoring on sandy beaches

As beach width narrows in response to armoring structures:

- Upper intertidal, supralittoral and coastal strand zones are lost disproportionately.
- Loss of sand-trapping coastal strand vegetation zone inhibits sand accumulation and retention, reducing the formation of hummocks and dunes that can provide protection during storms and high surf.
- Loss of drier upper beach zones decreases number of habitat types available and buffer space for migration of intertidal habitats/zones and biota with changing ocean conditions.
- Reduction in habitat types reduces diversity and abundance of endemic biota.
- Loss of upper beach habitat eliminates nesting and resting habitat for sea turtles, fishes, birds, marine mammals.
- The absence of high tide refugia alters low tide distribution of even highly mobile low intertidal zone biota, such as sand crabs.
- Lack of dry sand habitat and increased wave reflection associated with structures alters deposition and retention of sand and buoyant materials, such as macrophyte wrack, further affecting beach widths and profiles and upper shore biota and processes.
- Intertidal predators, such as shorebirds, decline in response to a combination of habitat loss, decreased accessibility at higher tides, and reduced prey resources.

Valuation methods traditionally provide results expressed in quantifiable units, such as currency (e.g. USD), area (e.g. acres), or in biological contexts such as loss of a number or biomass of specific guilds, groups, or individual species. For beaches, these units could include direct losses of beach habitat on an armored beach. These losses may include immediate loss of beach under the armoring structure (placement loss), subsequent loss of beach habitats and degraded habitat quality due to erosion caused by fixing the position of the shoreline, reduced deposition of new sand via littoral transport caused by loss of space for that sand deposition to occur, prevention of sand inputs supplied by bluff erosion, and the progressive loss of beach area, habitat quality and accommodation space from sea level rise against a fixed back beach.

Ecological valuation

Given ongoing and projected losses of beaches in California (Vitousek *et al.* 2017), the need to develop ecologically sound and sustainable mitigation and restoration projects to conserve sandy beaches as intact ecosystems is urgent. In the past, sand placement and beach filling projects have often been called "beach restoration projects." However, the goals and implementation of these projects have not followed any of the biological, ecological guidance or goals that are required standards in restoration projects for other coastal ecosystems, such as seagrass beds or wetlands (Lawrenz-Miller 1991; Peterson and Bishop 2005; Peterson *et al.* 2006; Viola *et al.* 2014). Beach filling projects are expensive and have also proven to be short-lived in many sections of the California coast (Griggs *et al.* 2005). Sand supplies are rapidly becoming a limiting factor for these projects (Pilkey and Cooper 2014). To address these issues we propose the development of a more ecologically sensitive and sustainable approach to the restoration and mitigation of losses of sandy beach ecosystems resulting from coastal armoring.

As with all other types of coastal wetlands, the goal for beach ecosystems needs to be no net loss of habitat. To date, there has been substantial loss and fragmentation of the finite and decreasing California beach and dune ecosystems as a result of coastal development and other human impacts (Dugan *et al.* 2003; Dugan and Hubbard 2010a; Griggs *et al.* 2005; Orme *et al.* 2011; Pilkey and Cooper 2014). This has adversely impacted the ecological functioning of beaches and the viability of populations of vulnerable beach-dependent organisms particularly as these impacts accumulate over time in beach ecosystems (e.g. Page *et al.* 2009, Hubbard *et al.* 2014). Impacts include loss of biodiversity, loss of spawning habitat, and local extirpation of species.

1) For example, see California Coastal Commission, City of Solana Beach Major Amendment LCP-6-SOL-16-0020-1 (11 May 2017)

2) This study assumed that 20% of the EFGS would be applied to EFGS other than recreation and storm damage prevention, which were already accounted for elsewhere in the study.

Although zone widths and positions shown in Figure 1 can change rapidly, ecological zones are useful in deciphering the impacts of coastal armoring on sandy beaches (Table 4) and can serve as better proxies for habitat loss than beach width alone (Dugan and Hubbard 2006). Upon construction, the footprint of a coastal armoring structure covers and directly occupies beach habitat resulting in immediate "placement loss." Armoring structures tend to increase the amount of erosion and the intensity of wave reflection, thus the dry upper areas of a beach decrease in width and ultimately disappear under waves (Fletcher *et al.* 1997; Griggs *et al.* 2005). As placement loss and passive erosion cause declines in overall beach widths in front of armoring structures, upper shore zones lose beach habitat disproportionately. This means habitat losses due to armoring are greatest and manifest first in the landward-most beach zones. Organisms living in the upper beach zones and habitats are most strongly impacted by the effects of shoreline armoring, but effects extend to wildlife and lower intertidal zones (Table 4) (Feagin *et al.* 2005; Dugan *et al.* 2008; Dugan and Hubbard 2006, 2010b; Jaramillo *et al.* 2012). Upper shore zones support >40% of the intertidal biodiversity (Dugan *et al.* 2003) and represent critical habitat for foraging and nesting birds, pupping and early life stages of marine mammals, and beach-spawning fishes, such as California Grunion (Dugan and Hubbard 2016; Martin 2015). The upper zones also are the habitat required by numerous endemic species of plants, invertebrates, and reptiles (Dugan and Hubbard 2016). Upper beach zones have already been severely degraded as habitats and reduced in size in many areas of the California coast due to human activities (Dugan and Hubbard 2010a, 2016). Additional loss of this key habitat zone caused by coastal armoring will further fragment this fragile habitat and threaten its biodiversity and populations of endemic organisms (Hubbard *et al.* 2014).

Importantly, the mobile animals that live on sandy beaches can require large swaths of suitable habitat to adjust to changing beach conditions on a daily and seasonal basis. Each species may need a much larger potential habitat than is temporarily in use at any given moment (Dugan *et al.* 2013). This is a key adaptation to the natural variability of beaches in size e.g. width, depth and zone distributions, changing hourly with wave and tidal exposure, and seasonally and on longer scales (Bird 1996; Hubbard and Dugan 2003; Yates *et al.* 2009). The scope of changing beach area or width for cross-shore adjustments, or "ecological envelope" that allows animals such as invertebrates, fishes, marine mammals, and birds to adapt to changing beach conditions is integral to their survival. Fixing the shoreline with armoring reduces the scope for these "ecological envelopes" resulting in ecological impacts (see Figure 4, Dugan *et al.* 2013). For these reasons, the addition of buffers, such as those used to extend the protection of other sensitive habitats like wetlands, are recommended for beach ecosystems.

Ecological costs

As the climate shifts, organisms currently living on sandy beaches along the coast will need to adjust to rising sea levels as well as temperatures (Schoeman et al. 2014). These adjustments can include moving landward as beaches retreat upland, and moving poleward along the coast to follow suitable temperatures. Intertidal species that live in the narrow interface between ocean and land are predicted to be more strongly and rapidly impacted by climate change than fully marine or fully terrestrial organisms (Harley *et al.* 2006). In places where beaches have room to retreat, intertidal and upper shore organisms can follow the beach and suitable habitats landward. However much of the California coastline is rocky, and many sandy areas have limited scope for retreat, including shorelines that have been armored and those that are backed by resistant natural bluffs or cliffs (Vitousek *et al.* 2017).

As discussed above, the ecological components and functions of sandy beaches are highly dynamic. For this reason, quantitatively evaluating the sandy beach ecosystem, by identifying and cataloging all components on a given beach in detail is an expensive and time-consuming effort that is difficult to evaluate with sufficient confidence due to high variability in the biota and the form of sandy beaches (Barbier *et al.* 2011; Borja *et al.* 2014; Schlacher *et al.* 2008, 2014). All the key components of sandy beach ecosystems are capable of changing dramatically in the short term in response to wave climate, beach conditions, population dynamics, and season (Dugan *et al.* 2013; Hubbard and Dugan 2003; Revell *et al.* 2011). In addition, climate change may accelerate erosion and alter the scope of physical and biological dynamics of sandy beaches (Zhang *et al.* 2004; Griggs *et al.* 2005; Flick and Ewing 2009; Schoeman *et al.* 2014). Quantifying and valuing all the elements of fully functional beach ecosystems with confidence at the scale of individual projects would require prohibitively expensive and time-consuming data collection and analyses beyond the scope of most property owners and coastal residents (Barbier *et al.* 2011; Borja *et al.* 2014; Schlacher *et al.* 2014).

For these reasons, in cases where a natural retreat process is not feasible or where the Coastal Act allows the property owner to armor their property (subject to mitigation), we recommend using the cost of restoring a sandy beach ecosystem, either on-site or nearby, as a simple and more robust valuation approach for mitigating the ecological impacts of coastal armoring. This alternative avoids expensive and complicated quantitative assessments of the ecological components and functions that may be altered or lost on a given stretch of sandy beach due to shoreline armoring. This valuation approach would allow greater consistency and accuracy than can be achieved with attempts to confidently identify, replicate, and monitor the lost ecological components of a specific stretch of sandy beach. The latter is particularly problematic for a beach that may have been altered years earlier and impacted over a long period of time (Orme *et al.* 2011). Such a site may retain little of its original character, yet it still represents a coastal ecosystem lost to nature, but one that may have the potential for rehabilitation (Dugan and Hubbard 2010a, Dugan *et al.* 2010, 2012, Schooler *et al.* 2017).

THE PROPOSED VALUATION METHOD EXPLAINED

The purpose of ecological valuation is to address impacts of human activities on natural ecosystems, in this case of shoreline armoring on sandy beaches. A substantial proportion of the California coastline, especially the populous southern region, has been armored at this time; therefore, areas available for restoration though possible managed retreat projects already are limited in some regions. With improved and more comprehensive valuation methods the immediate, future, and cumulative impacts of shoreline armoring may be reduced and better mitigated for the California coastline.

No net loss

An approach that embraces "no net loss" of beach habitats or beach zones as a result of future development will be critically important to the ability to maintain, and in some areas to restore healthy resilient beach ecosystems along the coast. In California current valuation methods employed by the California Coastal Commission evaluate loss of sand, erosion impacts, loss of beach area, and loss of recreation. These metrics do not adequately address the loss of ecological value or functioning. For this purpose, **we strongly suggest treating sandy beaches as tidal wetlands, and applying the concept of "no net loss" to their preservation and restoration.** With this approach, we propose that mitigation for armoring projects could be achieved by ecological restoration projects of suitable scope on beaches, either in the project area or on a nearby coastline, ideally in the same littoral cell and sand-shed. These ecological restoration projects could include the removal of existing or derelict armoring or infrastructure and other forms of managed retreat, as well as removing barriers to littoral sediment transport.

Our proposed approach fits into the third type of California's CEQA mitigation as discussed earlier (repairing, rehabilitating, or restoring the impacted environment) as well as the fifth type (replacing or providing substitute resources or environments). This approach optimistically assumes that well-designed restoration projects, with attention to local and regional physical and biological processes, biodiversity and metapopulations, seeding, management and monitoring, can potentially provide reasonable habitat equivalency with natural sandy beaches in the same area and littoral cell and be sustainable and self-repairing. Sand replenishment or beach filling projects are not included on this list due to the high ecological impacts of this practice (Manning *et al.* 2013, 2014; Peterson *et al.* 2000, 2006, 2014; Viola *et al.* 2014) and the typically short lifespan of these projects (e.g. Leonard *et al.* 1990).

Quantifying ecological damages

The loss of beach area is often used for the calculation of sand mitigation and recreation mitigation, and it could also potentially be used as a component of the calculations of ecological loss valuation. However, there are concerns with using this approach for ecological valuation. The estimations of area lost must consider placement loss due to the area of the structure, the effects of the structure on dynamic coastal processes, including the loss of the ability of the shoreline to retreat by fixing the back of the beach, and the loss of sand storage and beach habitat zones to erosion during the lifetime of the permit. The increased erosion of the beach and the loss of ability to store sand that can be caused by an armoring structure are not necessarily accounted for in the average erosion rates currently used by the California Coastal Commission. The loss of ecological zones over time, in particular the disproportionate loss of vegetated and upper beach zones and biodiversity relative to lower beach zones needs to be addressed in loss calculations. Loss of area currently or potentially used for feeding, roosting, or reproduction of wildlife, particularly species of special concern, must also be recognized in mitigation efforts (Schlacher et al. 2014).

Importantly, the highly dynamic nature of the beach and biota are problematic for an approach that relies on simple estimates of beach area and/or the use of a variety of biotic measures to calculate value. If only a few metrics and estimates of erosion rates and beach ecology are available for use in valuation, then it is critical to capture the coastal processes and especially the potential for shoreline retreat in the 20-year lifespan of a project. Making accurate quantitative predictions of erosion and habitat loss rates for beach ecosystems in front of newly installed armoring structures is fraught with challenges. Quantifying every crab, clam, worm, fish, or bird of a dynamic beach ecosystem with sufficient confidence is not only time-consuming and prohibitively expensive, it often requires destructive sampling of the biota. The dynamics of the beach and its mobile biota mean that on any given day measurements – be it zone width, numbers of sand crabs or numbers of shorebirds, or rates of water filtration – will most certainly be different the next time they are measured. Width and sediment characteristics of beaches vary with lunar tidal cycles, seasons, swell events, interannual cycles, and with oceanographic conditions such as ENSO and PDO phases (Dugan *et al.* 2013; Revell *et al.* 2011; Barnard *et al.* 2017). Erosion and accretion rates fluctuate with precipitation, wildfires, wave energy, climate cycles, and other factors. With every shift of the tide and swell, the mobile and often cryptic animals of beaches shift in location and their estimated densities per unit area of habitat will change dramatically (Dugan *et al.* 2013). For these reasons, the use of projections from long-term average rates of erosion or shoreline retreat may not be very applicable or constructive for determining the actual ecological conditions or components on any given beach. We suggest that determining the specific ecological conditions and services of a beach will not be sufficiently accurate or precise for valuation purposes without considerable study and effort.

These concepts provide the rationale for the restoration approach to valuation of the ecological functions, goods, and services of sandy beaches we propose here. Using the costs to restore beaches as functional ecosystems as the basis for mitigating the loss of ecological value of beach ecosystems caused by armoring provides a viable approach to ecological valuation that can be applied to the dynamic coastal ecosystem represented by sandy beaches.

It is crucial to **understand that pouring concrete or placing rocks on the beach habitat fixes a line on the shore and eliminates the potential for future adaptation or even recovery from low sand levels. The real impacts to the coast accumulate over time as any armoring structure interacts with coastal processes**. These impacts are not adequately captured in per square foot metrics. The difficulty of forecasting erosion rates for different ecological zones and high variability in beach width due to seasonality and other factors (Dugan *et al.* 2013; Revell *et al.* 2011), makes using beach area to estimate loss of ecological functioning problematic. We propose that a more appropriate, sustainable, and robust way to mitigate for beach ecosystem losses from an armoring project would be to "free" another stretch of beach from armoring so it is able to interact freely with coastal processes and evolve naturally over time. For these reasons we suggest that shoreline length may be the most reliable and defensible way to quantify overall beach ecosystem loss over the life of an armoring structure. We emphasize that "length of restored beach" is in terms of beach with ecological functions, which requires consideration of other parameters such as width and sediment, as well as allowing for future sea level rise.

Although the loss of beach habitat area over time can be challenging to estimate for use in mitigation, the immediate loss of habitat area due to placement loss from the structure is an additional component that should be added to the shoreline length calculation. The area of beach directly covered by the installation of a shore-parallel armoring structure, such as a seawall or a revetment, or placement loss, is a straightforward calculation that is likely to be part of the engineering study for any new armoring structure application. This initial impact of the footprint of the structure is strongly influenced by the structure type. As an example, a revetment built to currently accepted design standards will need to have a width to height ratio of at least 1.5:1 or 2.1:1 to be able to maintain structural integrity during strong storms (Griggs and Fulton-Bennett 1988). Thus, a revetment that is 15 feet high will immediately cover about 30 feet of cross shore beach habitat. A seawall at the same location would cover much less cross shore habitat, ~6 feet.

The placement loss caused by a new structure has an immediate impact on habitat and disproportionately affects the upper shore habitats with negative impacts on overall biodiversity, birds, fish, and ecosystem function. The estimated placement loss of these two types of armoring structures for a 50-foot stretch of coastline would yield a footprint of 300 ft^2 for the seawall vs. 1,500 ft^2 for the revetment, a fivefold difference in the immediate loss of beach habitat. Over time, both types of structures would cause more significant beach habitat losses by fixing the shoreline and generating erosion.

In summary, since any coastal armoring structure prevents natural retreat of the shoreline and limits a beach's ecological functioning and dynamics over the lifetime of the structure, we suggest that using an approach based on the linear feet of armoring to be installed represents a simple and robust approach to forecasting beach loss over time and valuation. Placement loss from the installation of new armoring structures can be significant and should also be accounted for in the valuation process. Further, any attempt to measure habitat loss by area of beach lost is likely to involve legal and other disputes about the actual width of the beach, since, as discussed previously, beach width varies significantly and thus it is difficult to establish a true beach width. In addition, requests to armor a length of coastline are most common on *already eroded* shorelines, which would have little value if measured using an ecological metric based on area.

Mitigation ratios

Resource and regulatory agencies usually require the restoration of additional habitat acreage beyond that lost directly through development. This is because of interim losses in habitat acreage and functional capacity, and the uncertainty of the success and resulting value of compensatory mitigation projects. The ratio of habitat created or restored, to the habitat lost to development, is termed the mitigation ratio. We proposed that beaches be treated similarly to the way that many policies and jurisdictions treat wetlands (CCC 2015). In the U.S. and many other countries, the loss of wetlands is often mitigated by using offset ratios—for every loss of existing wetland habitat displaced by a project, (e.g. 1 acre) one must mitigate by creating new wetlands using an offset ratio determined by a number of economic, political and ecological considerations. Offset ratios of 3:1 or 4:1 are not uncommon for wetlands given that restored wetlands often have lower ecological functioning than the original ecosystems. The exact mitigation ratio applied has political as well as an economic and ecological aspects, but the basic principle of most offsets is that newly restored habitat provides lower EFGS than older established ecosystem, and thus an offset ratio greater than 1:1 is necessary.

Restoration costs

The approach we have developed here involves using replacement cost as a significant factor in estimating the values of ecological functions, goods and services (EFGS) provided by sandy beach ecosystems. To illustrate this approach, we provide examples of replacement costs for California beach ecosystems using estimates from recent beach restoration projects in California in Table 5 (Battalio 2015, updated for this paper; see also The Nature Conservancy 2016). All of these projects involved restoration of ecological health and functioning as well as improving the recreational qualities of the beaches. The dollar estimates in Table 5 are from the time of the construction bid/estimate and have not been adjusted to 2018 dollar values. Like wetland mitigation and river flood plain restoration, these projects required removal of built assets and construction of replacements farther landward. Hence, these projects represent a "managed retreat" strategy to adapt to erosion and future sea level rise. Retreat distances ranged from 50 feet to 150 feet. These projects also provide recreation, hazard reduction, and other benefits including outputs from elements located landward of the restored beaches. Consequently, if one applies an offset approach, care must be taken to avoid counting some benefits, such as recreation, twice.

The costs of these restoration projects are quite high ranging from $2,000 to $50,000 per linear foot or $1 million to $200 million per acre. The cost of the shoreline restoration projects in our case study vary by project and include many facets, e.g. private property acquisition (Ocean Beach Master Plan, Pacifica State Beach), removal of existing infrastructure (every project cited in our case study), and dune restoration (Pacifica State Beach, Surfer's Point). The acquisition of coastal property in California is quite high and how to incorporate these costs is controversial. In cases of retreat, it may make sense to value the land being lost as a "taking" in many legal settings. However coastal armoring is typically proposed to avoid losing inland property at the expense of coastal EFGS. Consequently, in our restoration cost approach, the relevant land acquisition costs are the costs of land acquisition in the restoration projects proposed as mitigation. In the cases cited, the land used was a mix of publicly and privately owned land. The costs presented only include the costs of acquiring private property for the project. A policy-maker may also want to value the potential loss in public land for other uses. These costs also do not include any future costs of maintenance/

Table 5.
Recent backshore beach and dune restoration costs in California.

Project name	Year constructed/ estimated	Cost (millions)	$/linear foot	$M/acre	Beach dimensions (approximate) Length (ft)	Width (ft)	Area (acres)	Retreat (ft)
Pacifica State Beach, Pacifica[1]	2004-2005	$4.0	$2,000	$1.0	2,000	85	4	50
Surfers Point, Ventura[2]	2010-2013	$3.1	$2,800	$1.4	1,100	85	2.2	80
South Ocean Beach, San Francisco[3]	2015	$200	$50,000	$22	4,000	100	9.2	150
	2015(B)	$80	$20,000	$8.7				
Goleta Beach, Santa Barbara County[4]								
Goleta 2.0	2011	$3.5	$5,000	$3.5	700	65	1	80
First cost: Goleta 1.5	2007	$4.7	$2,500	$1.7	1,900	65	2.8	
20-year cost: Goleta 1.5	2007	$8.4	$4,400	$3.0	1,900	65	2.8	

1) Constructed back beach and dune restoration, landward relocation of public assets, demolition of private development.
2) Constructed back beach restoration and landward relocation of public development.
3) Planned shore and backshore restoration requiring roadway realignment. Planning and conceptual design completed. The lower estimate (B) does not include a seawall to protect a wastewater facility, a stormwater treatment wetland and street car extension.
4) Proposed backshore restoration and park reconfiguration, proposed in 2005 (Goleta 1.0), 2007 (Goleta 1.5), 2011 (Goleta 2.0) but not implemented. Goleta 2.0 had reduced restoration and different backshore. "Goleta 1.5 20 year" includes allowance for ongoing sand placement as an additional cost not included in "Goleta 1.5".

Source: Bob Battalio, PE Files: refinement of data previously provided to the State of California and The Nature Conservancy for limited use.

preservation/monitoring, which could also be significant.

In addition, we suggest a linear metric instead of an area-based one, as is typically used for many environmental projects. The use of a linear metric has numerous advantages for the dynamic habitat of beaches, particularly when applied to coastal armoring projects. First of all, since these cases are frequently litigated, in California and elsewhere, a linear metric does not lend itself to legal dispute — indeed the applicant must disclose the length of armoring project. The width of the beach, however, is highly disputable, exactly because beaches are dynamic ecosystems. In litigation, beach width is often disputed; the length of the coastline is rarely in dispute.

Second, coastlines are usually measured in terms of length, so the length of coast may be as important a contributor to market price as acreage of the coastal property. Despite this logic, many estimates of the ecological value of coastline depend upon area and ecological benefits are often determined by value per acre. One problem with this approach is that parts of the coastline that are naturally narrow, or have been made narrow by erosion, armoring or other coastal development, receive very low or no valuation. This is particularly problematic with coastal armoring precisely because it is typically applied to an already eroded beach. However, any analysis of mitigation for coastal armoring that ignores the length of the coastline that is being eliminated, effectively forever by armoring, may seriously underestimate the losses of ecological value.

In adaptation planning, it is common to set aside portions of the coastline (again typically measured in length) for armoring/development and parts of the coastline for retreat or some hybrid. When analyzing the economic benefits and costs, the ecological loss of beaches, other than recreation or storm-damage benefits, are frequently overlooked. When they are included, the standard practice is often to use a measure based on area, which necessarily provides low and likely inaccurate values for already eroded shorelines, particularly sandy beaches. Our case study results recommend that when mitigating against loss or when evaluating loss of beaches in adaptation planning (e.g. for sea level rise) the following principles should be given serious consideration:

1) The length of coastline lost to a proposed seawall or other structure should be a significant parameter in the evaluation of ecological loss.

2) A significant component of the economic valuation metric should address replacement cost of functional beach ecosystems.

3) Replacement costs should be based on the costs of actual restoration projects that *fully restored* significant sandy beach.

Policy-makers, such as the California Coastal Commission, may also wish to categorize beaches and other coastal ecosystems by type (e.g. wave-dominated, tide-dominated, dune backed, bluff-backed, adjacent to estuaries, etc.) in order to preserve a wide variety of different beach and coastal ecosystems; different restoration cost metrics and different offset ratios may potentially be applied to different types of coastlines/beach habitats. Policy-makers may wish to take other factors into account as well, such the restriction of natural sediment processes in the area (due to dams, sand mining or other human activities). However, we believe one of the virtues of the method suggested in this paper is its simplicity, and regulators should weigh the benefits of added factors against the regulatory and legal costs of a more complex regulatory environment.

MITIGATION BANKING

Mitigation banking is a common method for mitigating loss of wetlands and other natural resources. In a very broad sense, a mitigation bank acts as an intermediary, matching up mitigation losses with mitigation gains, and applying some established criteria, generally an offset ratio. In the U.S. government established the practice of mitigation banking in the Clean Water Act (Section 404), and many other jurisdictions also use mitigation banking schemes (U.S. EPA 2018).

For beaches and other coastal ecosystems, mitigation banking could be applied to loss of shoreline due to armoring or other coastal development, and also to compensate for loss of shoreline due to climate change impacts. A mitigation bank would generate credits through restoration projects or through improving coastal management practices (e.g. eliminating beach grooming). Any coastal development that degrades coastline/shoreline habitats would be required to pay into the bank either in terms of sponsoring a local coastal development project, or by funding an array of other projects in the area. In general, the mitigation should occur as close to the initial environmental impact as possible. For beaches, a jurisdiction may require mitigation within the jurisdiction or within the littoral cell. Recreational benefits of any proposed mitigation project could also be incorporated into the analysis, though we believe these should be accounted for separately.

All mitigation banking relies on offset ratios, often in units of area (e.g. acres). For loss of coast*line* and shore*line,* we suggest that a linear metric be applied with an offset ratio and that the *full* cost of shoreline restoration be included. This often includes property acquisition and removal of existing infrastructure, as well as coastal restoration (e.g. dune restoration). A mitigation bank may also want to consider the different types of beach morphology (e.g. wave-dominated, tide-dominated, dune-backed, bluff backed), loss of specific types of beach habitat (e.g. snowy plover), etc. Mitigation banks may also want to consider issues within a littoral cell such as reduced sand supply (e.g. due to flood control).

SUMMARY OF POLICY IMPLICATIONS

At the boundary of land and sea, sandy beaches are edge ecosystems characterized by intense dynamics in habitat area, key features, and biota. This plasticity contributes to the important ecosystem functions of beaches including buffering upland areas from wave energy during storms, but it also poses challenges for valuing beach ecosystems. It is precisely the dynamic nature of beaches that make their ecological value difficult to evaluate.

First, beaches are often primarily evaluated in terms of recreational or storm-buffering value, with less attention paid to many other vital ecological functions and services provided by beaches. A mitigation approach for coastal armoring of beaches based solely on recreation necessarily ignores other EFGS provided by beaches and implies that many beaches have little intrinsic value, at least in the types of benefit/cost analyses often employed in adaptation studies.

Second, exactly because beach width is dynamic, the width/area of a beach is often a poor metric for evaluating beach ecosystem function. All too frequently, beaches with low recreational and storm buffering ability receive no or low valuation. Armoring is most often proposed once a beach has already eroded to a point where any measurement of ecological function and services based on width or area will result in low estimated value.

Perhaps because of beaches' dynamic nature, or perhaps for other reasons, beach ecosystems are less well understood and monitored than many other types of coastal ecosystems. As a consequence, few ecosystem metrics for beaches are readily available beyond recreation and storm buffering. However, only accounting for recreation and storm buffering of beaches ignores the precautionary principle. Just because we do not understand these ecological components and EFGS today, does not mean we will not find them valuable and difficult to replace later.

To better characterize these edge ecosystems whose habitat area and features vary strongly over time, our approach also suggests that shoreline *length* be considered as a key parameter when mitigating for beach loss. This not only simplifies calculations, it provides a more robust estimate of the potential value of a beach over time. In the case of coastal armoring, a mitigation fee based on length also avoids disputes between applicants and regulators over the "correct" beach width — since beach width varies by season, storms, years, and other factors. The economic and political science literature on regulation generally favors simple transparent regulations over more complex ones (e.g. see Posner 1974). Busy policy-makers often do not have time to collect data or evaluate expert analyses submitted by applicants to justify mitigation. In practice, applicants also have a strong incentive to underestimate the ecological damages created by armoring.

While it is relatively common to apply dollar-based estimates to the recreation and storm damage prevention benefits of beaches, estimating the dollar benefits of other ecological services and functions is much less common, and, in practice, these services are often not incorporated into benefit/cost analyses. This in turn makes it more difficult to develop strictly economic arguments for preservation of these important coastal ecosystems. Much like tide pools, kelp forests, and coral reefs, beaches are intimately connected with other marine and terrestrial habitats. The premise that the value and benefits of intact beach ecosystems are far greater than a sum of the parts can be used to support approaches that maintain entire beach ecosystems and their many functions and services.

Since using high dollar values can often be politically controversial, it makes sense to consider alternative mitigation methods. For wetlands, mitigation banking is a common practice. New projects must pay into or submit proposed projects to offset the negative impacts for a proposed development. These mechanisms are often seen as practical since they actually fund ecological preservation. Some economists and environmentalists have proposed a "Cap and Trade" system, where new armoring projects must be offset by purchasing someone else's right to armor within a littoral cell or jurisdiction (e.g. see Colgan and Newkirk 2016). However, these schemes must also consider that beach and other ecosystems that are as intact as possible are more valuable than those perforated by armoring or other development.

A "no net loss" policy for beach ecological functioning can also help regulators implement meaningful offsets since "no net loss" typically implies that diminishing ecological function at one beach must be compensated by generating additional ecological functions and services through restoration and policy elsewhere. Restoration projects such as those in Table 5 are a common way to achieve this goal, but less expensive policies, such as eliminating or minimizing mechanized grooming of beaches (a common practice on many tourist beaches) and restoring degraded dunes might be used to achieve ecological benefits at lower costs.

These methods involve the creation of an offset mechanism based on some evaluation of EFGS and some assessment of suitable restoration sites/projects. Although we suggest that beaches should be treated similarly to the way many jurisdictions treat wetlands, one significant difference is our recommendation that beaches and other coastal ecosystems be evaluated, at least in part, based on length and not just area. Since coastal armoring is generally measured in terms of length of seawall or revetment, our recommendation could also reduce regulatory costs and litigation. The proposed approach may also reduce responsibilities for width or area-specific performance criteria of restoration projects during episodic (e.g. El Nino) or long-term (sea level rise) pressures.

CONCLUSIONS

In California and elsewhere, coastal development often inhibits the ability of a beach to retreat and armoring is frequently used as an adaptation strategy. However, by the time armoring is proposed/implemented, the beach often has already lost a considerable amount of its area and ecosystem functioning. Numerous studies indicate that armoring significantly diminishes the ecological functioning of beaches not only by reducing beach width and the types of functioning ecological zones, but also by denying a beach the ability to adjust and retreat naturally in response to changing conditions, limiting the ability of key ecological components and functions to persist.

As sea level rises and coastal storms become more intense and frequent, many sandy beaches will diminish or even disappear (Vitousek *et al.* 2017). The pressure to armor coastlines in order to protect existing development is already enormous. In order to preserve and protect sandy beaches and other threatened coastlines, adaptation strategies that only evaluate coastal recreation and storm buffering ignore many other ecological functions and services. We propose that any evaluation of beaches and coastal habitat, even if already degraded, should include some baseline ecological value based on the cost of replacing or restoring a similar coastal ecosystem. Further, if as is often the case, a simple metric must be applied to mitigate or value EFGS lost, then a linear metric is superior to an area/width metric for sandy beach ecosystems.

We propose a very simple mitigation approach to coastal armoring that is based on the replacement cost of beaches in California, calculated by length. The exact valuation metric applied may vary depending upon economic, political and ecological considerations. However, the principle involved is that in adaptation and other analyses, beach ecosystem functions cannot be ignored or reduced solely to recreational and storm damage prevention value. The length of coastline permanently lost to armoring should be an integral consideration in mitigation strategies for adaptation and other coastal policies.

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