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Literature review

Pressures on coastal biodiversity in South Africa: a cross-realm review

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South Africa's coastal zone comprises diverse ecosystems and species, and provides important benefits to people. It is also under significant pressure from numerous activities that take place on land, in estuaries, and in the sea, and that are rarely considered together. Here, we review the pressures on coastal biodiversity in South Africa, taking a cross-realm perspective. The pressures are reviewed under 10 themes: biological resource use; energy production and mining; pollution; coastal development; transportation and service corridors; natural systems modifications (sand-flow disruptions, estuarine hydrological regime change, livestock grazing and browsing); human intrusions and disturbance; aquaculture, agriculture and plantation forestry; invasive and other problematic species and diseases; and climate change, severe weather and ocean acidification. Many of these are intense or pervasive cross-realm pressures, often with cumulative, synergistic impacts that are collectively causing habitat fragmentation and loss, declines in species richness and abundance, altered animal behaviour, reduced ecosystem resilience, and declines in capacity to provide ecosystem services. However, the inter-connected nature of these pressures also means that integrated coastal management provides opportunities to address multiple pressures and impacts cross-realm. Sustainable development that is mindful of long-term climate projections is imperative in the coastal zone to safeguard this national asset into the future.

Keywords: biodiversity crisis, biological resource use, climate change, coastal management, flow reduction, mining, pollution, sustainable development

Online supplementary material: Supplementary Table S1, available at <https://doi.org/10.2989/1814232X.2026.2635131>, lists alien plant species introduced deliberately and planted to stabilise dunes along the south coast of South Africa.

Introduction

Global initiatives to halt and reverse the current biodiversity crisis (e.g. Convention on Biological Diversity 2022) are underpinned by growing recognition of the accelerating rate at which pressures are impacting biodiversity by causing habitat fragmentation and loss, declines in species richness, and shifts in community composition (Kuipers et al. 2021; Keck et al. 2025). Coasts are particularly

susceptible to these impacts (Defeo and Elliott 2021) because they are exposed to pressures from both the landward and seaward sides, and tend to have higher human population densities than the hinterland (Cosby et al. 2024), which concentrates the pressures and impacts. This leads to disproportionately high levels of ecosystem degradation and risk of ecosystem collapse in the coastal

zone (Harris et al. 2022). More than 50% of the coast is degraded in 85% of countries worldwide, with intact coastal regions being globally rare (Williams et al. 2022).

Understanding the impacts of pressures on biodiversity is the first step in identifying management interventions to reduce and reverse biodiversity loss. However, a key concern for coastal zones is that the terrestrial, estuarine and marine components are largely considered separately, despite the many critical cross-realm connections among them (Harris et al. 2025a). Consequently, pressures on coastal biodiversity are rarely considered holistically (Williams et al. 2022). This is important to address so that coastal biodiversity, ecological infrastructure and the ecosystem services on which many people depend for their livelihoods can be managed sustainably. Therefore, our aim was to review all pressures on coastal biodiversity in South Africa (Figure 1), emphasising and elaborating on cross-realm impacts across the land–estuary–sea continuum. South Africa is an interesting example in having a myriad of pressures acting on an ecologically diverse coast (Harris et al. 2025b), with additional contrasts between critically impacted and near-pristine regions. We discuss the pressures under the 10 themes used by the International Union for Conservation of Nature for classifying threats to biodiversity (IUCN 2022). Given the breadth of content, it is not possible to review each pressure comprehensively in a single article. Instead, we provide a high-level summary, with additional details available in related papers and reports (e.g. Sink et al. 2019; Skowno et al. 2019; van Niekerk et al. 2019a, 2022b; Harris et al. 2021). Reference to the ‘coastal zone’ in this review is to the ecologically determined coastal zone (EDCZ), *sensu* Harris et al. (2025b).

Biological resource use

Fishing and invertebrate harvesting

Biological resource use (Figure 1a,b) is a significant pressure in South Africa’s coastal zone. Although most biological resources are extracted for human consumption, other uses include bait, animal feed, crafts, construction, ornamental and aquarium trade, and traditional medicine (Shackleton et al. 2007; Simon et al. 2021). There are 17 marine fisheries targeting fish or invertebrates that occur wholly or partly in the EDCZ, namely: demersal inshore trawling; crustacean trawling; small-pelagic fishing; tuna-pole fishing; squid-jig fishing; commercial line fishing; small-scale fishing (e.g. fish, crustaceans, mussels); beach-seining; gillnetting; recreational fishing (including bait harvesting); shark control (bather protection); as well as commercial harvesting of South African abalone *Haliotis midae*, oysters, white mussels *Donax serra*, west coast rock lobsters *Jasus lalandii*, south coast rock lobsters *Palinurus gilchristi*, and east coast rock lobsters *P. homarus*. Recreational and small-scale fishing also extend into estuaries, with fishers using a variety of gears, such as lines, cast-nets, gillnets and traditional fish traps.

A key issue is the amount of South Africa’s fish and invertebrate resources that are harvested each year—both legally and illegally. Unsustainable resource use

risks the persistence of the target species, such as the dusky kob *Argyrosomus japonicus* (globally Endangered, nationally Critically Endangered: Fennessy 2020; Farthing et al. 2025), abalone *Haliotis midae* (Endangered: Peters 2021), *Donax serra* (Endangered: Harris et al. 2025c), and predators of target species, such as the African penguin *Spheniscus demersus* (Critically Endangered: BirdLife International 2024). Furthermore, growth and recruitment overfishing in estuaries (i.e. removing juveniles before they can recruit to adult fish stocks) is the biggest threat to estuarine-dependent marine fishes in South Africa, having caused stocks of most of the fishery species to become overexploited or collapsed (James et al. 2026). Other impacts from fishing and invertebrate harvesting include habitat damage (e.g. from trawl nets, spades, crowbars, bleach and blades), bycatch and ghost fishing from lost gear. These, together with reduced abundances of target species, cause knock-on effects for biodiversity by impacting nursery habitats, abundances and sex ratios of some species, predators of target species, and trophic structure and energy-flow through ecosystems (e.g. Blaber et al. 2000; Moloney et al. 2013). Removing larger fish also reduces reproductive output and recruitment in a population (Barneche et al. 2018), and excavating non-target species during bait collecting can lead to disproportionately high predation rates of those disturbed species (Wynberg and Branch 1991), both of which further impact trophic structure and food webs.

The escalation of fishing effort in estuaries is concerning, especially the accelerating amount of illegal gillnetting in KwaZulu-Natal Province (KZN) as a result of easy online purchasing of low-cost gillnets, and reduced capacity for enforcement. Increased gillnetting nationally has amplified capture, trade and consumption of cormorants, grebes, fish eagles and other waterbirds. There is also bycatch with high mortalities of reptiles, coastal aquatic mammals and African penguins attributed to illegal and ghost gillnetting (e.g. Crawford et al. 2017). Emerging illegal fishing pressures include shade-cloth and mosquito-net seines targeting penaeid prawns, small and juvenile fish in estuaries, and use of fish aggregating devices (FADs) in the sea.

Wildlife hunting, trapping and poaching

Coastal animals are captured for use in traditional medicine, cultural regalia and food, with some animals killed incidentally in snares (Shackleton et al. 2007; Williams and Whiting 2016). In terms of traditional medicine, 147 vertebrate species representing ~9% of the total number of vertebrate species in South Africa are traded in the Faraday Market in Johannesburg, South Africa’s largest traditional medicine market (Whiting et al. 2011), recognising that this includes non-coastal species. More than 300 uses have been documented for these traded animals (Williams and Whiting 2016). International wildlife trafficking syndicates are increasingly impacting species desired for overseas markets, and poaching is reducing wildlife populations and threatening their persistence, including in coastal protected areas (Streicher et al. 2025). Hunting, trapping and poaching animals can drive increasing risk of species extinction by causing significant declines in populations, as is the case for several mammal species in South Africa

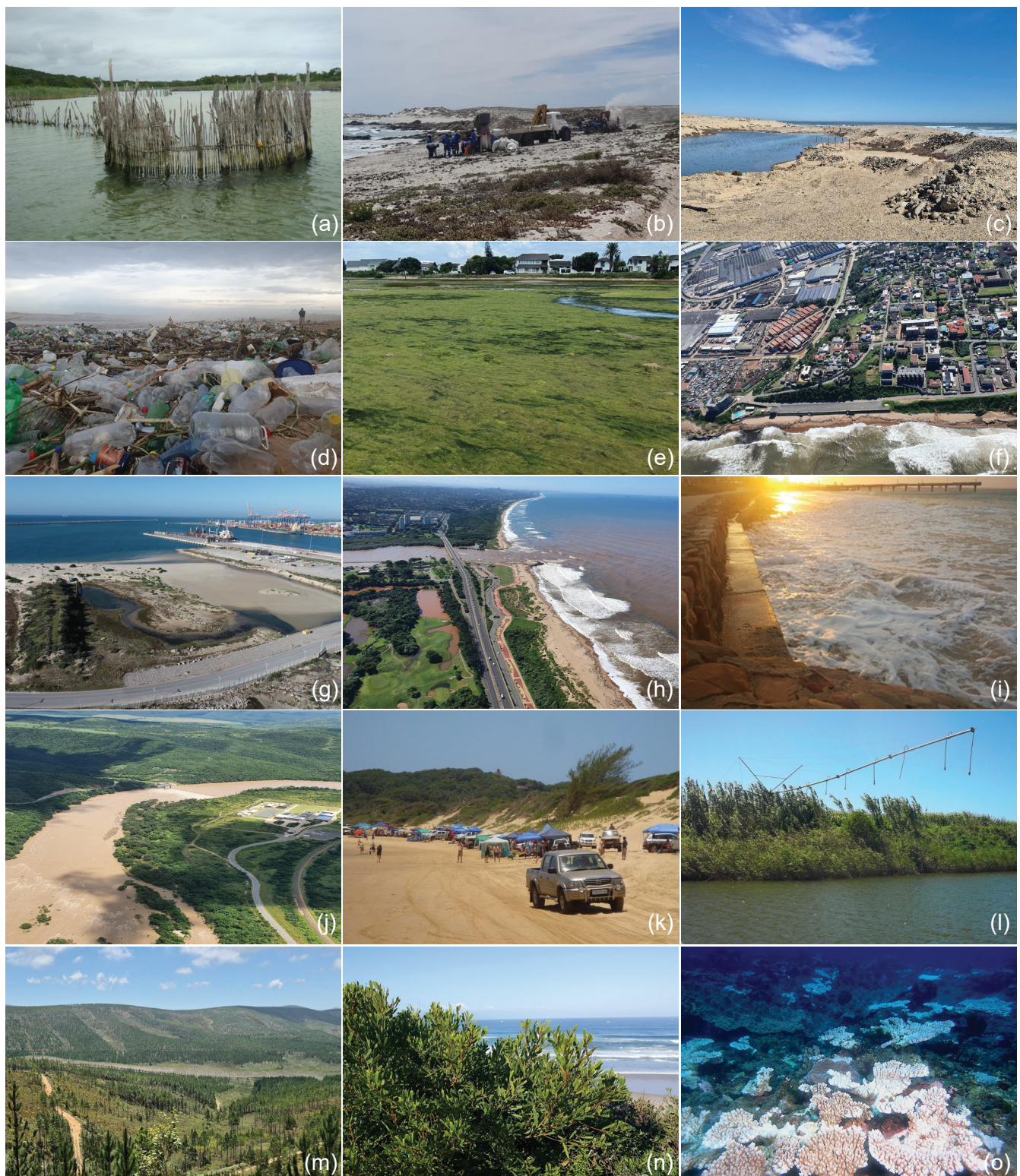


Figure 1: Pressures on coastal biodiversity include: biological resource use, such as (a) fishing, and (b) wrack harvesting; (c) energy production and mining; pollution, including (d) solid waste and plastics, and (e) waste-water discharge, causing, *inter alia*, eutrophication; (f) coastal development; transportation and service corridors, such as (g) port and harbour activities, and (h) roads and railway lines; natural systems modifications, such as (i) disrupted sand flows by seawalls, (j) hydrological regime change and freshwater flow reduction; (k) human intrusions and disturbance, such as aquaculture, (l) agriculture, and (m) plantation forestry; (n) invasive and other problematic species, such as rooikrans *Acacia cyclops*; and (o) climate change, severe weather and ocean acidification (e.g. causing coral bleaching). Photograph credits: Linda Harris (panels a–c, i, k, m, n), Fiona MacKay (d, f, h, j), Nicola James (e), Riaan Weitz (g), Daniel Lemley (l) and Sean Porter (o)

(Child et al. 2017). In some instances, poisons are used to kill target animals (Ogada 2014; Manqele et al. 2024), which likely has additional impacts on non-target animals and, potentially, on local water supplies. Research on hunting, trapping and poaching specifically for coastal animals in South Africa is largely limited, and would benefit from dedicated investigations.

Seaweed harvesting and beach grooming

Kelp (mainly *Ecklonia maxima*) is harvested for various kelp-based products, including abalone feed in mariculture, and red seaweeds like *Gelidium* and *Gracilaria* are harvested for agar. These macroalgae are taken either from live stocks in the shallow subtidal or by removing beach-cast wrack from the shore. Wrack is also removed from certain popular beaches, called beach grooming, because the smell as it decomposes is considered unpleasant. Seaweed harvesting and beach grooming can impact multiple species and ecological processes. Subtidal kelp harvesting can reduce wave-dampening effects and natural coastal protection, remove feeding and nursery grounds of coastal fishes, influence local food webs, and reduce the availability of food to different trophic levels (Lorentsen et al. 2010). On the shore, removing wrack reduces the carrying capacity for wrack-dependent organisms, some of which are Endangered or Near Threatened species (Harris et al. 2025c), with knock-on implications for foraging seabirds (Dugan et al. 2003), nutrient remineralisation, and local productivity of sandy shores. Wrack removal also reduces trapping of wind-blown sand that is important for initiating foredune formation (Nordstrom et al. 2011), and reduces the abundance and diversity of native dune plants and associated species (Dugan and Hubbard 2010).

Plant collecting and poaching

Plants are commonly used as traditional medicine in South Africa for both healing ailments and symbolic purposes (Whiting et al. 2011). Over 2 000 indigenous plant species have documented traditional medicinal uses, and just over a quarter of these are traded annually in the country (Williams et al. 2013). Most plant material is obtained from open-access communal lands for personal use or else sold to traders and traditional healers in urban markets. The portions of the coast under most pressure from medicinal plant harvesting are communal areas in the Amathole and OR Tambo districts in the Eastern Cape Province (EC). Harvesting plants for other uses is common in some estuaries; for instance, Ncema grass *Juncus kraussii* and the common reed *Phragmites australis* are harvested for traditional crafts; and mangroves are harvested in many EC estuaries for construction purposes, and in the Kosi Estuary for building traditional fish traps (Adams and Rajkaran 2020). There also appears to be increasing use of coastal plants (e.g. coastal red milkwood *Mimusops caffra*, coast silver oak *Brachylaena discolor*) by communities in KZN, including invasive alien species, such as the Brazilian peppertree *Schinus terebinthifolius*, which is used for ornamental purposes, fencing and traditional medicine (Patočka and de Almeida 2017; Mxoliso Mabaso, Wildlands, pers. comm.). Plant poaching

is an escalating concern, particularly in the Namaqualand region of the Western Cape Province (WC), where 878 species were included in confiscations between 2022 and 2024 (SANBI, unpublished data); slow-growing, rare, range-restricted succulents and geophytes are the main targets. Consequently, the rich succulent flora, restricted to the northern Namaqualand coast, is under pressure from illegal collection.

Energy production and mining

Mining

Mining (Figure 1c) for sand, diamonds and heavy minerals (e.g. ilmenite, zircon, rutile) are destructive practises present in South Africa's coastal dunes, estuaries, shores and offshore, including legal and illegal operations (Manona et al. 2024; McKelvey and MacKay 2025). The impacts of mining are numerous and often intense (e.g. Biccard et al. 2018; Rangel-Buitrago et al. 2023), including habitat destruction from deforestation, clearing native vegetation, kelp cutting, excavation and sand removal. Habitat damage is also caused by building mine-associated infrastructure, altering dune and shoreline morphology, increasing erosion, anchoring, abstracting water from natural sources, changing the water table depth, and disturbing the hydrological regime of coastal rivers, wetlands and estuaries via access routes. Biota are crushed, buried, poisoned, physically damaged or displaced, with changes in the feeding behaviour and distributions of birds, mammals and fish, changes in plant species distributions, and proliferation of alien and invasive species. Mining causes pollution in the form of tailings and waste disposal, wind-blown dust, air pollution, derelict machinery and infrastructure, noise, resuspension or introduction of heavy metals, oil and chemical leaks, and organic loading. Suspended sediments increase turbidity, potentially reducing primary production, decreasing the efficiency of filter feeders, and clogging fish gills, with associated changes in community structure. Mining tailings can change the beach morphodynamic type and associated biodiversity, including causing species extirpations (McLachlan 1996; Pulfrich and Branch 2014).

Serial mining along the west coast is impacting nearly the full extent of bioregions, and thus the full distribution of some endemic coastal species and ecosystem types. Consequently, mining is a key driver of the risks of coastal species extinction (Harris et al. 2025c) and ecosystem collapse (Harris et al. 2022). The extent of sand mining (legal and illegal) in South Africa's estuaries is also substantial, contributing to estuarine habitat decline and loss of sediment supplied to beaches (McKelvey and MacKay 2025).

Petroleum activities

Petroleum activities span from exploration to extraction and production, and include seismic surveys, infrastructure installation, drilling, and transporting oil and gas to land-based processing facilities and pipelines. In South Africa, the impacts on coastal biodiversity are concentrated more in the marine environment than in estuaries or on land, with increasing interest in offshore petroleum as part of national imperatives to grow the blue

economy. Petroleum activities can cause habitat loss from infrastructure installation; introduction and proliferation of alien and potentially invasive species; chemical pollution from water- and oil-based drilling muds, blowouts and oil spills; noise pollution; light pollution; and impacts from helicopter operations and flaring (Page et al. 2006; Pretorius 2018). These result in disrupted marine species migrations, feeding and communication; altered species distributions and aggregations; and potential physical and physiological damage (Hawkins and Popper 2014; Pichegru et al. 2017; Pichegru et al. 2022). Associated increases in shipping activity also increases the probability of ship-strikes to migratory species (Pretorius 2018). Because most petroleum activities in South Africa are outside of the EDCZ, the impacts of most concern for coastal biodiversity include oil spills and chemical and noise pollution. Oil spills in particular have the potential to cause catastrophic impacts to coastal biodiversity by oiling species, degrading ecosystems and disrupting ecological processes, and also cause potential health risks to people (Wolfaardt et al. 2009). Furthermore, the chemical dispersants used in cleaning up oil spills may impact marine life and in some cases can be more toxic than the oil itself (Brown 1982).

Renewable energy production

Renewable energy is key to achieving energy security, reducing climate-change impacts, and supporting socio-economic growth in South Africa (National Planning Commission n.d.). Existing and emerging renewable energy installations include wind farms near Oyster Bay and Saldanha Bay, planned photovoltaic solar plants for Saldanha and Cape Town, and planned green fuel (green hydrogen and green ammonia) initiatives for Boegoebaai, Saldanha Bay and Coega (DTIC 2023). Environmental impacts of renewable energy production on land include: habitat fragmentation and loss during construction; potential alteration of microclimates and species compositions, and disruption of ecosystem functions; and soil compaction, leading to changes in hydrology. Wind turbines present high risk of collision and barotrauma to birds and bats, and turbine noise and low-frequency vibration may disturb animal behaviour (Doty and Martin 2013; Perold et al. 2020). Green hydrogen development also requires extensive new infrastructure, likely including desalination plants, with associated brine discharge being an important environmental concern for coastal ecosystems. Other potential impacts include pollution from the production and transportation of hydrogen derivatives, like ammonia or methanol, which use catalysts and chemicals that could contaminate soil or water if not properly managed.

The potential for marine renewable energy (MRE) in South Africa includes offshore wind, current, wave and thermal energy sources (DFFE 2021). Although no MRE projects currently exist, there are plans for development; for instance, a floating offshore windfarm at Richard's Bay is under assessment. Potential impacts of MRE include habitat disturbance or loss during construction, and collision risks with wind turbines for seabirds. Wave and current devices may impact cetaceans, turtles and fish through

collision risk, electromagnetic fields and underwater noise, and marine benthic and pelagic habitats and communities could be impacted by changes to natural seawater flows and sediment transport. Small installations might have minimal impacts, but large commercial arrays could significantly alter marine systems over time.

Pollution

Solid waste and plastics

Plastic pollution is present all along the South African coastline (Ryan et al. 2018), with consistent patterns along the shore over time. Key concerns for biodiversity across all realms, but especially in the estuarine and marine environments, are: entanglement (Cliff et al. 2002; Ryan 2018); ingestion causing gastric obstructions and mortality (Roman et al. 2021); accumulation in animal tissue of chemicals from plastic ingestion (Tanaka et al. 2013); and potential increases in the spread of alien and invasive species (Gregory 2009). Coastal species recorded with ingested plastics or microplastics in South Africa include: stranded turtle hatchlings (Ryan et al. 2016), marine invertebrates (Ferguson et al. 2024), sharks (Cliff et al. 2002), fish (Naidoo et al. 2016) and birds (Witteveen et al. 2017). There are also increasing concerns that plastic is entering the human diet through consumption of shellfish that have ingested microplastics, but the health implications are not yet clear (Smith et al. 2018). Quantities of plastics on beaches do not appear to be related to local population densities but are strongly related to urban and industrial centres (Nel et al. 2017; Ryan et al. 2018). Thus, although ocean currents contribute to plastic loading on beaches from remote sources, plastics are largely generated from local land-based sources and enter the sea via rivers (Ryan et al. 2018), with substantial quantities of plastics washing into the coastal zone during flood events (Chikodzi et al. 2021) (Figure 1d).

Land-based wastewater discharge

Wastewater represents a significant source of chemical pollution and encompasses a range of inputs, including industrial and municipal effluents, brine discharges from desalination plants, effluents from aquaculture operations, and stormwater and agricultural runoff. Wastewater discharge into the sea through estuaries and outfalls impairs water and sediment quality, and causes a shift in the primary producer and benthic invertebrate community near the discharge point to more pollution-tolerant forms (CSIR 2017). Approximately 655 000 m³ of mostly municipal wastewater is discharged daily into South African estuaries (Skowno et al. 2025), causing greater impacts in areas with weak flushing and long retention. High organic and nutrient loading is causing excessive eutrophication (Figure 1e), fuelling red tides, harmful algal blooms (HABs) (see below), ammonia toxicity and anoxia (Adams et al. 2019; Lemley et al. 2019a), often leading to fish kills. Consequently, coastal water quality is substantially degraded near major urban centres. The associated microbial pollution is also having serious socio-economic impacts, resulting in beach closures and a loss of recreational value

and tourism income. Coastal groundwater discharge is similarly enriched by human settlements, impacting supratidal spring-fed living microbialite ecosystems (Rishworth et al. 2020), and septic tank input can contaminate coastal aquifers (Rishworth et al. 2017). Although most wastewater discharge is a chronic source of pollution, pulse events can be catastrophic; a recent example is the highly toxic chemicals that were from the UPL agrochemical warehouse at Cornubia released into the Ohlangua River and Estuary during the riots in KZN in 2021 (Whitfield 2021).

Metals and hydrocarbons are common pollutants in estuaries, ports and harbours (Newman et al. 2015; Mehlhorn et al. 2021). Emerging pollution pressures include pharmaceutical compounds and personal care products (Ojemaye et al. 2022), other organic pollutants (Vogt et al. 2018; Olisah et al. 2021) and microplastics (Mokgalaka-Fleischmann et al. 2024). The bioaccumulation and biomagnification of these compounds in food webs can pose toxic risks to lower and higher trophic level biota and to the humans who consume them (Bosch et al. 2016; Mbandzi-Phorego et al. 2024). High concentrations of metals, other chemicals and pollutants have been detected in South African sea turtle eggs, seabird eggs, fish, cetaceans, corals, sediments (particularly in ports and harbours) and surf zones of popular recreational beaches (Bosch et al. 2017; du Preez et al. 2018; Porter et al. 2018; van Aswegen et al. 2019; van der Schyff et al. 2020). High lead exposure and toxicosis is evident in Nile crocodiles *Crocodylus niloticus* in Lake St Lucia from ingesting lost fishing weights (Humphries et al. 2022), and bioaccumulation of herbicides and pesticides has been found in coral reef organisms (Porter et al. 2018; Tyohemba et al. 2022). There is also bioaccumulation of metals and persistent organic pollutants in various estuarine biota, and uptake of these contaminants by salt marshes, seagrasses and reeds (Olisah et al. 2021; Ndhlovu et al. 2024).

Light pollution

Artificial light at night (ALAN) can degrade the habitat of some species by making dark areas lighter, thus interrupting species' natural circadian rhythms and altering species' natural night-time activity through either negative or positive phototaxis. For example, Endangered Cape pill bugs *Tylos capensis* (nocturnal sandy beach isopods) (Harris et al. 2025c) are significantly less active at night when exposed to higher light intensities, which reduces their foraging time (Siggala 2017). This same result has been found for other *Tylos* species (Duarte et al. 2019), beach mice (Bird et al. 2004) and beach amphipods, with the latter case demonstrating reduced food consumption and slower growth rates (Luarte et al. 2016). ALAN also alters the foraging ecology of rocky shore species (Underwood et al. 2017), affects a variety of species associated with reefs, as well as their interactions and community ecology (Davies et al. 2023; Fobert et al. 2023), disrupts sea turtle nesting and disorients hatchlings (Thums et al. 2016), and impacts shorebird roosting and fish spawning (Simons et al. 2021). Intertidal fish exposed to ALAN have lost their endogenous circatidal and circadian activity cycles (Pulgar et al. 2019), and nocturnal positive

phototaxis to ALAN has caused higher rates of stranded seabirds (Burt et al. 2024). Evidence also suggests direct physiological impacts on plants, and indirect impacts, such as by changing pollinators' activity patterns (Bennie et al. 2016). This pervasive pressure affects a myriad of coastal species and their behavioural ecology (Marangoni et al. 2022), with effects propagating to community and likely even ecosystem levels.

Noise pollution

Sound conductivity is greater through water than air, making underwater noise pollution a particular concern in aquatic environments, especially because ocean-based activities are rapidly diversifying and intensifying (Jouffray et al. 2020; Duarte et al. 2021). Sources of sound include seismic surveys, shipping traffic, bunkering, various other commercial activities, and boating. Elevated noise can cause direct mortality, lower immunity and increase health risks (Masud et al. 2020), and alter species distributions and disrupt foraging when predators, prey or both avoid noisy areas (Monaco et al. 2016; Pichegru et al. 2017), potentially causing population declines (Pichegru et al. 2022). Underwater noise can disrupt marine animal reproduction, communication and social behaviour (Butler and Maruska 2020; Purdon et al. 2025). The latter may further reduce some species' ability to catch prey in cases where vocalisations are part of hunting (Thiebault et al. 2019). These impacts are similarly recorded in estuaries, where underwater noise from boat engines disrupts the social interactions and swimming behaviour of soniferous fish, including overexploited and threatened species such as *Argyrosomus japonicus*, spotted grunter *Pomadasys commersonnii*, and syngnathid seahorses and pipefish, and negatively impacts their growth and reproduction (e.g. Coetzee 2024). Some species experience elevated stress levels when exposed to underwater noise (Rolland et al. 2012), and potentially a loss of hearing (Nelms et al. 2016). Where impacted species are harvested (e.g. *P. commersonnii*) or underpin ecotourism (e.g. African penguins, cetaceans), there can be possible knock-on socio-economic consequences as well. Although the known impacts from underwater noise are diverse, there are still many gaps in our understanding of this pressure (Elliott et al. 2019).

Dumped ammunition

Disposing obsolete ammunition in the marine environment was practised in South Africa from the 1970s until 1995 (Godeschalk and Ferreira 1998), before the London Protocol (1996 Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter) came into effect. Dumped ammunition can cause damage to or smothering of ecosystems and habitat-forming species; may potentially detonate, causing localised destruction; and will corrode, causing pollution and toxicity, especially from heavy metals (Beck et al. 2018; Beldowski et al. 2019). There is evidence of munition compounds bioaccumulating in marine food webs, which is predicted to increase with time and climate change (Scharsack et al. 2021; Beck et al. 2022). Presumably, dumped munitions in South Africa have corroded over the past 30–50 years, but the impacts are largely unknown.

Coastal development

Coastal development (Figure 1f) includes the construction of buildings, ports, harbours and other hard structures. It is correlated with the sum of all other pressures on coastal ecosystems (Harris et al. 2015), indicating that it is a critical driver of ecological degradation. Of South Africa's 3 113-km-long coastline (Harris et al. 2011a), ~17% has development located within 100 m of the shore (Sink et al. 2012). Broadly, areas associated with ports and harbours are the most intensively developed (Harris et al. 2015). The WC and KZN have the highest number of structures built adjacent to the shore (Claassens et al. 2022), and the Indian Ocean Coastal Belt extending along the eastern seaboard is the terrestrial biome most affected, with 2 350 km² (26%) of natural habitat lost to development in the EDCZ. It is also the terrestrial biome with the greatest landcover change between 1990 and 2022, with ~954 km² (22%) of natural habitat lost during this time within the EDCZ (Skowno et al. 2025). Loss of estuarine habitat to urban infrastructure comprises 9% of the total estuarine functional zone (EFZ) extent (Skowno et al. 2025), and almost all of the large commercial ports (i.e. Port Elizabeth, Ngqura, East London, Durban and Richards Bay) are situated in or near estuaries. There is proposed development of a new deepwater port at Boegoebaai, linked to the green hydrogen hub planned for the Northern Cape Province (see 'Renewable energy production', above), including associated rail infrastructure, pipelines and storage facilities (CSIR 2025).

Coastal development is a critical pressure because it is largely irreversible. It causes fragmentation and loss of habitat, ecological degradation through interruption of physical and biological processes, loss of biodiversity and coastal ecosystem services, and compromised ecosystem resilience (Dugan et al. 2011). Habitat loss from coastal development is a key driver of extinction risk to species, causing extirpations, declines in abundance, reduced species richness and changes in community composition (Lucrezi et al. 2014; Harris et al. 2025c). Habitat specialists with small ranges are particularly susceptible, either through direct loss of their habitats or through indirect effects, such as reduced food availability (Dugan et al. 2008). Building too close to the shore (Figure 1i) breaks down key linkages and processes between the land and sea, for instance exchanges in sediment (see 'Natural systems modifications', below) and nutrients, and blocked movement paths of high-shore biota, affecting distributions and cross-realm predator–prey relationships (Defeo and McLachlan 2025). Inappropriate development within the EFZ often results in additional impacts, such as estuary mouth manipulation to prevent property damage, and lately using ambiguous environmental authorisations to purloin sections of estuaries under the guise of restoration or 'working with nature'. Infrastructure can also restructure and shade shallow-water habitats, causing associated fish assemblages to alter feeding, reproduction and migration activities, and reducing nursery habitats for juvenile fish (Munsch et al. 2017). In turn, the loss and degradation of coastal habitat and biodiversity from coastal development may suppress the provision of important coastal ecosystem services (Firth et al. 2016; Gittman et al. 2016).

Transportation and service corridors

Port and harbour activities

Ports and harbours (Figure 1g) are hubs of activity and points of access to the ocean, and are sources of several forms of pollution, described above. Numerous chemical pollutants accumulate in ports and harbours because they are sheltered, retentive areas, which leads to long-term declines in water quality, ecological condition and toxic risk to aquatic fauna and flora (Vogt et al. 2018). Port and harbour development, expansion and maintenance require dredging—removal of accumulated sediment from a body of water, usually harbour and marina entrance channels—with the dredge material dumped at sea. This activity is performed by the National Ports Authority in South Africa as part of routine port management and maintenance. Environmental impacts from dredge disposal include decreased primary production and predator success from increased turbidity (Essink 1999), and increased bioavailability of pollutants that can impact the health of sensitive species (Smith et al. 1995). Various attributes of the disposal practice can determine the intensity of these impacts (Smith and Rule 2001). In the long term, dredge disposal can change local bathymetry, affect currents and waves, and alter natural sediment deposition and erosion cycles (Vander Pluym et al. 2017). The changes in water circulation and flow, combined with pollutants, can cause detrimental consequences to marine and estuarine life (e.g. fish kills).

Ports and harbours are also high-risk entry points and refugia for alien and invasive species from ship hulls and ballast water (see 'Aquatic invasions', below), and anchorage can cause physical damage to benthic habitats. As points of access to ocean resources, ports and harbours can lead to declines in the ecological condition of marine ecosystem types in the surrounding area, as well as burgeoning industrial and residential infrastructure development on the landward side (Harris et al. 2022). Offshore bunkering (i.e. the ship-to-ship transfer of petroleum) takes place within the port limits of Algoa Bay. A critical risk of this activity is oil spills, which have oiled African penguins and other seabirds. This is particularly concerning given the already high risk of extinction of these species (Stassen and Stander 2024). Additional associated impacts include increased maritime traffic and underwater noise, which may have caused the collapse of the African penguin population at St Croix Island in Algoa Bay (Pichegru et al. 2022).

Shipping

South Africa is a maritime nation with eight commercial ports that receive international trade. The main biodiversity impacts associated with shipping are: impacts from oil spills as a result of shipping accidents (Galieriková and Materna 2020); underwater noise (Duarte et al. 2021; Pichegru et al. 2022); introduction and spread of invasive alien species through ballast water discharge and hull fouling (see 'Aquatic invasions', below); pollution impacts from dumping of waste materials, leaching of toxic compounds from anti-fouling paint, and accidental oil leakages; ship strikes with large marine animals (Pirodda et al. 2019);

and air pollution. Ships can also lose their cargo in rough seas, which can then become a shipping hazard and cause significant pollution in the marine environment (e.g. the plastic nurdle spill in Durban Harbour in 2017 (Schumann 2019), and the loss of pharmaceuticals from cargo ships along the southeast coast in 2024 (SAMSA 2024). Because many of the trade routes go around the tip of southern Africa, and many ships stopover in South African ports, the relative intensity of shipping is higher closer to the coast than farther offshore, although the bulk of this pressure does fall outside of the EDCZ.

Roads and railway lines

Many roads and railway lines that run alongside the South African coastline break connectivity of ecological processes across the land–sea interface, and in some places are very precariously positioned on the foredunes and on bridges over estuaries (Figure 1h). This transportation infrastructure is at risk of temporary closure or even failure during floods, heavy swell from storms and sea-level rise (e.g. Smith et al. 2007a)—phenomena that are all predicted to increase with climate change. Roads and railway lines on bridges over estuaries stabilise dynamic estuarine channels, and cause extensive erosion of sediments during heavy floods. This is often linked to extensive deposition of the eroded sediment downstream of the bridge. The resulting changes in sediment distribution and tidal flows can lead to changes in habitats and biota, and even premature mouth closure in smaller temporarily open and closed estuaries. When this linear infrastructure severs connectivity between estuaries and the sea, it can result in eutrophic freshwater conditions and a loss of important intertidal habitats such as mangroves (Adams and Rajkaran 2020).

Natural systems modifications

Disrupted sediment flow

Natural sources and flows of sand that form and maintain beaches and dunes originate both on land and in the sea. Sand is transported to and along the coast by rivers and estuaries, wind, waves and currents. Sand naturally erodes, accretes and moves onshore and offshore as well as alongshore within the littoral active zone (connected dune–beach–surf zone: Tinley 1985). These flows of sand have not been well recognised in the past and have been interrupted by: replacing dunes with buildings and defending them with seawalls; constructing breakwaters and piers; mining sand out of estuaries; reducing freshwater flows that bring sediment to the coast; and blocking land–sea connections with hard infrastructure (Lubke and Sugden 1990). Development within the littoral active zone (Figure 1i) deprives beaches of the sand stored in dunes, reducing the inherent resilience of the coast to high wave-energy events and sea-level rise (Harris et al. 2011b; El Mrini et al. 2012). Coastal development can also alter shoreline morphology, with sand flows in longshore drift or headland bypass systems blocked or altered by artificial structures (breakwaters, piers, groynes), sometimes necessitating an artificial movement of sand or other coastal engineering solutions to mitigate downstream erosion. Where sand movement is altered, it can also lead to

changes in community composition on subtidal reefs (Porter et al. 2017). Removing and trapping sediment in rivers through mining, dams and weirs reduces sand delivery to the shore, impacting beaches downstream. For example, the uThukela coast in KZN switched from a state of accretion to erosion following mining and weir construction in the river (Figure 1j), leading to an inland retreat of up to 200 m near the river mouth (Goble and MacKay 2024). Coastal mud belts are similarly impacted when natural cross-realm flows of mud through rivers and estuaries to the sea are disrupted.

A critical, historical intervention that disrupted sediment flows occurred when mobile sand was stabilised with invasive plants. In the mid-1800s, dune sand started blowing onto the ‘hard roads’ in the WC following removal of shrubs and grasses for firewood and thatch. In 1845, a dune stabilisation programme was initiated by the Central Roads Board, and in 1875 it became a function of the Cape Forestry Department (Avis 1992). At the time, stabilising mobile sand was considered best practice, and sand flows through South Africa’s barrier dunes were cut off by planting invasive species (see Figure 1n) and building coastal infrastructure (Avis 1992; McLachlan and Burns 1992; La Cock and Burkinshaw 1996). By 1974, the implications of dune stabilisation began showing as beaches and dunes eroded and the extent of storm damage increased, such that a new position was taken by the Department of Forestry in 1980, that “drift sands were natural areas and should be preserved as such” (Avis 1992). Today, areas upwind of stabilised barrier dunes (or areas where vegetation was cleared for coastal development) experience impacts of wind-blown sand encroaching on inappropriately placed development and infrastructure, and beaches downwind are eroding because their sand supply has been removed, threatening failures of adjacent infrastructure (Lubke and Sugden 1990; La Cock and Burkinshaw 1996). Given the extent of development in the path of the historically mobile dunes, it is largely not an option to rehabilitate these systems back to their natural state. Consequently, all of the large headland-bypass systems (e.g. at Gqeberha and Cape St Francis) and large climbing–falling dune systems (e.g. Hout Bay to Sandy Bay) that were so iconic of the south coast have lost their form and function and are effectively collapsed (extinct) dune types in South Africa, with only remnants remaining.

Estuarine hydrological regime change

Healthy, functioning rivers deliver freshwater, nutrients and sediments through estuaries to the ocean—an essential cross-realm process for maintaining estuaries, beaches and coastal mud belts. However, more than 30% of estuaries in South Africa are impacted by reduced freshwater flow, especially the fluvially dominated and larger permanently open estuaries (e.g. Orange and Groot Berg). Flow modification results from several activities (Figure 1j), chiefly freshwater abstraction, large impoundments and small farm dams. These changes cause compromised salinity regimes, lower water quality and accumulated sediment in estuary mouths, often increasing the risk of coastal flooding. Flow reduction can cause extreme environmental conditions (e.g. the current acidic state of Verlorenvlei estuarine lake in WC:

Lakane et al. 2025), and limits estuarine connectivity with the sea. The latter leads to habitat loss and impacts marine fisheries (e.g. Lamberth et al. 2009) by affecting species lifecycles (e.g. *Argyrosomus japonicus* and eels *Anguilla* spp.), compromising estuarine nursery functions (e.g. sole and prawns), and changing sediment and nutrient transport into the marine environment, impacting beaches and marine mud systems. Activities that increase the freshwater inflow to estuaries include inter-basin transfer schemes, discharge from wastewater treatment works, and stormwater runoff from hardened catchments such as residential areas and road networks. In some estuaries, wastewater and agricultural return flow have become the main freshwater input during the low-flow periods.

Estuarine mouth manipulation includes artificial breaching, stabilisation or canalisation, and creating or diverting an inlet, and is often driven by an increase in closed mouth conditions linked to water resource development. Artificial breaching is the most pervasive of these manipulations and occurs when there is back-flooding of adjacent low-lying developments (Whitfield et al. 2012; van Niekerk et al. 2013). It is often not timed to coincide with natural freshwater inflow events, with a tendency of recent breaching to occur well below recognised breaching levels, resulting in premature closures (van Niekerk et al. 2019b). In these cases, artificial breaching can have potential cascading effects on the physico-chemistry of the estuary and the biological components. These effects include reductions in carrying capacity, changes in the normal timing of species migrations and genetic exchange between estuaries and the adjacent marine environment, and increased risk of invasions by alien species (e.g. Whitfield et al. 2012; van Niekerk et al. 2019b). Estuary mouth manipulation may even change the type of estuary, such as from a temporarily open to a permanently open system.

Livestock grazing and browsing

Although coastal rangelands are generally a biodiversity-compatible land use, under some circumstances they can pose risks to coastal ecosystems. Livestock might access coastal dunes and shores in search of evergreen forage and water, particularly in dry periods in the Indian Ocean Coastal Belt. If not well managed, this can lead to trampling, reduction in dune-stabilising native vegetation cover, and ultimately dune destabilisation. A reduction in dune stability increases the vulnerability of these coastal ecosystems to erosion, blowouts (Hesp 2002) and storm surge, and the replacement of persistently grazed native vegetation with grazing-intolerant or invasive alien species further degrades ecological condition. Livestock can also hamper dune restoration efforts (Mpanza et al. 2009), and cause trampling, sediment compaction and erosion of estuarine banks. Cattle browsing on established white mangrove *Avicennia marina* results in stunted tree growth and forms canopy gaps, and consumption of mangrove propagules decreases tree regeneration, influencing population structure (Hoppe-Speer and Adams 2015; Machite 2023). Overgrazing of salt marshes in estuaries (e.g. Great Berg and Keiskamma) can also cause a reduction in biomass, loss of blue carbon, habitat fragmentation, and in severe cases the development of bare areas that cannot recover owing to changes in the soil structure and salinity.

Human intrusions and disturbance

Coastal disturbances (Figure 1k) include non-extractive human activities in the seashore zone, such as off-road vehicle (ORV) driving, trampling, boating and in-water recreation, which may cause declines in species abundance and diversity, reduced fitness of biota, spatial shifts of species, shifts in community structures, and ecosystem degradation (Schlacher and Thompson 2012; Ryan 2013). This is one of the most widespread pressures in the EDCZ (Harris et al. 2015), with almost half (43%) of South Africa's shores being exposed to disturbance. The most destructive form of coastal disturbance is ORV driving, causing habitat degradation, erosion, dune destabilisation, and lethal and sublethal crushing of beach fauna and shorebird nests (e.g. Schlacher et al. 2007). In South Africa, this pressure has been largely mitigated by a beach-driving ban (RSA 2001). Since its implementation, there has been a significant increase in the abundance, number of breeding pairs and breeding success of several coastal bird species (Williams et al. 2004), indicating the impact that ORV driving was having. It is now strictly regulated, and is restricted to only a few conditions in particular locations (e.g. launch sites).

Biota get crushed and dislodged when trampled by people (Bally and Griffiths 1989; Moffett et al. 1998), and coastal birds are sensitive to human presence (Lewis et al. 2022). Shorebirds get disturbed during breeding (Leseberg et al. 2000) and foraging (Thomas et al. 2003), spending more energy on vigilance and flushing away from approaching people and dogs, which can decrease their fitness and influence habitat selection (Meager et al. 2012). Unleashed dogs also chase birds and pose risks to chicks and eggs (Paijmans 2016). Trampling further causes losses of dune vegetation (Santoro et al. 2012). Dune plants vary in their resistance to trampling and disturbance, with some species reducing in height by 50% after as few as five passes (Avis 1992). In turn, this destabilises the dunes, which can lead to blowouts (Hesp 2002) and increased erosion. The coverage of seagrass beds is similarly reduced by human trampling (Mead et al. 2013). Recreational boat use has direct and indirect impacts on a variety of estuarine and marine species through anchoring or mooring, noise, waves, pollution, propeller strikes and increased turbidity (Demers et al. 2013; Rako et al. 2013; Whitfield and Becker 2014). Boat activity in estuaries can contribute to the extent of bank erosion and cause losses of sensitive intertidal salt marsh and seagrass habitats.

Aquaculture, agriculture and plantation forestry

Aquaculture and mariculture

Mariculture along the South African coast takes the form of aquatic operations using long-lines, rafts, racks or cages suspended directly in the sea in Saldanha Bay and Algoa Bay and in a limited number of estuaries, as well as land-based operations that abstract seawater, pass it through a culture facility, and then return it to the sea. The coastal impacts depend on the species, culture method, stocking density, feed type, husbandry practices and hydrography of the site. Key concerns include: introduction of alien and potentially invasive species to the natural environment (Haupt et al. 2010; Bolton et al. 2016), transfer

of disease and pathogens to local populations, emergence of 'superbugs' when antibiotics are used (Arechavala-Lopez et al. 2013; Cabello et al. 2016), and genetic exchange between farmed and wild populations (Cognetti et al. 2006; Arechavala-Lopez et al. 2013). Mariculture may also change the behaviour of apex predators (Díaz López 2017), and can cause ecosystem impacts from infrastructure construction, pollution and modification of nutrient cycles (Wiber et al. 2012; Gozlan 2017). Commercial marine aquaculture in South Africa is currently relatively limited but has been identified as one of the key growth sectors for the ocean economy (DAFF 2015, 2017).

Agriculture

Agricultural practices (Figure 1l) vary in their impact on coastal biodiversity. Cultivation of croplands requires clearing natural vegetation, thus resulting in a loss of natural habitat. Since 1750, 26% of South Africa's EDCZ has been converted to cropland (calculated by combining the secondary natural class and the cropland class in 1990 and adding the new croplands developed between 1990 and 2022: Skowno et al. 2025). Of all the terrestrial biomes across the country, the Indian Ocean Coastal Belt has had the highest proportion of recent (1990–2022) habitat loss to agriculture. Currently, agriculture is responsible for ~16% of total land-cover change in EFZs (Skowno et al. 2025). In subtropical estuaries, agriculture mainly comprises sugarcane farming, with increasing macadamia nut farming. In warm-temperate estuaries, the floodplains were intensively cultivated in the 1950s to 1970s but then were left fallow. Unsustainable cattle grazing and alien plants are now common in these fallow areas, further degrading the abandoned croplands. In cool-temperate estuaries, floodplains are prone to agricultural development (e.g. grain and fodder, vegetables, fruit orchards, vineyards), and grazing by sheep and cattle. Farmers also often set reeds and wetlands alight in the hope of improving grazing or allowing cattle access to drinking water and the shore. Key concerns about agricultural activities in EFZs are habitat loss and contaminated agricultural runoff polluting aquatic systems and resulting in eutrophication (Lemley et al. 2018) (Figure 1e).

Plantation forestry

Plantation forestry (Figure 1m), especially of nonindigenous *Pinus* and *Eucalyptus* species, have replaced large areas of coastal grassland, fynbos, forest and wetland communities in South Africa, particularly in the Indian Ocean Coastal Belt and the Grassland biome (Jewitt et al. 2015). Altogether, 4.5% of terrestrial habitat in the EDCZ has been lost to plantations (Skowno et al. 2025). In addition to habitat loss, commercial afforestation threatens a host of plants, invertebrates, amphibians, birds and mammals through loss of indigenous vegetation and habitat fragmentation, causing loss of habitat connectivity and migration, and declines in biodiversity (Rebelo et al. 2019). Of significant concern is the impact of plantations on declining coastal groundwater resources, especially near estuaries, rivers and wetlands (Grundling et al. 2013; van Wilgen et al. 2021). Plantations typically mine water at greater depths than most natural species. In water-stressed environments, this can cause

severe impacts on the local water resources and natural vegetation, especially if plantations lower the water table below the rooting depth of the indigenous plants. Shading by the dense canopies in plantations, combined with thick litter layers and soil acidification and aridification, can suppress understory growth and nutrients available to indigenous biota (Rebelo et al. 2019; van Wilgen et al. 2021), further contributing to the long-term degradation of the ecological function and resilience of coastal ecosystems.

Invasive and other problematic species and diseases

Land-based invasions

In coastal areas, many invasive alien plants (IAPs) were introduced deliberately to stabilise sand dunes (Supplementary Table S1), which at the time was considered best practice (McLachlan and Burns 1992). The invasion rate for erosion control and dune stabilisation ($n = 68$ species) ranked second in terms of species that were deliberately introduced, and fourth out of all 44 subcategories of invasion pathways (van Wilgen and Wilson 2018). Consequently, many areas of secondary natural vegetation along the south coast are dominated by alien or invasive species, with Port Jackson willow *Acacia saligna* and rooikrans *Acacia cyclops* (Figure 1n) among the 10-most-abundant invasive plants (van Wilgen and Wilson 2018).

The impacts of IAPs in South Africa are similar to those for plantation forestry, described above. They change natural community structure and ecological processes, often reduce groundwater resources, and outcompete native species causing declines in biodiversity (van Wilgen et al. 2021). IAPs can contribute to wildfires and altered fire regimes, particularly when combined with drought conditions (see 'Climate change and severe weather', below), which can favour fire-adapted species, particularly IAPs, further altering coastal community composition, structure and ecosystem resilience (Kraaij et al. 2018; van Wilgen et al. 2021; Chapungu et al. 2024). IAPs also reduce mean annual runoff, exacerbating effects from climate change. Using estimates from van Wilgen and Wilson (2018) for the four most prevalent species (Supplementary Table S1), namely *A. saligna*, *A. melanoxylon*, *A. cyclops* and *Pinus pinaste*, the estimated reduction in mean annual runoff as a result of IAP species having been deliberately introduced to stabilise dunes is at least 125.86 million m³. Furthermore, invasive trees stabilising dunes (e.g. *Casuarina* spp.) can change the incubation environment for sea turtle eggs (de Vos et al. 2019), and some IAP species are toxic (e.g. *Oleander*, *Lantana*) and their leaf litter can be potentially lethal to fish. Of the 494 threatened species of plants, butterflies, dragonflies and damselflies, spiders, amphibians, birds, reptiles and mammals in South Africa, 176 species (36%) are impacted by 'invasive non-native/alien species/diseases', almost half (45%) of which are threatened plants, and most of the others are threatened butterflies, amphibians and birds (SANBI 2025, unpublished). Notably, the majority of these threatened species are present in the EDCZ.

Aquatic invasions

In contrast to land-based invasions, the introduction of alien species to the estuarine and marine realms in South

Africa has been generally unintentional. There are 119 species that have been introduced as transport stowaways by ship or boat hull fouling (68 species) or by ship or boat ballast water (51 species), and 12 species that have escaped from aquaculture or mariculture facilities (van Wilgen and Wilson 2018). Robinson et al. (2020) report 95 marine alien species from the South African coast, predominantly on the west and south coasts, primarily originating from the North Atlantic. Of these 95 marine alien species, a third are crustaceans and 56 are invasive, with the Mediterranean mussel *Mytilus galloprovincialis*, dwarf mussel *Semimytilus patagonicus* and Pacific acorn barnacle *Balanus glandula* being the most abundant and widespread in South Africa (Robinson et al. 2020). The invasive Asian clam *Corbicula fluminea* has recently established in the Orange River Estuary and is likely to spread to estuaries and catchments throughout the coastal zone (DFFE, unpublished data). Invasive alien aquatic plants (IAAPs) (e.g. common water hyacinth *Pontederia crassipes* and water fern *Azolla filiculoides*) are also increasingly affecting South African estuaries (Adams et al. 2020; Lakane et al. 2024).

Invasive alien species can pose a significant threat, causing both ecological and economic damage. They can impact community structure and functions by modifying spatial and food-web resources, with direct or indirect effects on the occurrence of indigenous species (Robinson et al. 2020; Whitfield et al. 2021). In estuaries, the dense growth of IAAPs reduces light, oxygen and flow, negatively impacting biodiversity, productivity, fish movement and human recreation. Introduced species (e.g. red seaweed *Asparagopsis taxiformis*) can be especially problematic in seagrass habitats, where impacts occur in a relatively short period of time (Williams 2007). Economic impacts include: burrowing activities that can result in damage to banks and dykes (also causing embankment erosion), mass occurrences clogging the water intake filters of industrial cooling-water and drinking-water plants, and alien species preying heavily on native species of commercial importance. Nevertheless, there are occasions when invasive alien species can benefit selected species (e.g. increased chick survival in African black oystercatchers *Haematopus moquini* feeding on invasive Mediterranean mussels: Loewenthal et al. 2016).

Harmful algal blooms, pathogens and disease

Harmful algal blooms (HABs) are increasingly impacting the ecological integrity of South African estuaries and coastal waters. The upward trajectory of HAB frequency and magnitude is strongly linked to anthropogenic nutrient loading, which predominantly stems from municipal wastewater, urban stormwater and agricultural sources (Adams et al. 2020). The microtidal and low-inflow nature of South African estuaries increases their susceptibility to HAB accumulations, with blooms being recorded in 18% of South African estuaries, primarily in the warm-temperate coastal region. In addition to human health risks, some of the most common HAB impacts in estuarine and coastal waters include hypoxia, reduced biodiversity, altered food webs and feeding behaviour of mugilid fishes, and mass faunal mortalities (Bornman et al. 2021, 2023; Nodo et al. 2023).

Mass mortalities from HABs can have significant effects on populations, including aquaculture operations (Pitcher et al. 2019), with a population of *Donax serra* taking 14 years to recover after a mass mortality event (de Villiers 1979). Examples of HAB species documented in South African estuaries include *Heterocapsa rotundata*, *Heterosigma akashiwo* and *Prymnesium parvum* (Lemley et al. 2019b, 2023; Bornman et al. 2021), *Lingulodinium polyedra*, *Mesodinium rubrum* and *Dinophysis acuminata* recorded in the country's coastal waters (Pitcher and Louw 2021; Lemley et al. 2024).

Several other pathogens and diseases can affect coastal animals. For example, high pathogenicity avian influenza (HPAI) was detected in coastal seabirds in South Africa in 2017 following an outbreak in the commercial poultry and ostrich industry (Roberts et al. 2023). This disease was recorded in 15 species of coastal seabirds, including already threatened species, with a second outbreak in 2021, and sporadic cases continuing in 2023 (Roberts et al. 2023; Abolnik et al. 2024). The pathogenic water mould *Aphanomyces invadans* causes epizootic ulcerative syndrome in fish and was first reported in South Africa in 2011 (Huchzermeyer and van der Waal 2012), and is now found in almost all South African estuaries. More recently, rabies has been verified in seals (Roberts et al. 2023) throughout their South African and Namibian range. Incidents of rabies and other pathogens (e.g. the microscopic parasite *Toxoplasma gondii*) are often associated with high-density human settlements, pets and livestock.

Climate change, severe weather and ocean acidification

Sea-level rise and coastal squeeze

Sea-level rise occurs from above-ground ice melting due to increasing temperatures and thermal expansion of the world's oceans, and is accelerating (Chen et al. 2017; Nerem et al. 2018). Current rates of sea-level rise along the southern African coastline are 2.74 mm y⁻¹ in the Indian Ocean, and 1.87 mm y⁻¹ in the South Atlantic Ocean (Mather et al. 2009). In response, shores would normally realign inland *sensu* Bruun's rule (Bruun 1962). However, when constrained by coastal development, shores get trapped in a 'coastal squeeze', whereby they are narrowed, inundated and lost (Pilkey and Cooper 2014; Defeo and Elliott 2021). Coastal squeeze is one of the main drivers of beach species' extinction risk (Harris et al. 2025c), which is concerning given their high rates of endemism (Harris et al. 2014). Supralittoral habitat loss reduces prey availability for top predators (e.g. shorebirds: Dugan et al. 2008) and reduces habitat for focal species to complete life-history stages, such as nesting (Fish et al. 2008; Clausen and Clausen 2014). Recreational opportunities during high tides are also lost, with associated socio-economic losses from declining beach tourism.

For estuaries, sea-level rise may increase saline penetration and alter the mouth state, changing estuarine ecology (van Niekerk et al. 2022a). Mangroves and salt marsh habitats may not be able to keep pace with rising seas, or mangroves may outcompete salt marshes. These changes have knock-on effects through the estuarine system, affecting nursery functions and likely

increasing turbidity, the latter altering primary productivity and community structure (van Niekerk et al. 2022a). Implementing buffer areas for salt marshes and mangroves to expand into in response to sea-level rise is essential for ensuring landward migration and habitat persistence, which may require purchasing privately owned land (Raw et al. 2020; Adams et al. 2025).

Storminess, rainfall, runoff and coastal flooding

Climate predictions for South Africa include altered rainfall patterns and increasing extreme events such as droughts, storms and floods (Engelbrecht and Monteiro 2021). The east coast of South Africa is projected to get wetter, despite an overall drying trend for southern Africa, particularly through more frequent extreme rainfall in summer and spring (Davis-Reddy and Vincent 2017; Engelbrecht and Monteiro 2021), with evidence that climate change played a key role in recent flooding in KZN (Engelbrecht et al. 2025). Conversely, the already arid west coast is expected to get even drier (Engelbrecht and Monteiro 2021). Recent droughts attributed to climate change on the west coast have already been a significant driver of increased risk of extinction of South Africa's endemic plants (Skowno et al. 2025), with further implications of drought for both water and food security in the country (Engelbrecht and Monteiro 2021).

The number of climate change-related storm events has increased in South Africa since 1980, with this trend expected to continue (Davis-Reddy and Vincent 2017). During storms, massive amounts of sand can be eroded offshore by heightened wave action (Smith et al. 2007b) or blown inland through wave spray (Cooper and Jackson 1999), with erosion exacerbated by development and seawalls (Lucrezi et al. 2010; Harris et al. 2011c). Post-storm erosion can persist as equilibrium profiles re-establish (*sensu* Bruun [1962]), causing inland retreat (Smith et al. 2010). Beach macrofauna are generally able to withstand storms (Harris et al. 2011b), unless the shoreline is completely eroded down to bedrock. Storms also reduce nesting and hatching success of shorebirds and turtles (Van Houtan and Bass 2007; van de Pol et al. 2010), and impact rocky shores, reefs and kelp forests by dislodging biota, causing shifts in communities and decreasing diversity and community complexity (Walker et al. 2008; Byrnes et al. 2011; Abesamis et al. 2018).

Storms can also impact estuaries, with resulting mouth closures causing flooding and mangrove loss (Adams and Rajkaran 2020), and breaching can change estuarine habitats, community composition and ecosystem functioning (Riddin and Adams 2010). Changing precipitation patterns alters the magnitude and timing of runoff into rivers, estuaries and the coast, ultimately driving changes in estuarine connectivity and salinity regimes, and shifts in nutrient and sediment supply through estuaries to the coast. Human adaptation strategies to reduce risk, including river impoundment and land-use change, will increase the rate of change in primary inputs (flow, sediment and nutrients) to estuaries and coastal waters, exacerbating impacts. Recovery of estuarine communities to pre-flood conditions is usually fairly rapid, but consecutive flood events increase recovery time, and when floods and droughts result in

prolonged loss of available habitat (habitat squeeze), this can drive species declines (van Niekerk et al. 2022a).

Temperature change

Land-based air temperature increases over subtropical southern Africa have been more than twice the average global increase (Engelbrecht et al. 2015; Engelbrecht and Monteiro 2021), with an average warming of 0.4 °C per decade (Davis-Reddy and Vincent 2017). Estuaries are warming even faster, by as much as 0.6 °C per decade in temperate regions (Prum et al. 2024). Sea surface temperature trends are mixed: the east coast of South Africa is warming at a rate of 0.5 °C per decade (Rouault et al. 2009), with localised cooling along the west and south coasts (Lima and Wethey 2012; Potts et al. 2015) reflecting increased upwelling from intensified southeasterly and easterly winds (Rouault et al. 2010; Duncan et al. 2019). Temperatures along the warm-temperate coast are thus predicted to become increasingly variable.

Species are shifting their distributions in response to these temperature changes (e.g. Cockcroft et al. 2008; Bolton et al. 2012), potentially creating new biological interactions with established species for the same resources (Steinke 1999; Hoppe-Speer et al. 2015). Pioneer species may trigger ecological successions (Whitfield et al. 2016); for example, shifts in the distribution of marine prey species have induced shifts in their predator distributions (Crawford et al. 2008; Crawford et al. 2009). Many of South Africa's coastal endemics are found along the south coast (Harris et al. 2025b) and may experience a temperature squeeze from both the east and west (Whitfield et al. 2016). Tropical and subtropical estuarine vegetation (e.g. mangroves) is expected to move southwards into warm-temperate habitats (e.g. salt marshes) (Steinke 1999; Hoppe-Speer et al. 2015), although dispersal and coastal geomorphology may constrain mangrove range expansion (Raw et al. 2023). On land, warming and increased berg winds increase the likelihood and spread of fires, impacting vegetation, changing phenology and promoting a spread of invasives (Chapungu et al. 2024). Higher temperatures can also dry up waterholes and alter the reproductive behaviours of wildlife (Chapungu et al. 2024), with altered rainfall patterns compounding the impacts to terrestrial species.

Extreme temperatures may increasingly cause significant impacts on biota. Southern Africa already has more heatwave days annually than the rest of Africa (Engelbrecht et al. 2015). Although heatwaves are expected to increase along the South African coast, the duration is predicted to be lower than heatwaves in the interior, with the northwestern part of the country expected to be most impacted (Mbokodo et al. 2020). On land, heatwaves can cause mortality of native plants and favour alien species (French et al. 2017), and in the sea, marine heat waves (MHWs) can cause coral bleaching (Figure 1o) and subsequent mortality of sensitive species (Porter et al. 2021). Along South Africa's warm-temperate coast, both MHWs and upwelling are increasing in intensity and frequency (Schlegel et al. 2017; Duncan et al. 2019). When MHWs are followed by upwelling events, the resulting thermal shock can result in extensive fish and invertebrate washouts and kills along the coastline (van der Walt et al. 2021; Lubitz et al. 2024).

Ocean acidification

Eastern boundary upwelling systems, like the Benguela Current, are more susceptible to impacts from ocean acidification owing to their naturally lower pH and carbonate saturation state compared with other regions because the upwelled water is rich in carbon dioxide from the remineralisation of organic matter (Gruber et al. 2012). The ocean pH levels around South Africa are variable in space and time, sometimes seasonally, but average 8.1 units in the southern Benguela (Gregor 2012) and in Algoa Bay (Edworthy et al. 2022), and 8.3 units in St Helena Bay (Pitcher et al. 2023). Interestingly, macroalgal habitats have higher pH levels than their surrounding environment, and may serve as ocean acidification refugia for coastal species (Edworthy et al. 2022, 2023). Ocean acidification will ultimately have significant impacts on biotic communities; however, natural variability in estuarine and coastal pH levels should be considered when predicting the impacts of ocean acidification. For example, natural fluctuations in pH may play a role in developing resilience in biotic assemblages (van Niekerk et al. 2022a); conversely, it may combine with the effects of coastal acidification to produce even more extreme events, resulting in even greater impacts on biota (Hofmann et al. 2011; van Niekerk et al. 2022a).

Synthesis and conclusions

We noted in the Introduction that coasts globally are sites where pressures accumulate, with disproportionately higher levels of impacts and degradation. This holds true in South Africa. The EDCZ proportionately contains about five-times more mining, three-times more development and plantations, 50% more agriculture, and twice the overall habitat loss and rate of natural habitat loss (0.2% versus 0.1% per annum) when compared with the rest of

the country's landmass (DFFE 2024; Skowno et al. 2025) (Figure 2). Consequently, there is proportionately more ecological degradation and, in turn, a higher proportion of threatened ecosystem types in the EDCZ than in non-coastal areas in South Africa (Harris et al. 2022). Broadly speaking, biological resource use, mining, natural systems modifications, and residential and commercial development are the most severe pressures on coastal biodiversity in South Africa (Figure 3).

Importantly, the pressures discussed in this review have clear cross-realm and cumulative impacts on coastal biodiversity. Flow modification, for example, is a critical cross-realm pressure that severely affects estuaries and downstream beaches, dunes and river-influenced marine ecosystem types (Figure 3). Similarly, coastal infrastructure has cross-realm impacts on terrestrial, estuarine and marine ecosystems, causing habitat fragmentation and loss, and blocking cross-realm ecological processes and animal movements between realms. When these kinds of coastal pressures interact, they create synergistic impacts, with climate change often acting as a multiplier. For example, freshwater flow reduction, coastal development, coastal mining and IAPs that have stabilised large mobile dune systems have all reduced the sand supply to beaches, with dune trampling and increasing storminess and sea-level rise further amplifying erosion of sand off the shore. Likewise, the combination of IAPs impacting groundwater, reduced freshwater flow, increased pollution and subsequent eutrophication and HABs are having substantial impacts on South Africa's estuaries, exacerbated by increasing droughts and floods and changes in precipitation and runoff. Ports and harbours also play a key role in cumulative coastal pressures. They cause direct habitat loss and habitat modification in adjacent areas (e.g. building breakwaters and modifying natural sand movement along the shore), provide access points for

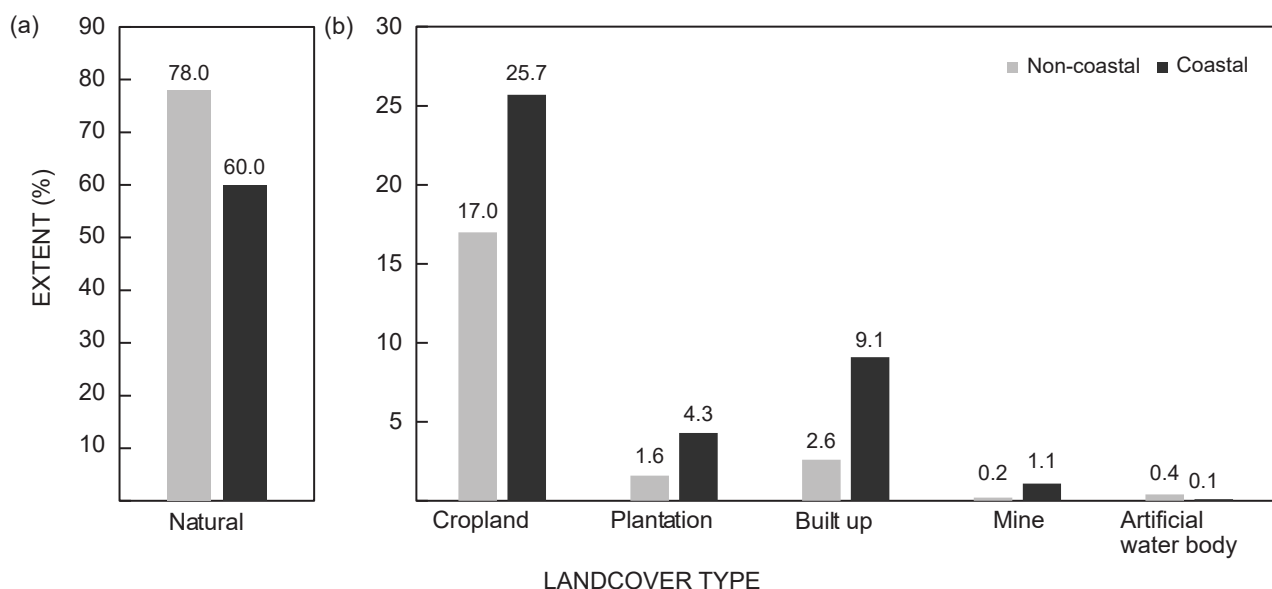


Figure 2: Comparison of the extent (%) of coastal and non-coastal land (in 2022) in various landcover categories: (a) natural areas; (b) modified areas. Data values are presented above the bars

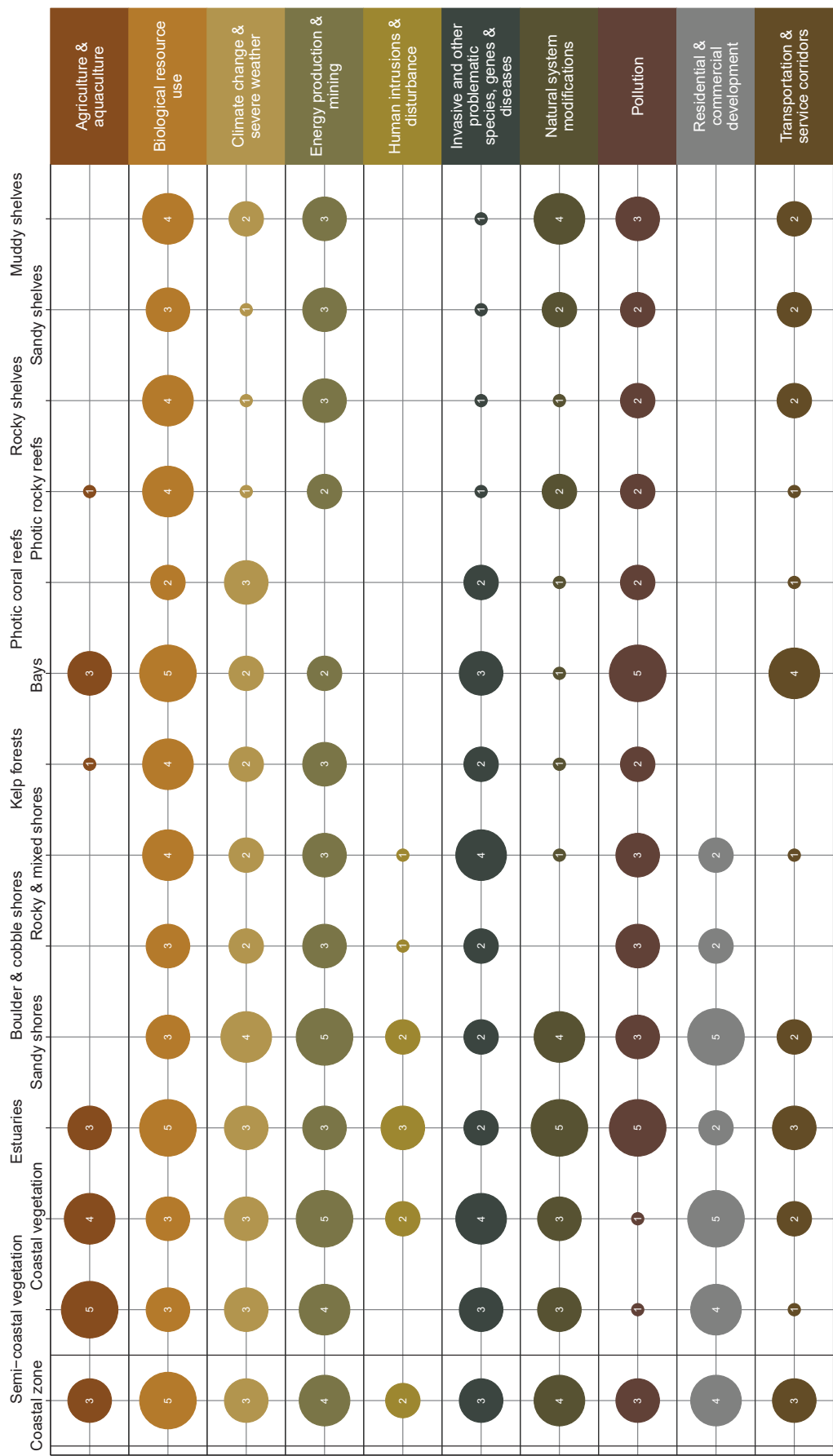


Figure 3: Synthesis of the severity of pressures on the coastal zone (overall, first column) and on the broad ecosystem groups comprising the coast, largely from inland to offshore (arranged from left to right). Increasing bubble size and corresponding scores (1–5) represent increasing pressure severity in a relative, comparative ranking that accounts for both the intensity and extent of each pressure in South African coastal systems. Blank cells indicate where a pressure does not occur in a given ecosystem group

exploiting marine resources, and provide nodes from which urban development burgeons, leading to intensification of many other pressures. The corollary of the interconnected and synergistic nature of cumulative coastal pressures is that robust integrated coastal management provides good opportunities to address multiple pressures and impacts cross-realm (Figure 3).

South Africa's coastal zone is rich in ecosystem and species diversity (Harris et al. 2025b), and provides many important benefits to people (Harris et al. 2021). Recognising the immense biodiversity, social and economic value of the South African coastal zone, the number of activities taking place therein, the high demand for space and resources, and pending climate change impacts, careful planning and management of the biodiversity assets in this zone are essential (Harris et al. 2025a). Even with best-effort mitigation, it is more likely than not that the global climate will exceed thresholds for 'dangerous climate change', rendering some significant impacts as unavoidable and irreversible (Engelbrecht and Monteiro 2021). While it is crucial to invest in immediate and effective climate mitigation to curb the worst of these impacts to biodiversity and society (Engelbrecht and Monteiro 2021), it is imperative to minimise local pressures and impacts to ensure that South Africa's coastal biodiversity is as healthy and resilient as possible in the face of global change. Sensible and sustainable coastal management is more important now than ever before. Constructing new development behind scientifically determined setback lines, restoring the condition of degraded coastal ecosystems and ecological infrastructure, ensuring sustainable resource use, and rebuilding stocks of overexploited species are all high priorities. It is also essential that coastal planning and management are undertaken in a way that maintains the myriad of biotic and abiotic cross-realm connections that support South Africa's rich coastal biodiversity and underpin delivery of the many benefits provided by the coast (Harris et al. 2025a). These benefits include, *inter alia*, jobs, food security, enhanced health and wellbeing, and a rich natural heritage as a legacy for future generations.

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