Sandy beach social-ecological systems at risk: regime shifts, collapses and governance challenges

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Sandy beach social–ecological systems at risk: regime shifts, collapses, and governance challenges

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Approximately half of the world's ice-free ocean coastline is composed of sandy beaches, which support a higher level of recreational use than any other ecosystem. However, the contribution of sandy beaches to societal welfare is under increasing risk from local and non-local pressures, including expanding human development and climate-related stressors. These pressures are impairing the capacity of beaches to meet recreational demand, provide food, protect livelihoods, and maintain biodiversity and water quality. This will increase the likelihood of social–ecological collapses and regime shifts, such that beaches will sustain neither the original ecosystem function nor the related services and societal goods and benefits that they provide. These social–ecological systems at the land–sea interface are subject to market forces, weak governance institutions, and societal indifference: most people want a beach, but few recognize it as an ecosystem at risk.

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Accounting for nearly one-half of the world's ice-free coastline, sandy beaches support various human uses, especially recreation and tourism – both of which are expanding globally as a result of increased leisure time (McLachlan and Defeo 2018). The economies of many coastal states are dependent on this beach recreation–tourism link (McLachlan *et al*. 2013). With more than one billion visitors annually, tourism is a major industry, and even when other ecosystems are the focus (eg coral reefs), beaches are central to all coastal recreation experiences. Moreover, the global human population, currently approaching 8 billion, is increasingly concentrated in coastal areas, generating inevitable pressures on beaches despite inequities of access. Indeed, nowhere is a beach free from the human footprint, such that the interaction between their ecology and human activity cannot be ignored. This emphasizes the "triple whammy" affecting coastlines (Elliott *et al*. 2019; Fanini *et al*. 2020): increased urbanization and industrialization, increased use of physical and biological resources, and reduced resilience and resistance to climate change and other exogenous natural and anthropogenic pressures. Therefore, maintaining the ecosystem functions of the world's sandy shores in the face of increasing human recreational and aesthetic demands requires adoption of a more holistic social–ecological system (SES) perspective (see WebPanel 1 for definitions of selected specialist terms).

In a nutshell:

- Sandy beach ecosystems make up almost half of the world's ice-free ocean coastline and function as social–ecological systems
- No other ecosystem on the planet is subject to such a high level of human recreational use, which is increasing worldwide as demand for leisure time rises
- We illustrate a global trend in social–ecological shifts and collapses of sandy beach ecosystems due to local and distant pressures
- A lack of long-term policies and strategic planning reduces governance capacity, which must be participatory and resilient to environmental changes

Sandy beaches are the dominant land–sea interface worldwide and are closely coupled to adjacent surf zones and foredunes (Figure 1). These three systems form the core of the "littoral active zone" (LAZ), the section of the coast characterized by wind- and wave-driven sand transport (McLachlan and Defeo 2018) that provides important ecosystem services, including (1) recreation; (2) food; (3) wave dissipation and associated buffering against storms and sea-level rise (SLR); (4) assimilation of organic materials and pollutants; (5) maintenance of biodiversity, as well as nursery and nesting sites for various taxa, such as fish, sea turtles, shorebirds, and marine mammals; (6) water storage in dune aquifers and groundwater discharge; and (7) water filtration and nutrient mineralization and recycling (Defeo *et al*. 2009; Barbier *et al*. 2011). These ecosystem services are increasingly impacted by perturbations

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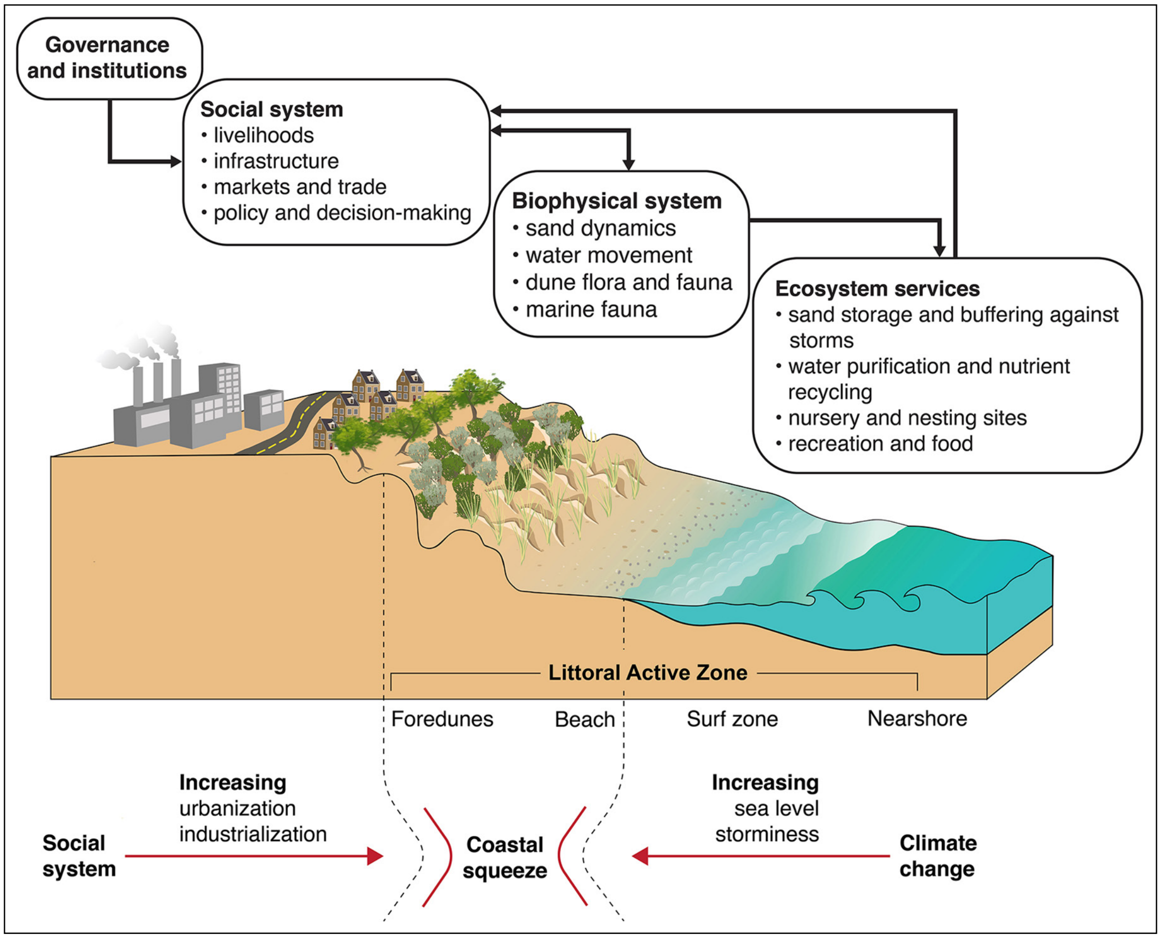

Figure 1. Sandy beaches as social–ecological systems, showing their main biophysical and social components, the ecosystem services and societal goods and benefits they provide, and the main drivers and pressures affecting them (see WebPanel 1 for term definitions).

ranging from transitory pulses with localized effects (eg trampling) to pressures with prolonged global reach (eg SLR) (McLachlan and Defeo 2018).

Proximate and distal factors (WebPanel 1) impair the capacity of beaches to provide recreation and food, protect livelihoods, maintain water quality, and recover from environmental stress (WebFigure 1). These drivers – also defined as endogenic managed (proximate) and exogenic unmanaged (distal) pressures (Elliott *et al*. 2019) – translate into ecological and socioeconomic impacts, given that ecosystem changes affect their dependent human communities and vice versa. Sandy beach SES encompass elements within the biophysical (biota and the environment) and human (economic, cultural, ethical, and sociopolitical) subsystems, which interact through feedback relationships (Figure 1). These proximate and distal pressures increase the probability of social–ecological collapses and regime shifts (ie sudden and irreversible shifts in ecosystem function and structure; WebPanel 1), leading to alternative system states that can sustain neither the original ecosystem functions and services nor the resulting societal goods and services. How beach ecosystems respond to drivers of change is poorly understood, because few studies provide long-term data. There has been limited focus on sandy beaches as compared to other coastal ecosystems, but greater effort is required to develop a "baseline" understanding of sandy beach SES, including identifying drivers of change, alternative and collapsed states, and appropriate management measures.

Here, we use case studies of vulnerable social–ecological processes in sandy beaches to reflect the social–ecological coupling and the multidimensional and multifactorial nature of these ecosystems, and illustrate key challenges confronting them globally. We highlight the overarching challenge of beach reduction due to the combined forces of SLR, erosion, and coastal development, as well as emerging threats associated with algal blooms, pollution, and climate perturbations, considering the way these and other threats, acting individually or synergistically, can lead to social–ecological traps and collapses (WebPanel 1). We emphasize the implications for managing these interface systems, which are especially prone to fragmented governance, and identify barriers to and opportunities for more effective governance (eg in tourism, fisheries, and transportation sectors), along with features of sandy beach SES that make them more or less "governable".

Coastal squeeze

The major long-term threat facing sandy beaches worldwide is "coastal squeeze" (Figure 1), where the LAZ is constrained or lost due to seaward encroachment by recreational, urban, and industrial development on land, while the seaward boundary migrates landward in response to SLR and erosion (Defeo *et al*. 2009). These opposing forces meet at the LAZ, with profound social and ecological consequences for beaches and dunes. Development and supporting infrastructure, as well as the demand for access and resources, all affect the LAZ, often encroaching to reduce or remove the dune component. In addition, SLR amplifies effects of storm surges, which are also increasing in size and frequency due to warming (Bindoff *et al*. 2020), pushing the LAZ landward and causing retreat of beaches and dune erosion (Summers *et al*. 2018). Pulse perturbations, such as the El Niño–Southern Oscillation (ENSO; hereafter El Niño), when superimposed on SLR, tend to exacerbate erosion (Barnard *et al*. 2015). Yet sandy coastlines, particularly in regions with high population density and coastal development, have no capacity to respond naturally to SLR and the landward migration of the LAZ (Arkema *et al*. 2013; Bindoff *et al*. 2020).

When caught in the vise between the long-term press perturbations of SLR and expanding human occupation, the LAZ (Figure 2a) loses its most sensitive system first: namely, the foredunes (Figures 2b and 3). If coastal squeeze persists, the beach will continue to diminish until only the surf zone remains (Figures 2c and 3), where, in extreme cases, waves break directly against an armored shoreline. When only the foredunes are forfeited, the primary loss is their sand reservoir and its buffering capacity against storms. Where the shoreline is hardened or armored, or where there are pocket beaches not backed by dunes or other sediment supply, the beach will most likely disappear entirely (Figures 2c and 3), as will the functional LAZ and its ecosystem services, leading to social–ecological collapse (WebPanel

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Figure 2. The three phases of the littoral active zone (LAZ) under coastal squeeze: (a) intact LAZ; (b) loss of foredunes; and (c) beach loss leaving only the surf zone, such that the LAZ and its ecosystem services are no longer functional.

1). The integrity of the SES becomes degraded, with substantial long-term losses of natural and human capital.

Beaches are increasingly sand-starved due to dune stabilization and sand-mining practices, as well as to the presence of inland dams and along-shore artificial hardened features including concrete groins and breakwaters, all of which cut off sediment supply (Brown *et al.* 2008). At present, it is estimated that nearly one-quarter of beaches worldwide are eroding rapidly (Luijendijk *et al.* 2018); erosion interacts with SLR to squeeze the LAZ, especially if beaches lack access to the sand reservoir usually held in foredunes (Short and Hesp 1982). The key approach to preventing loss of the LAZ and ecosystem deterioration is the principle of setback (Figure 3), whereby development is relocated well landward of the active dunes, which creates space for the LAZ to remain intact while retreating landward. However, retreat and removal of structures is not feasible on highly developed coasts where the coastal zone manager must pursue other protection options, such as hard (eg concreting, groins) or soft (eg sand nourishment) engineering (McLachlan and Defeo 2018).

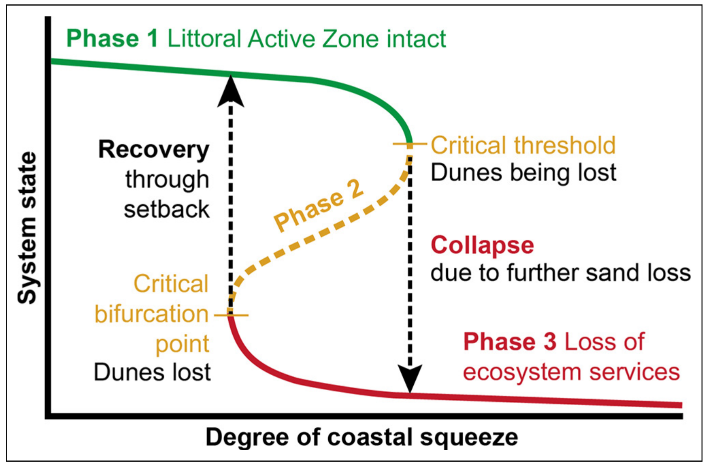

Figure 3. Response of sandy beaches to coastal squeeze: in the natural state (phase 1), the LAZ is intact and dunes hold a vital sand reservoir; in phase 2, the dunes are being lost due to encroaching development and/or increasing sea-level rise (SLR) and erosion; in phase 3, as SLR and erosion continue, the beach is lost, leaving the surf zone as the only remaining core subcompartment of the original LAZ.

Algal blooms

Green and golden tides of drifting macroalgae

Eutrophication and nutrient enrichment can create increased algal growth, forming golden (*Sargassum* spp) and green (*Ulva* spp) "tides" (Figure 4): extensive mats of drifting macroalgae deposited along sandy beaches after having been detached and transported by coastal currents (Smetacek and Zingone 2013; Quillien *et al.* 2015). The frequency, intensity, and periodicity of these pulse perturbations have been increasing worldwide (Ye *et al.* 2011). Golden tides, which were originally limited to beaches between the Gulf of Mexico and Bermuda, have expanded in geographic range, reaching unprecedented levels on Barbadian beaches in 2018, in response to which the government declared a national emergency (Langin 2018). Algae are also becoming more common in the tropical Atlantic and Caribbean (Wang *et al.* 2019), where they can accumulate into anoxic mats that produce toxic hydrogen sulfide (H_2S) and alter the biological, chemical, and physical properties of water and sediment (Smetacek and Zingone 2013); recent green tides along the coastline of Brittany, France (Figure 4b), for instance, affected the food web and diversity of intertidal benthic deposit feeders and bivalves (Quillien *et al.* 2015).

Massive accumulations of algae on sandy beaches (Smetacek and Zingone 2013; Quillien *et al.* 2015) cause economic losses associated with amenity deterioration and consequent impacts on tourism and fisheries, as well as the cost of removing and disposing of thousands of tons of beached algae. The eutrophic conditions responsible for algal mat formation may derive from activities within or outside the sandy beach system, including intensive stock rearing, overfertilization of crops, tourism, and coastal aquaculture (Ye *et al.* 2011). For example, the influx of *Sargassum* in the Caribbean has been linked to land use in the Orinoco River Basin, Amazon River discharge (Wang *et al.* 2019), and even land-use change in West Africa (Langin 2018).

Red tides of microalgae

Harmful algal blooms (HABs), which are often associated with microalgae, are increasingly affecting sandy beaches, threatening public health, ecosystem services, and socioeconomic activities (Berdalet *et al.* 2017). The neurotoxins produced by some phytoplankton species adversely impact human health (eg outbreaks of *Ostreopsis* that have been increasing along Mediterranean beaches in recent decades), causing toxicological symptoms and acute respiratory irritations (Berdalet *et al.* 2017). These disruptive events are perceived as threatening to public health by beachgoers, who are then discouraged from using beaches for recreation. Anthropogenic climate change and other anthropogenic activities, such as nutrient and organic enrichment, are increasing HAB occurrence (Anderson *et al.* 2012), posing a challenge to management where clam fisheries experience mass mortalities and clams are unsafe for human consumption. This can also cascade into food webs and be biomagnified in upper trophic levels, including fishes (Berdalet *et al.* 2017).

Fishery closures to prevent human consumption of seafood during HABs lead to increased unemployment and lost income. For example, the Uruguayan yellow clam fishery has been increasingly affected since a shift to a warm ocean climate period began in the late 1990s (Gianelli *et al.* 2021). Fishery closures in Uruguay due to HABs swelled from <20 days annually in the early 1980s to total closure in 2017 (Figure 5). Similarly, the southern coast of Chile was recently adversely affected by an extensive red tide of *Alexandrium catenella*, with widespread beach clam mortalities damaging the local fishing economy, most likely due to warming of nearshore waters during the 2015–2016 El Niño. On-site response tools and shore-based stations near sensitive HAB targets enable monitoring, which will help to develop early-warning systems and guide decision making concerning beach closures. However, monitoring is expensive, and is often beyond the limited economic resources available in many developing countries.

Other pollution sources

Sandy beaches are subject to contamination and pollution from anthropogenic sources ranging in size from molecules to large debris. Impacts on the LAZ can be acute, temporary (pulse perturbations), and localized, or more chronic (press perturbations) and widespread (Fanini *et al.* 2020).

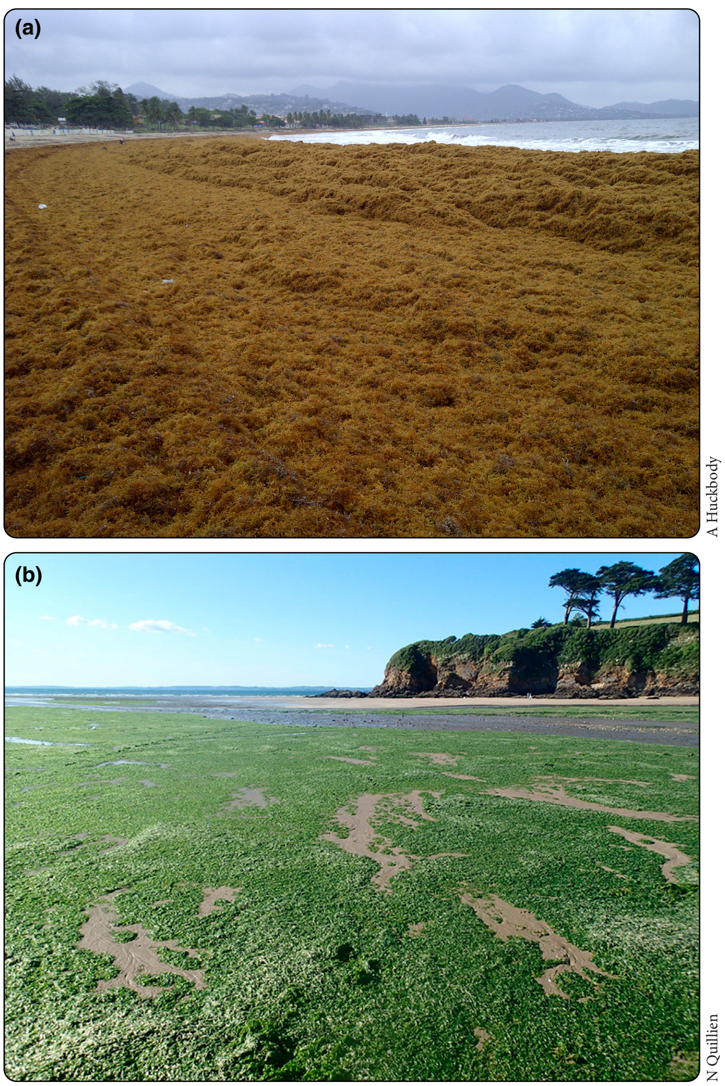

Figure 4. (a) Extensive deposits of *Sargassum* forming a golden tide on a Sierra Leone beach. (b) A green tide (*Ulva*) event on Sainte-Anne la Palud beach, Douarnenez Bay, France.

Oil spills

Oil buried in beach sand alters the physical characteristics of the sediment, clogging interstitial spaces and reducing water flow and oxygen supply (Bejarano and Michel 2016). Birds that feed on the beach or surf zone or nest among the dunes are directly affected; for example, 62% of all dead birds found on beaches in Newfoundland, Canada, over a 16-year survey were found to have oil on their feathers (Wiese and Ryan 2003). In addition, beach cleanup activities also disturb organisms and their nests; for instance, oil spilled from the *Deepwater Horizon* drilling rig in the Gulf of Mexico reduced long-term sea turtle nesting on Florida beaches directly (mortality) but also indirectly, as cleanup activities deterred nesting (Lauritsen *et al.* 2017). Remediation efforts caused a regime shift in microbial communities (Engel and Gupta 2014) and supralittoral macrofauna were highly susceptible because oil accumulates at the top of the shore (Bejarano and Michel 2016). Oil spills also detract from the aesthetic value of a beach, affecting tourism that depends on public perceptions of clean beaches (McLachlan and Defeo 2018).

Plastics and microplastics

Sandy beaches are a major sink for marine litter, an escalating problem worldwide. Thousands of items of anthropogenic debris strand on each kilometer of Atlantic and Pacific beaches annually, of which a huge amount is plastic that is rapidly buried (Barnes and Milner 2005; Hidalgo-Ruz *et al.* 2012; Thiel *et al.* 2013). Microplastic ingestion by seabirds and sea turtles causes toxicity, and microplastics affect temperature and sediment permeability (Carson *et al.* 2011), which can influence sea-turtle nest properties and hatchling sex ratios (Nelms *et al.* 2016). Plastics also affect the benthic macrofauna across the LAZ (Horn *et al.* 2019). Finally, human health risks increase when plastic medical wastes wash ashore from coastal dumping sites (Keswani *et al.* 2016).

Sewage

Discharges from urban, industrial, and agricultural activities, together with increasing precipitation events, intensify sewage and nutrient inputs to beaches (Rech *et al.* 2014) and impact the LAZ; for instance, organic enrichment lowers dissolved oxygen levels in the water column and sediment, and promotes the development of anoxic layers, while freshwater runoff exacerbates erosion and reduces beach width, thereby changing community and ecosystem patterns (Jorge-Romero *et al.* 2019). Discharged raw sewage is a health hazard to humans and wildlife, and bacterial levels that exceed human health standards in surf zone waters are a frequent cause of beach closures and public warnings (McLachlan and Defeo 2018).

A canal built to drain wetlands and discharge close to a beach resort in Uruguay (Andreoni Canal) affected the entire

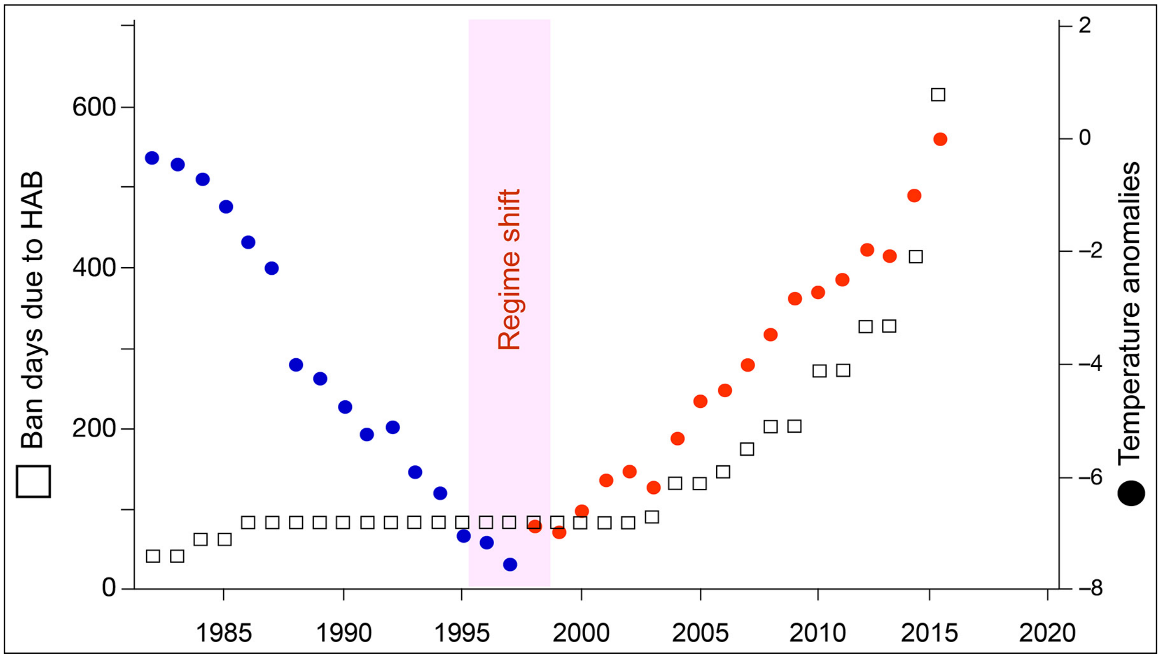

Figure 5. Cumulative number of closure days per year (open squares) in the Uruguayan yellow clam (*Mesodesma mactroides*) fishery due to a harmful algal bloom (HAB), together with the cumulative sum of standardized sea-surface temperature anomalies in Uruguayan waters. The regime shift in climate from a cool period (solid blue circles) to a warm period (solid red circles) is highlighted (data courtesy of L Ortega).

LAZ over several decades: a strong along-shore salinity gradient developed, the beach and dunes eroded, surf zone hydrodynamics and chemistry were altered, and considerable organic material accumulated on the beach (Jorge-Romero *et al*. 2019). As a result, habitat quality declined, affecting the resident fauna, with reduced biodiversity and smaller populations of the clams that supported a small-scale fishery (Defeo *et al*. 2016). In addition, the number of hotels and visitors has halved. This deterioration in the SES has clearly exceeded critical thresholds (tipping points), triggering a regime shift in which the biophysical and social components of the SES have moved from one state to a different state with altered ecosystem function and services, and severe socioeconomic consequences (Jorge-Romero *et al*. 2019).

Climate change and variability leading to social–ecological shifts and collapses

Climate change is threatening the LAZ and the ecosystem services it provides through SLR and warmer temperatures, with associated storminess, excessive precipitation, and flooding (Figure 1) resulting in erosion, beach retreat, and dune erosion (Bindoff *et al*. 2020). Up to 70% of beaches in southern California will be eroded by 2100 under SLR scenarios of 0.9–2.0 m (Vitousek *et al*. 2017), and El Niño pulses have led to long-term erosion across numerous Pacific (Barnard *et al*. 2015) and southern Atlantic (Orlando *et al*. 2019) beaches.

Regime shifts in beach morphology (Kuriyama and Yanagishima 2018) affect dune vegetation and drive changes in associated faunal assemblages (Bindoff *et al*. 2020). Where the LAZ has limited capacity to retreat landward in response to SLR, eroding and narrowing beaches reduce the carrying capacity for nesting sea turtles, and temperature increases are altering reproductive outcomes (Laloë *et al*. 2016; Patrício *et al*. 2019). The benthos shows biogeographical changes following warming: American and Australian beaches exhibit shifts in abundance and distribution of benthos, together with mass mortalities of cool-water species, offset by poleward expansion and increased dominance of species with tropical affinities (Schoeman *et al*. 2014). SLR and warming will seriously impact the LAZ by the end of this century through increased erosion, loss of dunes, and climatic sensitivity of beach fauna (Bindoff *et al*. 2020).

Long-term observations suggest that macrofaunal composition is reorganizing under the influence of climate presses and pulses (Bindoff *et al*. 2020). The southwestern Atlantic Ocean is a climate-change "hotspot", where sea-surface temperature is rising at several times the average global rate (WebPanel 1); as a consequence, the tropical Brazilian Current is shifting poleward, accompanied by increasing speed and frequency of onshore winds and storm surges (Franco *et al*. 2020; Gianelli *et al*. 2021). These changes have impacted the SES; for example, mass mortalities of the cool-water yellow clam (*Mesodesma mactroides*) coincided with the start of the climate shift during the 1990s and occurred sequentially in a poleward direction (Figure 6), tracking the movement of tropical waters (Ortega *et al*. 2016). The clam stock has not fully recovered despite fishery closures, with devastating socioeconomic effects. This transformation constitutes a clear social–ecological regime shift (WebPanel 1).

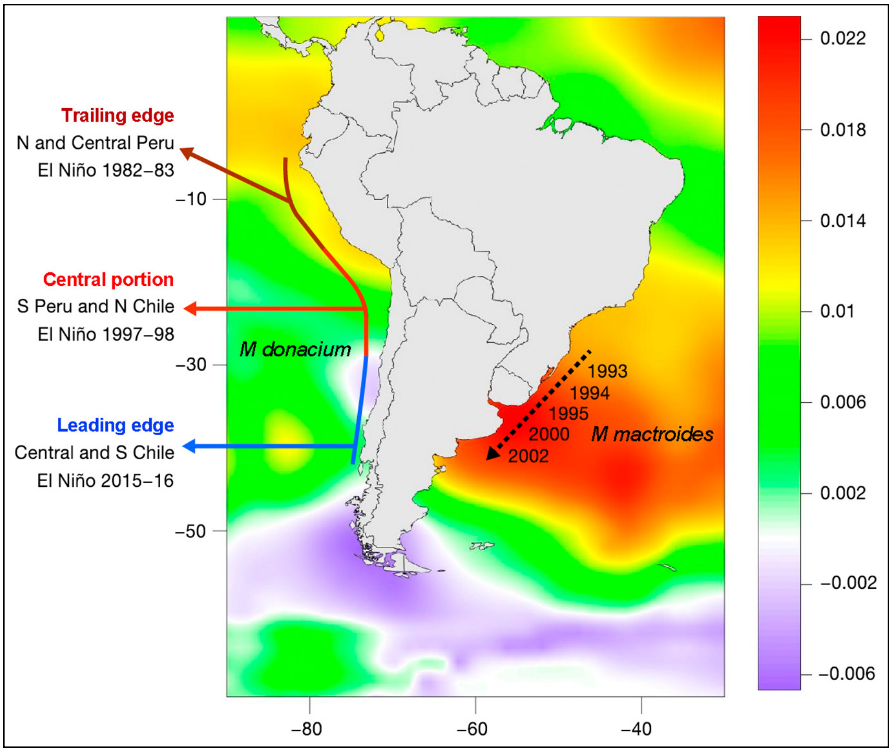

Figure 6. Dates of mass mortalities of two cold temperate beach clams, *Mesodesma donacium* (Pacific) and *Mesodesma mactroides* (Atlantic). El Niño events affected Pacific clams, whereas mortalities in the Atlantic followed the climate shift during the 1990s and occurred sequentially in a poleward direction. Ocean color indicates annual rate of warming (°C per year) for the period 1960–2019 (color scale in °C).

El Niño pulse disturbances led to regime shifts and collapses in the SES associated with a Pacific surf clam (*Mesodesma donacium*) fishery along the coast of Peru (Figure 6). Weak governance led to unregulated fishing and open access (Ortega *et al.* 2012), resulting in unsustainable harvest levels and causing a "poverty trap" (WebPanel 1) in which fishers, driven by a lack of economic alternatives, decimated the surf clam stock. The 1982–1983 El Niño affected the trailing edge of clam distribution, reducing abundance and preventing landings from returning to pre-mortality levels (Ortega *et al.* 2012). The following El Niño (1997–1998) affected fisheries in the central portion of the range (southern Peru and northern Chile), as was projected by climate-change models, with local clam extinctions and restructured benthic communities (McLachlan and Defeo 2018). The Peruvian surf clam fishery has remained closed since 1999, as surf clam populations have failed to recover (Figure 6). The lack of response of this stock to long-term fishery closures suggests that the system exceeded critical thresholds (ie tipping points; WebPanel 1), first shifting abruptly from one state to another and then triggering a social–ecological collapse. Finally, the 2015–2016 El Niño impacted populations at the leading edge of the range in southern Chile and led to the open-access fishing grounds being closed until 2022. In essence, pulse perturbations (El Niño events) and weak governance (open-access system) acted in concert to trigger a social–ecological collapse (WebPanel 1); the crash of clam stocks led to fishery closures and economic hardship for the fishing community.

Projected increases in press and pulse climatic events, together with non-climatic anthropogenic drivers, will continue to heighten the exposure and vulnerability of sandy beach SES with profound socioeconomic consequences, including a reduced ability to deliver ecosystem services along with societal goods and benefits, such as recreation, tourism, fisheries, wildlife habitat, and coastal protection (Bindoff *et al.* 2020).

Divided jurisdiction and weak governance

Sandy beaches provide functional links between terrestrial and marine systems, and are especially prone to fragmented and sectoral governance (Defeo and Castilla 2012; Pittman and Armitage 2016). Indeed, the "governability" of sandy beaches is especially challenging because of their multidimensionality and complexity (Table 1). For example, despite long-term success in participatory governance of small-scale fisheries (Defeo *et al.* 2016), the decline of surf clam populations demonstrates the vulnerability of coastal SES, and sandy beaches more generally, when dealing with economic and climate shocks (Ortega *et al.* 2012). Such drivers of change and their implications underscore the critical role of governance in any SES, particularly those spanning the land–sea interface (Pittman and Armitage 2016).

Several approaches could be taken to address the threats facing sandy beach SES. Participatory governance, community-based data collection programs, and community science provide useful tools. These may include shared action and decision making where local communities engage with both/either volunteer and/or professional scientists (Charles *et al.* 2020). There are few simple governance "solutions" to coastal social–ecological regime shifts (WebPanel 1) due to the challenges of boundary, scale, and knowledge mismatches (Nayak and Armitage 2018). There exists a diverse range of legal protections and mechanisms (eg conservation easements, protection zones) that vary greatly across jurisdictions, and even within some jurisdictions; for instance, strategies to mitigate *Sargassum* blooms require a regional approach, yet manifest in different enforcement tools, incentive systems, and levels of governing capacity within individual Caribbean nations (Table 1).

Ultimately, determining how different protection measures and policy tools (eg financial incentives for adjacent

Table 1. Selected governance attributes and challenges for sandy beaches

Selected SES governance attributes and challenges					
Boundaries: multiple drivers not easily captured in clearly delineated boundaries; institutions and rules rarely aligned with or match the spatial extent of ecosystem boundaries		**Scale**: governance initiatives must scale-up (eg climate change) and simultaneously scale-down to empower communities; governance unlikely to produce timely decisions at adequate scales relative to emerging threats		**Knowledge**: limited understanding of beaches as unique ecosystems or the threats they face; governance systems should access and apply diverse knowledge (eg Indigenous, scientific)	
Potential solutions					
Respect knowledge sources; foster knowledge coproduction to work across boundaries	Design nested incentive structures and rules for drivers of change at multiple scales	Emphasize changes in mindsets about beaches and the threats they face	Build multilevel governance networks; draw on local and Indigenous institutions	Foster social learning processes to engage stakeholders; encourage changes in values	Support leadership and capacity building specific to challenges
Examples					
Indonesia: application and reemergence of *sasi laut*, a community-based coastal resource management approach with participation of diverse stakeholders, leaders, communities, and external actors		**Eastern Caribbean**: governance actors addressing *Sargassum* impacts on beaches by matching the scale of response to the scale of the problem through coordinated initiatives and regional organizations		**Mexico**: community driven initiatives link spatial access rights, use of coastal commons, and livelihoods of fishers and beach-based tourism operators; new organizations enhance knowledge sharing; shift from open access to locally managed decision making	

Sources: Pittman and Armitage (2016); Armitage *et al*. (2017).

landowners) are implemented and enforced further highlights the generally limited capacity of stakeholders to effectively govern sandy beach systems. Experimentation is necessary, and there is potential to test more adaptive governance arrangements and institutional designs that emphasize collaboration and learning, and tackle key mismatches (Table 1; Armitage *et al*. 2017). In this regard, the governance arrangements needed to address social–ecological regime shifts for sandy beaches and coastal SES may differ only in their intensity and speed of response from those in place to address more incremental change.

Conclusions

Sandy beaches are among the most beautiful landscapes on Earth, and attract people to enjoy "sun, sea, and sand". The delight that beaches generate can strengthen the link between nature and people and raise awareness of the coastal environment. The LAZ as a whole provides important ecosystem services and societal goods and benefits, yet its integrity is jeopardized by the massive and growing demand for beach access and other threats. Despite their extent, beaches are undoubtedly ecosystems at risk (McLachlan and Defeo 2018). Social–ecological collapses (eg coastal squeeze worldwide, Peruvian clam fishery), regime shifts (eg Uruguay), and increasing and sustained social–ecological disruptions driven by macroalgal (eg Caribbean, France) and microalgal (eg Atlantic South America) outbreaks cause substantial ecological and socioeconomic losses. These are not isolated cases, as similar conditions are becoming more common worldwide. Proximate and distal drivers acting simultaneously impair the capacity of sandy beaches to provide recreation, food, livelihoods, and water quality. The main pressures include expanding urbanization and climate-related stressors acting with market forces and weak governance of natural resources. Continued assessment of social–ecological collapses based on long-term information will help bridge the gap between theory and practice in these systems.

Positioned at the land–sea interface, beaches are prone to complex governance challenges. Drivers acting simultaneously undermine the social–ecological status of beaches and require a multidimensional framework to assess resilience along the natural, social, and governance axes to improve system governability. But a lack of long-term policies and strategic planning; high uncertainty in ecological, economic, and political conditions; an absence of long-term data; and societal indifference all impose barriers to effective management and governance.

No other ecosystems are subject to such high levels of recreational use as are sandy beaches, and this is rising worldwide as leisure time increases. Considering subcompartments of the LAZ separately (ie surf zone, beach, or dune) is insufficient and leads to unsustainable use of ecosystem services. Ultimately, the LAZ must be viewed and managed holistically as a tightly coupled and integrated SES, with greater attention to adaptive and participatory governance under changing and uncertain conditions.

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Supporting Information

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FrontiersEcoPics

A king among queens

The society of spotted hyenas (*Crocuta crocuta*) is often depicted as a textbook example of uncontested female supremacy. Male hyenas are portrayed as pushovers that must show deference to hyper-aggressive females if they wish to mate or feed. Yet often, the reality is more complex – and far more interesting! Female hyenas do not dominate males unconditionally. In fact, males too can hold the alpha position. This is what happened to *Majani* (left) with the support from female relatives, when his mother, queen of the Lemala clan in Ngorongoro Crater, died.

Dominance relationships in spotted hyenas are not a matter of gender, body size, or aggressiveness. Rather, they are determined by the number of social allies one can rely on. Hyena mothers are the fiercest and most reliable allies; they support their young – daughters and sons – against members of lower-ranking matrilines and thereby ensure they hold the social rank right below their own. Sons of alpha females can thus inherit the throne, such as what happened with *Majani*. When his mother died, *Majani* could count on the support from his older sister *Vimba* (third from left) and his two nieces to make sure others respected his alpha status.

Cases like *Majani*'s are not rare but they often go unnoticed because kings rarely stay in power for long. Like other males, kings usually disperse after reaching sexual maturity, leaving the throne to a sister. Interestingly, males who remain in their birth clan do reproduce very successfully. To what degree these philopatric males impact the clan's social organization and genetic structure has yet to be unraveled.

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WebPanel 1. Definition of core terms and concepts, and selected references

Coastal squeeze: constriction of beaches and dunes between rising sea and encroaching human occupation; dunes are lost through intrusion by coastal development, while the low-water mark migrates landward in response to sea-level rise (Defeo *et al*. 2009; Pontee 2013).

Driver: any natural- or human-induced factor that indirectly brings about change in a system; this may originate in its immediate proximity (*proximate driver*: fishing, pollution, sea temperature) or far from it (*distal driver*: new technologies, opening of markets, changes in governance structure) (Hicks *et al*. 2016; Österblom *et al*. 2017). The term "driver" as used here is analogous to the term "pressure" used elsewhere (eg Elliott *et al*. 2019), which is defined as the mechanism of change to natural and human systems.

Global marine hotspots: regions of the marine environment where sea-surface temperature is increasing at several times the average global rate (Hobday and Pecl 2014).

Governance: the arrangements and processes of interaction and decision making through which societies make decisions about a collective problem. These interactions lead to the creation, reinforcement, or reproduction of social norms, rules, laws, and institutions (Armitage *et al*. 2019).

Littoral active zone (LAZ): the coastal geomorphic system that includes the nearshore, surf zone, beach, and dunes, which are linked by the storage and interchange of sand. Characterized by wave- and wind-driven sand transport, the LAZ lies between the outer limit of wave-driven sand movement and the landward limit of aeolian sand transport (McLachlan and Defeo 2018). It consists of two main ecosystems: (1) the marine beach/surf zone ecosystem, which is controlled by waves and tides; and (2) the terrestrial dune system at least as far inland as there is any wind-driven sand movement.

Perturbation: a disturbance that impacts an ecosystem. A *pulse perturbation* is an instantaneous and short-term disturbance causing a sudden change in a property of the system, such as an extreme climatic event; a *press perturbation* is a continuous disturbance causing some properties of the social–ecological system to change permanently, or as long as the perturbation is present (Harris *et al*. 2018; Kéfi *et al*. 2019). A pulse perturbation is regarded as being more acute and short-lived, whereas a press perturbation is chronic and long-lived but perhaps with a lower intensity.

Resilience: the capacity of a social–ecological system (SES) to regain its fundamental structure, processes, and functioning (or remain largely unchanged) following stresses or perturbations. A multidimensional view that includes ecological, socioeconomic, and governance resilience is used here to assess the performance of an SES (Folke *et al*. 2010; Guillotreau *et al*. 2017).

Social–ecological system (SES): A "bio–geo–physical" unit that includes its associated human users and institutions, and that emphasizes the integration of humans in nature (Berkes and Folke 1998; Ostrom 2009).

Social–ecological collapse: the endpoint of degradation of an SES that involves a rapid and substantial loss of identity (key actors, system components, and interactions) and capital, the consequences of which persist longer than the typical dynamics of the SES (Cumming and Peterson 2017).

Social–ecological trap: a situation in which feedbacks between social and ecological systems lead toward an undesirable state that may be difficult or impossible to reverse, typically because of unsustainable utilization of a resource. Such traps usually occur when the lucrative value of a natural resource drives stakeholders and managers to overlook or ignore the risks of its unexpected decline and the potential negative social and ecological consequences (Cinner 2011; Steneck *et al*. 2011; Kittinger *et al*. 2013).

Social–ecological regime shift: a large, abrupt, and persistent change in the structure and function of an SES that drastically alters the quality and quantity of the services provided by the ecosystem, with ramifications for societies that depend on these services (Nayak and Armitage 2018).

Tipping point: a critical moment in an evolving situation after which irreversible changes may occur. Surpassing a tipping point may cause a system to shift into an alternative state or regime (Scheffer *et al*. 2001).

Transition: loss of resilience due to the action of press and/or pulse perturbations acting independently or in concert, resulting in shifts between system states (Scheffer *et al*. 2009).

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WebTable 1. Coastal setbacks and reference points in selected countries/regions, ordered by setback distance

Country/region	**Setback distance (m)**	**Reference point**
Bahamas	5–15	Line of vegetation, ridge, or dune crest
Mexico	20	
New Zealand	20	
Turkey	50	Shoreline
Brazil	50–200	Tidal line
Costa Rica	50–150	Ordinary high tide
EU-Mediterranean	100 minimum	Highest winter water mark
Norway	100	Shoreline
Spain	100	Landward limit of the shore
Sweden	100	Shoreline
Germany	100–200	
Uruguay	250	High water mark
Denmark	300	
Australia		
New South Wales	1000	High water mark
Victoria	200	High water mark
South Australia	100	High water mark
US		
Alabama	Coastal construction line	Mean high tide
Delaware	30 300	3 m elevation height Mean high water (whichever is most seaward)
Florida	30 × erosion rate/coastal construction line	Seasonal high water (whichever is most seaward)
Georgia	Line of vegetation	Low water mark
North Carolina	Landward of crest of foredune or ocean hazard setback, whichever is most landward	Line of stable natural vegetation
Oregon	Line of vegetation; point of definite change in material type, landform, or vegetation line	Low water line in ocean shores Low water line in beaches
Texas	Line of vegetation Up to 300	Mean low tide, public beach Mean high tide, critical dune areas

Notes: for Australia and the US, examples are provided by region/state. For the US, data were converted from feet to meters to facilitate comparisons. Data are from Simpson *et al*. (2012) and modified from McLachlan and Defeo (2018).

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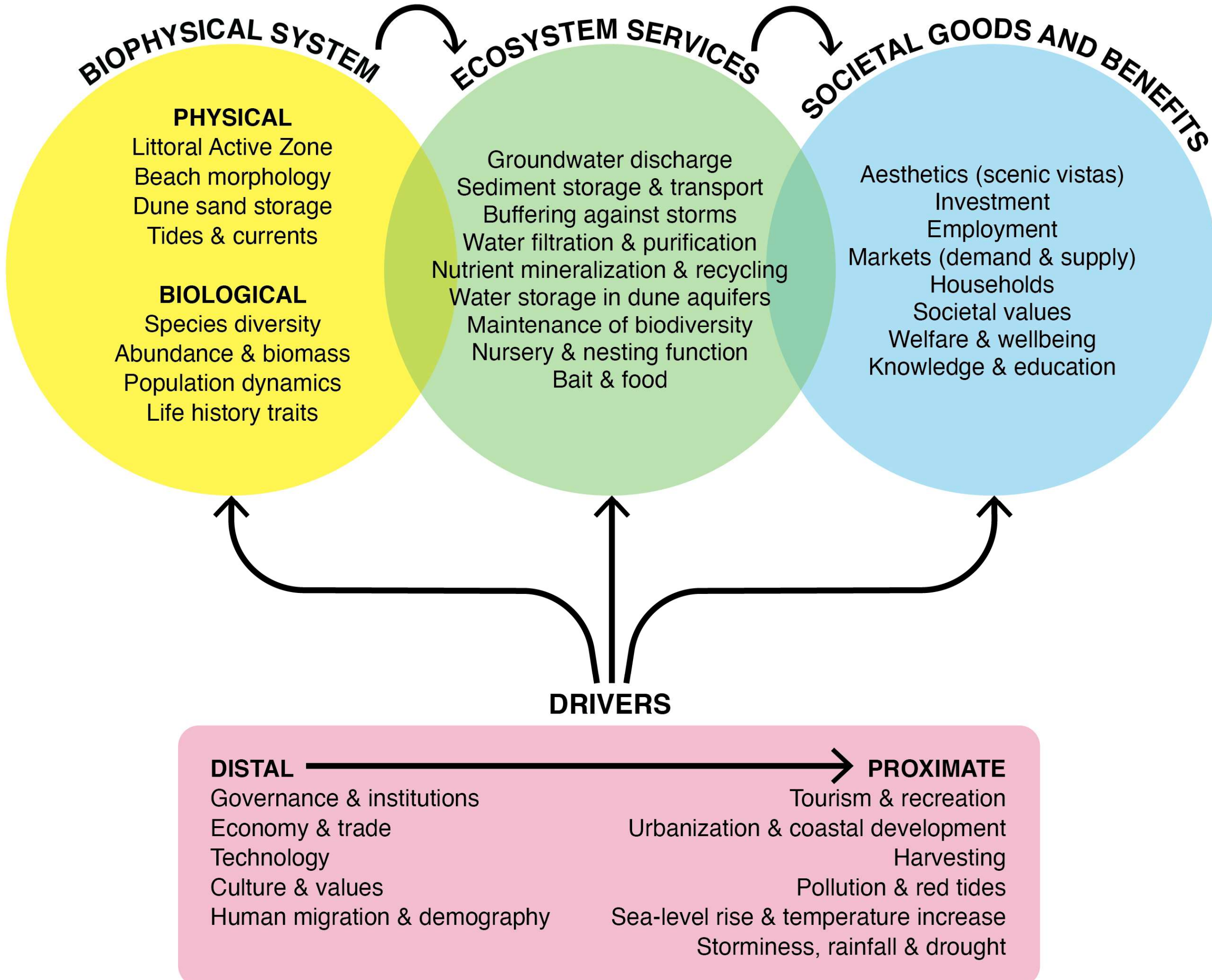

WebFigure 1. Sandy beaches as social–ecological systems. The upper compartments (circles) lead to and influence one another, and in turn are influenced by distal and proximal drivers and pressures (lower rectangle).