



Conserving cross-realm coastal biodiversity when real-world planning and implementation processes split the land and sea

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ABSTRACT

Conservation planning and implementation are typically applied in land and sea areas separately, placing already impacted coastal biodiversity – which spans the divide – at risk of being inadequately managed and conserved. In South Africa, we tested how well existing land-based and marine biodiversity priority areas cover coastal priorities that we identified cross-realm using Marxan with >1000 biodiversity features. Existing priorities covered 83% of coastal priorities, indicating good but incomplete coverage. Proportionately, the seashore (foredunes, shores) and estuaries had greatest selection as coastal priorities, confirming their important biodiversity value. Finally, we developed a map of Critical Biodiversity Areas for the South African seashore and estuaries, with management recommendations. To include coastal biodiversity in real-world planning, we propose: co-developing data and targets for cross-realm features; identifying broad coastal priorities that can be used in land-based and marine plans; and developing dedicated seashore and estuary priorities to seamlessly align land-based and marine prioritisation maps.

1. Introduction

Conserving a sufficient, representative portion of biodiversity patterns and ecological processes for a more sustainable world is an urgent global priority (Georgian et al., 2022; Leadley et al., 2022; Ripple et al., 2017), especially in the context of the Kunming-Montreal Global Biodiversity Framework (GBF) that requires 30% of all areas to be effectively conserved and managed by 2030 (CBD, 2022). Recognising the myriad of land and sea uses other than conservation, systematic conservation planning (SCP) is a widely used tool to design biodiversity

priority areas in a spatially efficient manner that minimizes conflict with other sectors (Ball et al., 2009), often to achieve multiple goals (Brown et al., 2015). Given that generally different legislation, management authorities, and governance processes operate on land and in the sea, planning tends to be done separately for these two environments. Although this is a completely valid approach for most biodiversity patterns and ecological processes, it is a poor approach for the coastal zone that has so many cross-realm connections (Beger et al., 2010a).

Connections through the coastal zone are both biotic and abiotic. For example, some species' distributions span both land and sea, e.g., certain

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plant seeds are dispersed along their coastal range via ocean currents (Nathan et al., 2008); some terrestrial invertebrates move onto the beach to forage (Colombini et al., 1998); shorebirds and seabirds nest on land and forage on the shore or at sea (Monk et al., 2020); turtles live in the sea but nest on beaches and dunes (Wallace et al., 2010); and many invertebrates, fish, and markedly catadromous eels migrate between the sea and estuaries, and in some cases, into freshwater rivers as well, sometimes all the way to the source (Arai, 2022; Hermoso et al., 2021). Further, there are ecological processes that operate across the land-sea interface, such as: flows of freshwater and sediment from rivers, through estuaries into the sea (Fang et al., 2018; Sheaves, 2009); wind-blown and wave-driven sand that moves on- and offshore (Cohn et al., 2018; McLachlan and Defeo, 2018); salt spray that drifts onto land (Du and Hesp, 2020); and exchanges of nutrients across the shore (Le Gouvello et al., 2017). Therefore, the danger of planning separately for the land and sea is inappropriately accounting for the cross-realm requirements of coastal biodiversity, placing an already vulnerable, intensively used, and highly threatened zone (Harris et al., 2022c) at even further risk, especially in the face of accelerating global change (Defeo and Elliott, 2021).

Consequently, there is a need for robust guidance on how to do meaningful land-sea integration in SCP in the real world to ensure that coastal biodiversity patterns and processes are properly managed and conserved. There are only a few examples of integrated land-sea planning in the literature, primarily considering land-sea processes only through catchments, but that nonetheless lay important foundations in this field. For example, studies have shown the benefit of including connectivity between forests and coral reefs in SCP, and how forest conservation can benefit reef condition through reduced sedimentation and pollution, and thus improve return on investment in reef conservation (Klein et al., 2012; Makino et al., 2013). Others have shown that spatial priorities through catchments are different when planning for conservation objectives in separate realms (Álvarez-Romero et al., 2016; Tsang et al., 2019; Tulloch et al., 2021), illustrating how improvements in marine water quality require upstream models of estuarine plumes and land-use change (Álvarez-Romero et al., 2016), and demonstrating the importance of including connectivity through rivers in land-sea planning (Tsang et al., 2019; Tulloch et al., 2021). Another example considered planning for amphibians, reptiles and fish through river, estuary and marine ecosystems, focussing on improving cross-realm connectivity for species that use more than one realm to complete their lifecycle (Hermoso et al., 2021). All these studies have a specific focus, and thus are often conducted in a small area, and – understandably – consider only the coastal ecosystems or species relevant to the conservation or management issue being addressed. In our study, we consider coastal biodiversity conservation and sustainable management in a broader sense, taking a more comprehensive view of the coast by including terrestrial, freshwater, estuarine and marine ecosystems, species, ecological processes, and culturally important sites. We also work across the whole coastal zone rather than just through catchments, at a national rather than local scale, and in an applied, real-world context, with its concomitant constraints of existing spatial planning and implementation processes, which are not always considered in theoretical, academic studies.

We explore these concepts using South Africa as a model country. South Africa has a rich coastal biodiversity, with high levels of endemism (Bradshaw et al., 2015; Griffiths and Robinson, 2016; Harris et al., 2014a). However, the coastal zone is more intensively used, in poorer ecological condition, and is more threatened than the non-coastal land and sea in the country, highlighting the critical need to plan carefully for coastal biodiversity (Harris et al. 2021, 2022c). We aim first to test how well existing land-based and marine priority areas for conserving and sustainably managing biodiversity (developed in separate planning processes, hereafter called ‘existing priorities’) cover a portfolio of coastal biodiversity priority areas (developed here in an integrated, cross-realm process); and second, to propose an approach by which

coastal biodiversity can be properly included in applied SCP. Specifically, we: (1) identify a portfolio of coastal biodiversity priority areas in a cross-realm planning domain that meets all feature targets (hereafter called ‘coastal priorities’), (2) quantify the overlap between these coastal priorities and the existing priorities, (3) develop a Map of Critical Biodiversity Areas and Ecological Support Areas (CBA Map) for the seashore and estuaries that can serve as the seam between land-based and marine CBA Maps, and (4) develop a set of management recommendations for the CBA Map categories that can inform the respective land-use and sea-use guidelines in support of integrated coastal zone management. Finally, (5) we reflect on our experience of this process, propose recommendations for practitioners around the world who are undertaking cross-realm coastal biodiversity planning, and identify priorities to further advance this work through iterative improvement.

2. Methods

2.1. Study area, planning domain and planning units

The study area is the South African coastal zone (Fig. 1). We refer to this as a cross-realm zone because it includes coastal portions of the terrestrial, freshwater, estuarine and marine realms (Fig. A1). Biodiversity is rich in this region, and rates of endemism are particularly high (Bradshaw et al., 2015; Griffiths and Robinson, 2016; Harris et al., 2014a) because of the contrasting influence of the warm Agulhas Current (Indian Ocean) down the east coast and the cool Benguela Current (Atlantic Ocean) up the west coast. However, anthropogenic pressures are also substantial, with higher rates of natural habitat loss in coastal vegetation types than non-coastal vegetation types (Harris et al., 2022c), and climate-related pressures like sea-level rise (Mather et al., 2009) and storms (Smith et al., 2010) causing additional impacts. In South Africa, the biodiversity sector’s primary input to multi-sectoral planning processes is through spatial biodiversity plans (Botts et al., 2019). These plans comprise: a map of biodiversity priorities developed using SCP that includes Protected Areas, Critical Biodiversity Areas (CBAs) and Ecological Support Areas (ESAs), called a CBA Map; and a set of use guidelines that indicate the compatibility of various activities with the management objective of the CBA Map categories that guide which activities should or should not be permitted in different areas (SANBI, 2017). There is demonstrated success of this approach in avoiding biodiversity loss, with sites identified as CBAs having significant reductions in land clearing compared with that in equivalent natural areas, and providing similar levels of avoided biodiversity loss as protected areas provide in other countries (Von Staden et al., 2022). Land-based plans (including terrestrial, freshwater and estuarine biodiversity) are usually developed at a provincial scale (Pool-Stanvliet et al., 2017), with some finer-scale plans for districts and metropolitans (Stewart and Reeves, 2014), whereas marine plans are largely developed at a national scale (National Coastal and Marine Spatial Biodiversity Plan, NCMSBP; Harris et al., 2022a; Harris et al., 2022b). Where useful, CBA Maps can be aggregated for the whole country and presented as a single map (Skowno et al., 2019a). There is some effort to align coastal terrestrial and coastal marine priority areas by ‘edge matching’, i.e., using biodiversity priority areas at the edges of terrestrial and marine maps to seed contiguous priorities into the adjacent marine and terrestrial areas, respectively (e.g., Harris et al., 2022b). However, there is currently no explicit consideration of land-sea biodiversity patterns and ecological processes, further challenged by the fact that the CBA Maps for the land and sea are created at different spatial scales.

Running a systematic conservation plan requires a spatially explicit area (planning domain) within which sites can be prioritised for conservation, divided into pixels (planning units) that can each be selected as priorities or not. Our planning domain, comprising a coastal study area surrounded by a 2-km buffer (Fig. 1), was delineated as follows (with additional details given in Appendix A). Quinary catchments – hydrological units that are hierarchically nested as a fifth division,

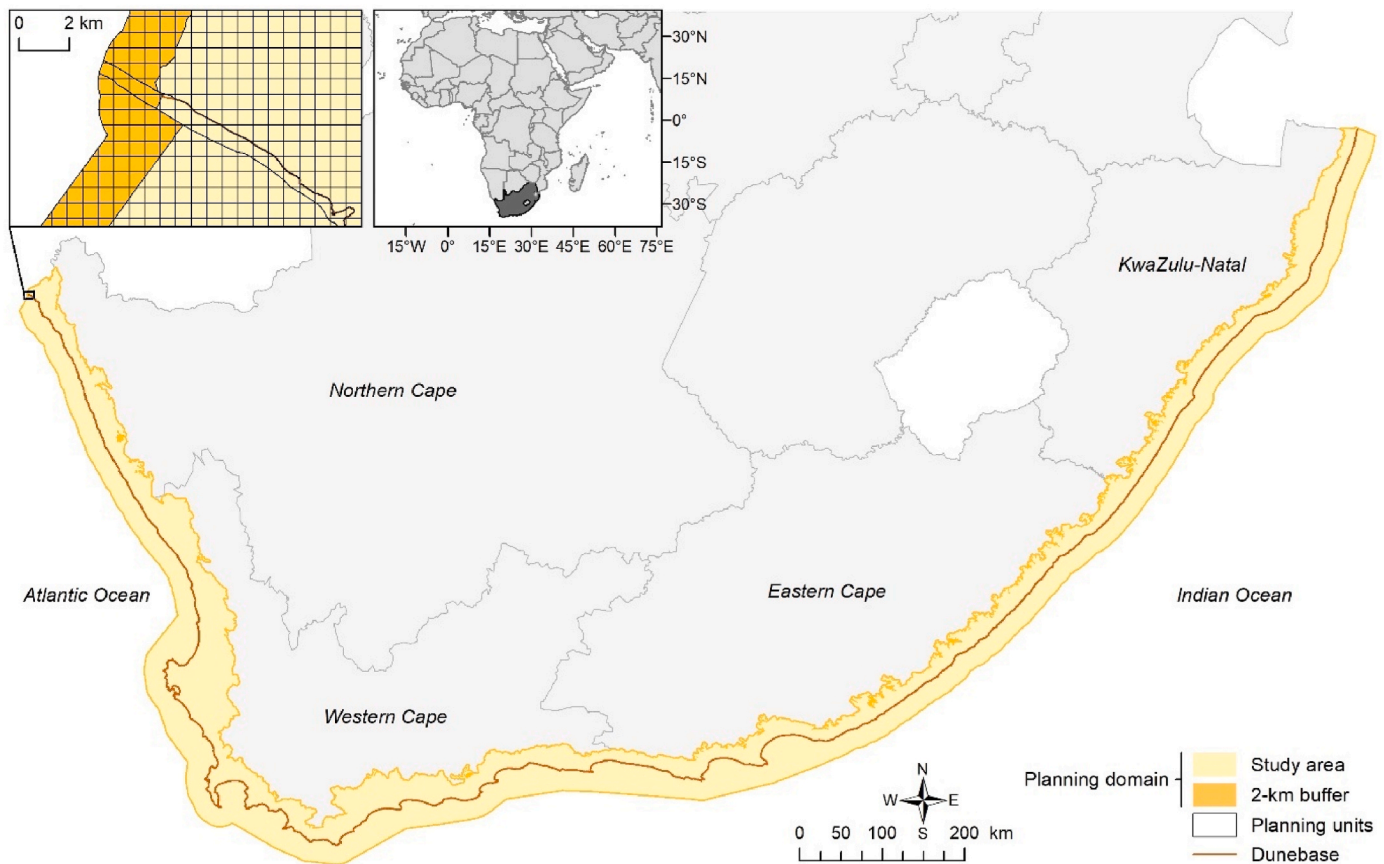


Fig. 1. The study area in South Africa, comprising coastal quinary catchments (Schulze and Horan, 2010; Schulze et al., 2010) and the territorial sea (Flanders Marine Institute, 2018). The planning domain is the study area plus a 2-km buffer. Coastal priorities were identified only in the study area; the 2-km buffer area served only to guide edge-matching and alignment. The inset (top left) shows the 20' planning units along the northern margin of the planning domain, with the shore extent (dunebase to the back of the surf zone, sensu Harris et al., 2019) forming part of the delineation of the planning units. See also Fig. A1.

aligning into quaternary, tertiary, secondary and primary catchments, and with an average catchment size of 165 km² (Schulze and Horan, 2010; Schulze et al., 2010) – were used as the basis of the landward extent. All quinary catchments within 10 km of the shore (Fig. A1), or that intersected the Estuarine Functional Zones (EFZs, Fig. A1) were included, with some adjustments to align with the catchment maps in the Western Cape. The threshold of 10 km aligned with previous thresholds for identifying coastal areas in South Africa (Harris et al., 2019) and, together with the scale of the catchments, identified an inland extent that was similar in size to that for the marine environment. We also wanted to ensure that the full extent of the river-estuary transition zones (Van Deventer et al., 2020) was included in the study area. This was generally the case, however, there were some instances where the river-estuary transition zones extended slightly beyond the coastal area that was defined by the quinary catchments. These river-estuary transition zones were buffered by 500 m and the buffer area was integrated into the inland extent of the study area. The seaward extent was defined by the 12 NM territorial sea (Flanders Marine Institute, 2018). Finally, to provide a zone within which existing biodiversity priorities could be locked in to facilitate edge-matching with existing biodiversity priority areas, a 2-km buffer was applied around the whole study area. The planning domain was divided into a grid of 20' planning units, with the boundaries of the shore (dunebase to the back of the surf zone; Harris et al., 2019) intersected into the planning units to form part of their delineation (Fig. 1).

2.2. Planning goal and objectives

All systematic conservation plans should have a clear planning goal and set of objectives (Margules and Pressey, 2000). In this case, the overall planning goal is to provide the best available science to support coastal conservation and sustainable development in South Africa, for the benefit of current and future generations. The key objectives are to: (1) provide a robust, systematic cross-realm spatial prioritisation for conserving and sustainably managing coastal biodiversity that follows international best practice in SCP; (2) adequately represent coastal biodiversity patterns and ecological processes (Section 2.3) in a design that is spatially efficient and well connected across the land-sea interface (including estuaries); (3) avoid spatial overlap (conflict) with other sectors where possible (Section 2.4), but still meet targets for all coastal biodiversity features (Section 2.3); (4) contribute to the biodiversity sector's input to land-use planning, integrated coastal zone management, estuary management, and the emerging marine spatial planning process (Section 2.6); and (5) provide a robust starting point to support other area-based processes, such as coastal protected area expansion, including land-based and marine protected areas and other effective area-based conservation measures (OECMs). These objectives, in turn, can help support the country in making progress in the GBF goals and targets (see Section 4.1).

2.3. Biodiversity features, design elements, and targets

The next step in SCP is to compile a set of biodiversity data and to assign the different features (e.g., ecosystem types, species distributions)

Table 1

Lists of the feature groups and number of features per group (n) for the two data classes: biodiversity features, and design elements that were included in the analysis (see Table A1 for details).

Feature group	n
Biodiversity features	1087
•Ecosystem types	314
•Species	704
•Unique or special habitats or features	23
•Ecological processes	26
•Ecological infrastructure	2
•Existing priority areas	18
Design elements	26
•Edge-matching and aligning priority areas	11
•Culturally important areas	5
•Estuary clusters	10
TOTAL	1113

to the planning units in which they are located. Biodiversity targets are then set, which are a user-defined amount of each feature that is required to be included in the final portfolio of sites that are selected as priorities, e.g., 30% of a feature's distribution (see below for details). Following Harris et al. (2022b) and Harris and Holness (2023), we divided the biodiversity data into two classes: biodiversity features and design elements (Table 1), where the difference between the classes is that the targets for biodiversity features are required to be met in

protected areas and CBAs, whereas the targets for design elements do not need to be met in these areas. The purpose of the design elements is rather to preferentially select sites in particular, strategic places (e.g., aligning with emerging conservation initiatives) where there is otherwise equal choice. Altogether, 1113 biodiversity features and design elements were included in the analyses (Table 1; see Table A1 for the full list of data and sources, and Fig. 2 for example maps of the features that were included).

Where targets already existed for certain features (e.g., vegetation types, Desmet and Cowling, 2004), those targets were used as given. For the remaining features, biodiversity targets were compiled by systematically applying the set of heuristic rules used in the NCMSBP (Harris et al. 2022a, 2022b) because, as demonstrated by Harris and Holness (2023), they provide a robust way to set targets in the absence of the information required to use data-intensive methods, e.g., species-area curves. The heuristic rules set out baseline targets for each feature type (e.g., ecosystem types), with additional rules for increasing or decreasing the baseline target (e.g., increase the target for ecosystem types with disproportionately high biodiversity), where the target amounts for each rule are derived from the literature. These heuristic rules were applied to all features that did not already have assigned biodiversity targets. See Table A2 for a full list of targets.

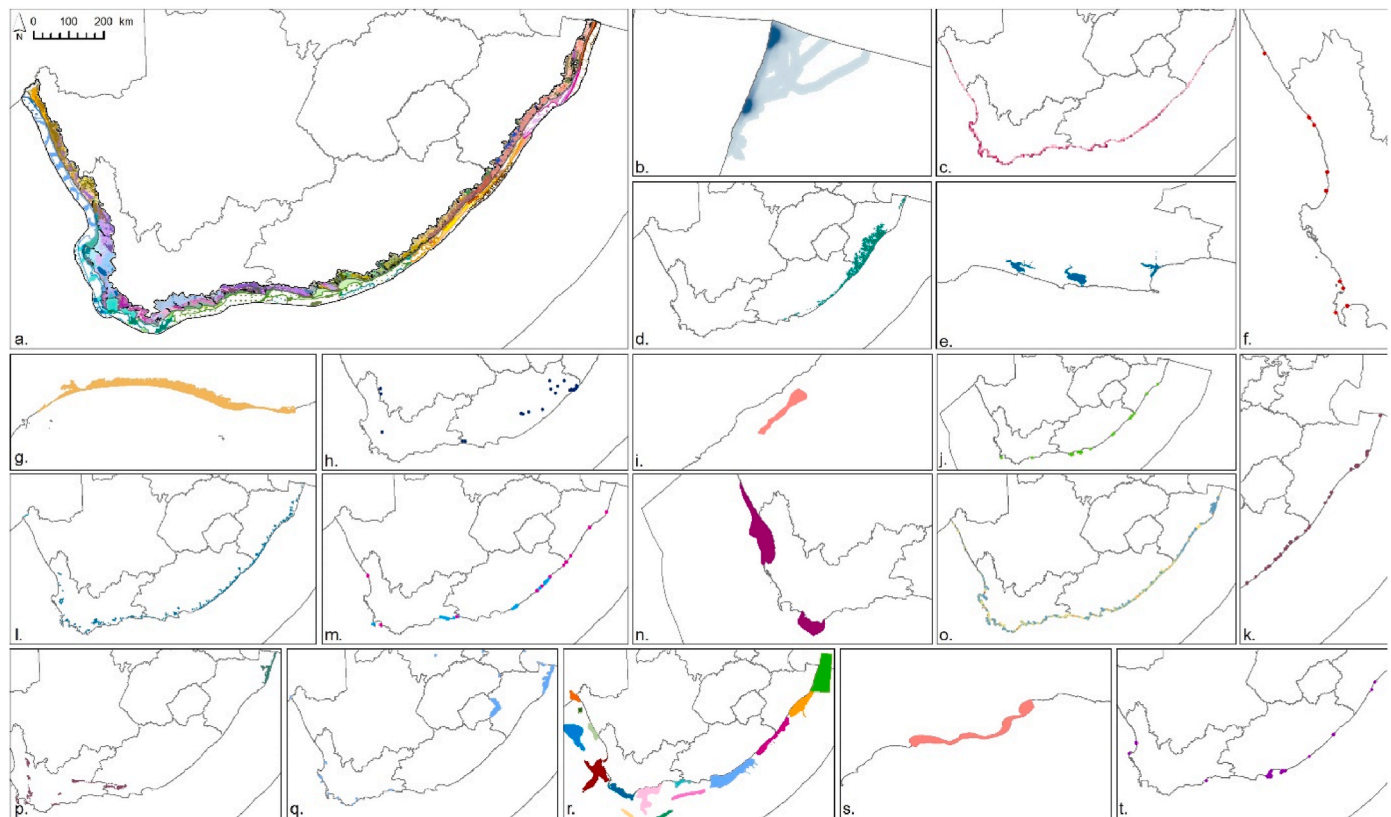


Fig. 2. Illustrative examples of biodiversity data included in the coastal prioritisation. Biodiversity features included (a) ecosystem types; distributions of species, such as (b) turtles, e.g., Near Threatened loggerhead (*Caretta caretta*) internesting areas, (c) shorebirds, e.g., endemic, Vulnerable African Black Oystercatchers, (d) threatened plants, e.g., Wood's Dispersis, *Dispersis woodii*, (e) freshwater and estuarine fish, e.g., Knysna seahorse, *Hippocampus capensis*, and (f) seashore invertebrates, e.g., Cape Beach Darkling Beetle, *Pachyphaleria capensis*; unique, rare or special habitats or features, including (g) the Alexandria dunefield, (h) waterfalls, (i) rhodolith beds, (j) stromatolites, and (k) mangroves; ecological processes, such as (l) river-estuary transition zones, (m) estuaries of flagship and non-flagship free-flowing rivers, (n) fish spawning and nursery grounds, e.g., snoek nurseries; (o) ecosystem services, e.g., ecological infrastructure providing coastal protection; and existing priorities, such as (p) World Heritage Sites inscribed for natural criteria, (q) Ramsar sites, and (r) Ecologically or Biologically Significant Marine Areas (EBSAs). Design elements included, among others, (s) edge-matching and alignment, e.g., Gouritz coastal corridor, and (t) culturally important sites. See Table A1 for data sources. Colours represent different features, and in panel b, darker shades indicate areas of higher use by turtles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Definitions of and criteria for identifying and delineating the CBA Map categories for the seashore and estuaries. EFZ = Estuarine Functional Zone.

CBA Map category	Definition	Criteria for delineation
Protected Area	Area recognised as protected under South Africa's Protected Areas Act	<ul style="list-style-type: none"> •All existing protected areas
Critical Biodiversity Area 1 (CBA 1)	Areas that are irreplaceable to near irreplaceable for meeting biodiversity feature targets	<ul style="list-style-type: none"> •Planning units with 100% selection frequency that are not already a protected area
Critical Biodiversity Area 2 (CBA 2)	Areas considered to be best design/optimal sites for meeting biodiversity targets	<ul style="list-style-type: none"> •Planning units with 30–99% selection frequency
Ecological Support Area (ESA)	An area that must be maintained in a natural or semi-natural state to support ecological functioning in a protected area or CBA	<ul style="list-style-type: none"> •All remaining natural and semi-natural portions of estuaries •All remaining natural and semi-natural portions of the seashore
Other Natural Areas (ONA)	Areas that are not protected areas, CBAs or ESAs but are in natural or semi-natural ecological condition	<ul style="list-style-type: none"> •Harbour mouths •Natural areas that are not protected areas or CBAs, and that are highly fragmented by development
No Natural Remaining (NNR)	Areas that are not protected areas, CBAs or ESAs and are in poor ecological condition	<ul style="list-style-type: none"> •All parts of estuaries with irreversible development •All parts of the seashore with irreversible development

2.4. Cost layer

A cost layer is included in SCP largely as a way to avoid conflict with other uses and users within the planning domain, i.e., where all else is

equal, to help meet the targets for biodiversity features in places that are not already used by another sector. The cost layer (Fig. 3) for this study was built for the land (LandCost), estuaries (EstuaryCost) and sea (MarineCost) separately, using realm-specific data, and then combined. For each realm, a cost layer was created (detailed below) that was scaled 0–100 so the values were comparable across the planning domain, and then the area of the planning units (in km², i.e., <3.5 in all cases) was added across the whole layer. Area was added to avoid non-zero cost, and where all else is equal, for Marxan (Ball et al., 2009, Section 2.5) to select spatially efficient solutions, following Harris et al. (2022a, 2022b). Cost was also rounded such that all values < 0.01 were given a value of 0.01. Because there was only one realm cost per planning unit, the cost for the coast (CoastCost) was calculated as follows (equation (1)):

$$CoastCost = (LandCost \text{ OR } EstuaryCost \text{ OR } MarineCost) + Area \quad (1)$$

For LandCost (equation (2)), the National Landcover Map 2020 (DFFE 2021; processed following methods by Skowno et al. 2021) was used to determine the proportion of each planning unit that is no longer in natural ecological condition by dividing the area of the planning unit that is modified (A_M) by the total area of the planning unit (A_T). These values were scaled linearly from 0 to 100, where $\geq 60\%$ modification was the highest cost of 100. This is because percolation theory states a critical threshold of 60%, which is the minimum area that needs to be intact to avoid a degree of fragmentation that would separate species (Svancara et al., 2005).

$$LandCost = \min \left[100, \frac{\left(\frac{A_M}{A_T} \right)}{0.6} \times 100 \right] \quad (2)$$

For EstuaryCost (equation (3)), the ecological condition of the

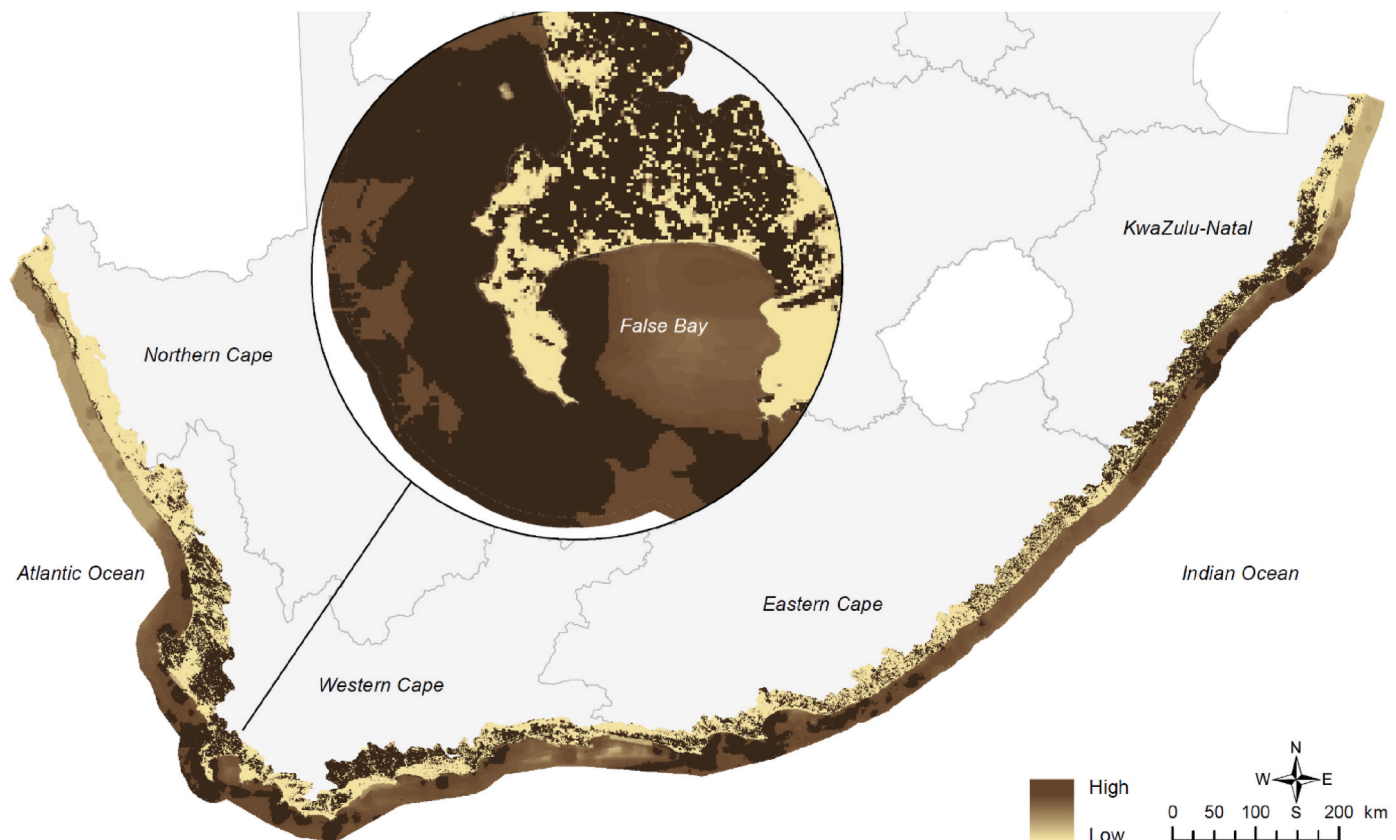


Fig. 3. The cost layer included in the coastal prioritisation. Darker browns indicate areas of higher cost that should be avoided, if possible, because the sites are important for other sectors, and are more degraded. Inset for False Bay in Cape Town shows the level of detail in the map.

estuaries from the National Biodiversity Assessment (NBA) 2018 was used in conjunction with four key pressures (Van Niekerk et al. 2019, 2022) to calculate the cost for planning units containing estuaries. Because this assessment of ecological condition was not performed for microestuaries (Van Niekerk et al., 2019), the cost for those systems is from the LandCost layer. Estuary ecological condition was translated into a score of 0–100 where: Natural = 0; Near-Natural = 25; Moderately Modified = 50; Heavily Modified = 75; and Severely/Critically Modified = 100. The four key pressures used to calculate EstuaryCost were: flow modification (FM); pollution (P); habitat loss (HL); and fishing effort (FE), where the ratings in Van Niekerk et al. (2019, 2022) were translated into scores of 0–100 as follows: None = 0; Low = 25; Medium = 50; High = 75; Very High = 100. The ecological condition (C) of the estuaries, which is a more integrated measure of their health, was weighted 60% of the cost, and the four pressures were combined and weighted 40% of the cost.

$$\text{EstuaryCost} = (C \times 0.6) + \left(\frac{FM + P + HL + FE}{4} \times 0.4 \right) \quad (3)$$

For MarineCost (equation (4)), the same approach was followed as in the NCMSBP (see Harris et al., 2022a; Harris et al., 2022b for details). It comprised three equally weighted components (each scaled 0–100), the first two of which specifically regard conflict avoidance with $n = 20$ sectors (or cost elements, i): petroleum, mining, 16 fisheries, aquaculture and transport (see Harris et al., 2022b for details on the data that were included). The third component, I_c is cumulative impact to marine ecosystems (Halpern et al., 2007), measured across 31 pressures in South Africa, as a metric of ecosystem degradation (Sink et al., 2019). These three components: sum and maximum of avoidance (v) across all sectors, and cumulative impact (I_c), were averaged to give a total cost value of 0–100.

$$\text{MarineCost} = \left(\sum_{i=1}^n v_i + \max \{v_1, \dots, v_n\} + I_c \right) \div 3 \quad (4)$$

There are three differences in the cost layer developed for this analysis and the NCMSBP (Harris et al. 2022a, 2022b). First, the confidential data for mining and petroleum used in the NCMSBP were not used to represent these sectors because the confidentiality agreement did not include use of the data in this study. The data were replaced with spatial information for those sectors from the NBA 2018 (Sink et al., 2019). Second, small-scale fishing was included as a sector for conflict avoidance. Because there is no map that is currently available to represent the sector (which is recognised as a high priority to address), the entire marine component of the planning domain was given the maximum value (100) to represent small-scale fishing effort as an interim step until a more accurate map is available. This layer was used in the calculation for component 1 (sum of all cost elements); however, it was excluded from the calculation of component 2, such that this component represents the maximum across the other 19 cost elements. This was because there is no relative intensity of use built into the small-scale fishing layer, which would mean that taking the maximum value across all sectors would be reflecting the maximum value of 100 assigned to small-scale fishing across the whole marine component of the planning domain. Third, although all sectors from the NCMSBP are present in the coastal planning domain, midwater trawling, and pelagic longlining barely extend into it.

2.5. Marxan analyses and comparisons with existing biodiversity priority areas

Running Marxan (Ball et al., 2009) requires a set of standard input files that are largely translations of the spatial data contained in the planning units into matrices. Marxan input files were created using the ArcMarxan Toolbox (Apropos Information Systems Inc) in ArcGIS 10.6. The boundary length file was generated using the Polygon Neighbors

tool in the Analysis toolbox, and extracting only those connections where neighbors shared a boundary. The input parameters required to run Marxan were calibrated following standard methods outlined in the Marxan Good Practices Handbook (Ardron et al., 2010), with the final settings including one billion iterations (length of the simulated annealing routine), 100 runs (number of times Marxan is run), and a boundary length modifier of 0.05 (to encourage clustering of selected planning units), run using Marxan v 2.4 (Ball et al., 2009). Marxan then searches the decision space, selecting a portfolio of planning units that meet feature targets for the least cost, using simulated annealing to solve the algorithm (Ball et al., 2009).

One of the outputs that gets generated is a matrix of how many times a planning unit was selected in each of the 100 runs, called selection frequency. The portfolio of coastal priorities was taken at the level of selection frequency at which all biodiversity feature targets were met, where targets were considered met when the amount included in the solution was at least 95% of the target amount. Areas excluded in land-based plans (non-natural land outside protected areas (DFFE, 2021; Skowno et al., 2021)) and marine plans (parts of fine-scale plans that were not identified as priorities (Holness et al., 2022)) were excluded from the output as well.

The coastal priorities were compared with existing priorities, comprising existing protected areas (CapeNature, 2022; DFFE, 2022; Oosthuysen, 2022) and CBAs (Hawley et al., 2019; Holness and Oosthuysen, 2016; KZN CBA Irreplaceable version 01022016, 2016; KZN CBA Optimal version 03032016, 2016; Pool-Stanvliet et al., 2017) in the coastal zone that were identified in separate land-based and marine planning processes. We chose protected areas and CBAs for the comparison because they are collectively the portfolio of sites that are required to meet feature targets in land-based and marine plans, and are thus conceptually comparable to the portfolio of coastal priorities that we developed in this study.

2.6. Developing the seashore and estuary CBA map and management recommendations

A CBA Map was developed for the seashore and estuaries (abbreviated to Seashore and Estuary CBA Map) based on the existing protected areas (CapeNature, 2022; DFFE, 2022; Oosthuysen, 2022), Marxan outputs from this study, and high resolution maps of coastal development (Harris, 2010; King, 2023). First, CBA Map categories were identified according to a set of rules (Table 2), developed in accordance with South Africa's Technical Guidelines for CBA Maps (SANBI, 2017). Because the planning units were a grid that often cut the seashore and estuaries into awkward shapes for management, the second step was to rationalize the boundaries of the different map categories according to a set of heuristic rules (Appendix A: Boundary rationalisation). The third step was to split the CBA 1 and 2 map categories by ecological condition from the NBA 2018 (Sink et al., 2019; Skowno et al., 2019b; Van Niekerk et al., 2019) to delineate the CBA Natural (CBA 1 and 2 that are in natural ecological condition) and CBA Restore categories (CBA 1 and 2 that are no longer in a natural ecological state). Fourth, high resolution maps of coastal development along the seashore and in the EFZs were embedded into the CBA Map as the No Natural Remaining (NNR) category. Lastly, a final check of the map was done to ensure that any natural areas that were highly fragmented with development were revised to 'Other Natural Areas'.

We tabulated a set of management recommendations for each CBA Map category. These recommendations were determined by establishing a broad management objective indicating the desired ecological state for each CBA Map category, and then providing management recommendations per realm that would be required in order to achieve the management objective and maintain or attain the desired ecological state. The recommendations were compiled based on expert judgement by considering each activity that currently takes place in each realm, and evaluating the impacts of those activities (drawing on the NBA, 2018

results in Sink et al., 2019; Skowno et al., 2019b; Van Niekerk et al., 2019) relative to the broad management objective for each CBA Map category.

3. Results

3.1. Coastal versus existing priorities

All but two biodiversity feature targets were met (at a $\geq 95\%$ level) in the portfolio of coastal priorities (Fig. 4). The two features that did not meet their targets were offshore marine ecosystem types that had only a small portion ($< 0.3\%$) of their extent in the planning domain. We thus considered it acceptable not to meet their targets because these ecosystem types are intrinsically not coastal, and their targets should rather be met more appropriately and efficiently in offshore areas. Coastal priorities comprised 57018.0 km² (45%), and were distributed throughout the study area (Fig. 4, Table A3).

The extent of the coastal priorities was slightly smaller than that of existing priorities in the study area (63851.8 km², 50.4%), where existing priorities overlapped with 82.7% (47181.1 km²) of the coastal priorities (Fig. 5). In other words, nearly a fifth (17.3%) of the coastal priorities are not included in the current portfolio of existing priorities in South Africa. In some cases, this is because alternative sites are selected to meet feature targets in a more connected coastal design, and in other cases because the plans included different biodiversity and cost data and therefore, different areas were selected. The proportion of the backshore, shore, and estuaries identified as existing priorities is much higher than that for the rest of the coastal land and sea (Fig. 5b–Table A3). The same is true for the proportion of the backshore

and estuaries identified as coastal priorities (Fig. 5b–Table A3).

The greatest difference between the existing and coastal priorities is proportionately for the shores (Fig. 5b–Table A3). Although the shore extent was built into the planning units for both this study and the NCMSBP (Harris et al. 2022a, 2022b), the size of the planning unit grid for the former is a third of that for the latter, allowing the coastal priorities to be more precise, particularly in this very narrow zone (Table A3). Further, the existing priorities for shores comprised areas identified in both the NCMSBP (768.6 km²) and the land-based plans (21.4 km²) because plans have not been cut to consistent boundaries that represent the land-sea edge (Harris et al., 2019). By area, the greatest difference between the existing and coastal priorities is for the land, primarily in the Eastern Cape. In this region, many more areas were identified as existing priorities, largely linked to riparian zones (Fig. 5a). Much smaller differences were evident in the Western Cape and KwaZulu-Natal, which partly reflects the higher proportion of development along the coast in these two provinces, such that there is much less natural area remaining in which to meet targets.

3.2. Seashore and estuary CBA map and management recommendations

Given the high biodiversity value of the seashore and estuaries (Fig. 5b), 92.1% of their extent was identified as a biodiversity priority area in the Seashore and Estuary CBA Map: 45.1% in protected areas, and 47.0% as CBAs (Fig. 6, Table A4). The highly impacted state of this zone is also reflected in the split between the two CBA categories, with 16.3% identified as CBA Natural and 30.7% as CBA Restore. Almost all the remaining extent of the seashore and estuaries was identified as an ESA (5.5%), with very small portions comprising Other Natural Areas

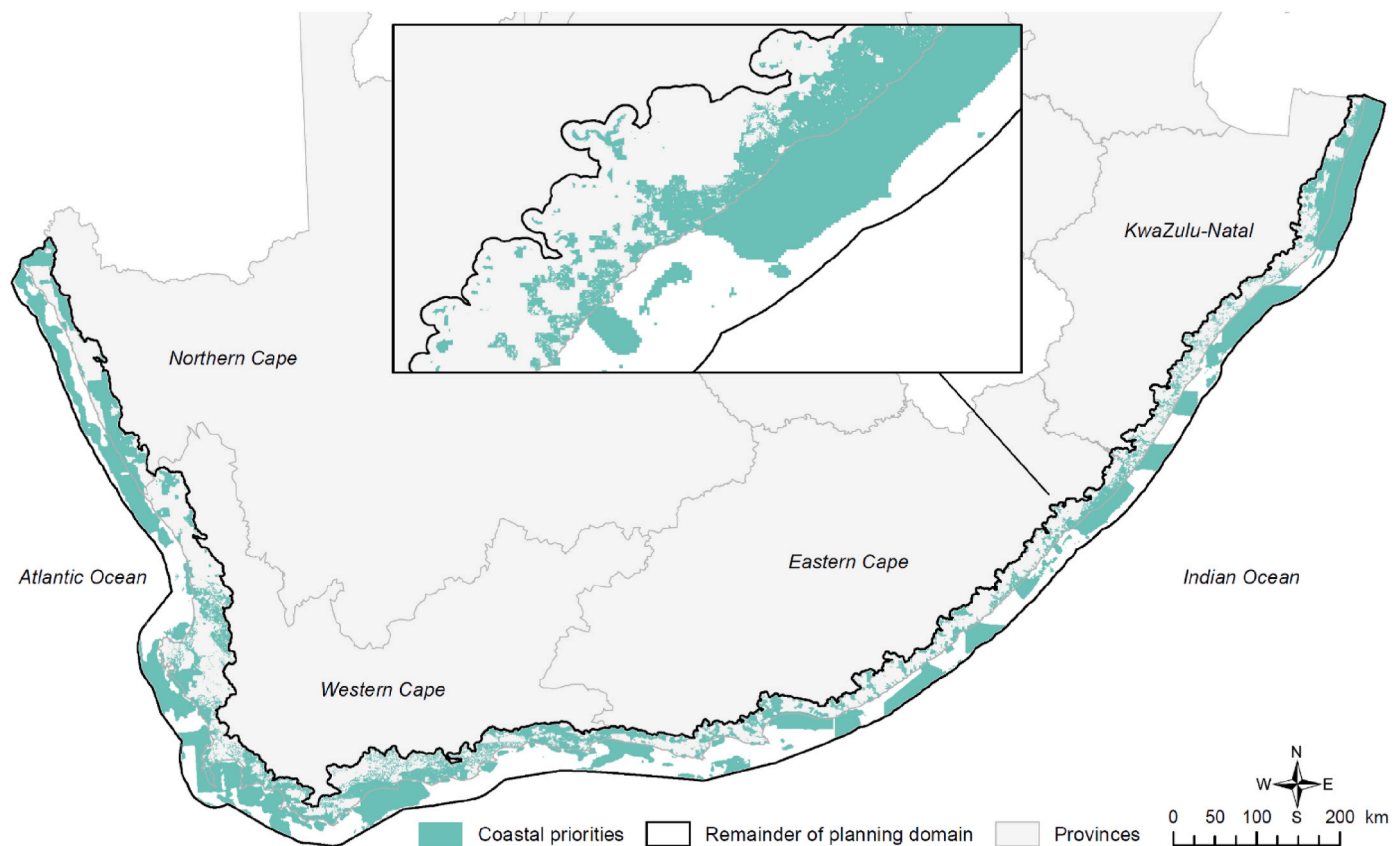


Fig. 4. Coastal priorities in South Africa, identified at the selection frequency (30%) at which all biodiversity feature targets were met at a $\geq 95\%$ level. The four coastal provinces are labelled, which also mark the seaward edge of the South African mainland landmass. The inset illustrates the level of detail in the coastal priorities.

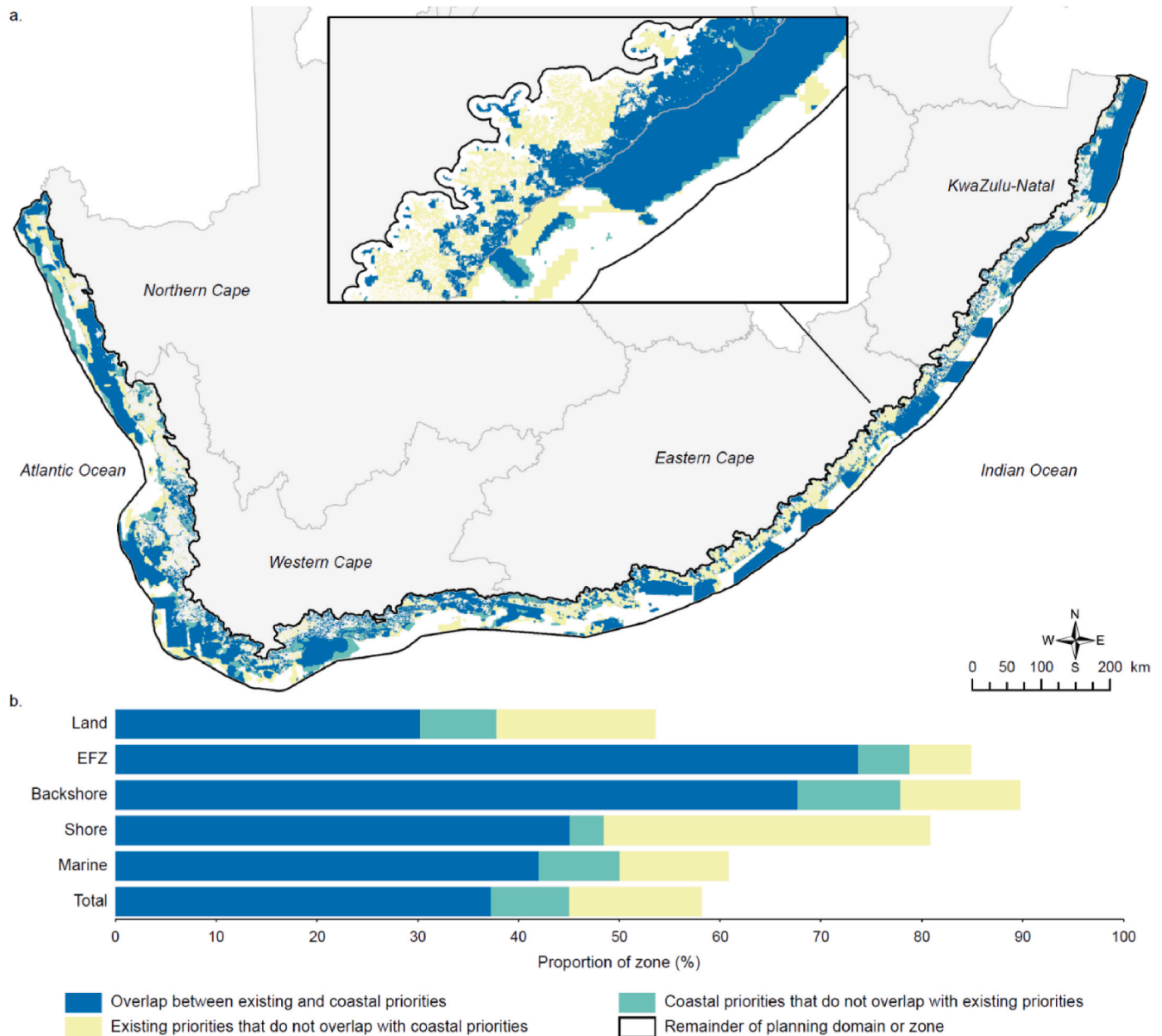


Fig. 5. (a) Map of the overlap between existing priorities (existing protected areas; CapeNature, 2022; DFFE, 2022; Oosthuysen, 2022), and Critical Biodiversity Areas (Hawley et al., 2019; Holness and Oosthuysen, 2016; KZN CBA Irreplaceable version 01022016, 2016; KZN CBA Optimal version 03032016, 2016; Pool-Stanvliet et al., 2017) and coastal priorities (from Fig. 4), and other parts of existing and coastal priorities that do not overlap. (b) Proportion (%) of the total study area and five zones (Fig. A1) that comprise the overlap between the existing and coastal priorities, and the other parts of existing and coastal priorities that do not overlap. EFZ = Estuarine Functional Zone.

(ONAs; 0.1%) and areas that have been permanently modified such that there is No Natural Remaining (NNR; 2.3%, Fig. 6, Table A4). The four CBA Map categories that have important biodiversity value (Protected Area, CBA Natural, CBA Restore and ESA) each have a broad management objective that outlines the desired state for sites in those respective categories (Table 3). Ideally, all management decisions should be based on whether a proposed action or activity is compatible with the management objective at a particular site, recognising that this would need to be evaluated on a case-by-case basis, and that some trade-offs may be necessary. Recommended management actions for each realm and each CBA Map category are summarised in Table 3 and detailed in Table A5.

4. Discussion

4.1. Good coverage of coastal priorities, but the seashore and estuaries need special attention

The degree of overlap between existing and coastal priorities was greater than expected. This is a positive result because it indicates that even though planning is being done separately for the land and sea, most coastal biodiversity is being adequately accounted for. We also expected the greatest difference between existing and coastal biodiversity priority areas to be in the marine environment because there should be more options where targets can be met given greater habitat loss on land constraining selection. However, this was not the case; the greatest difference (by area) was observed on land. This is likely because most of

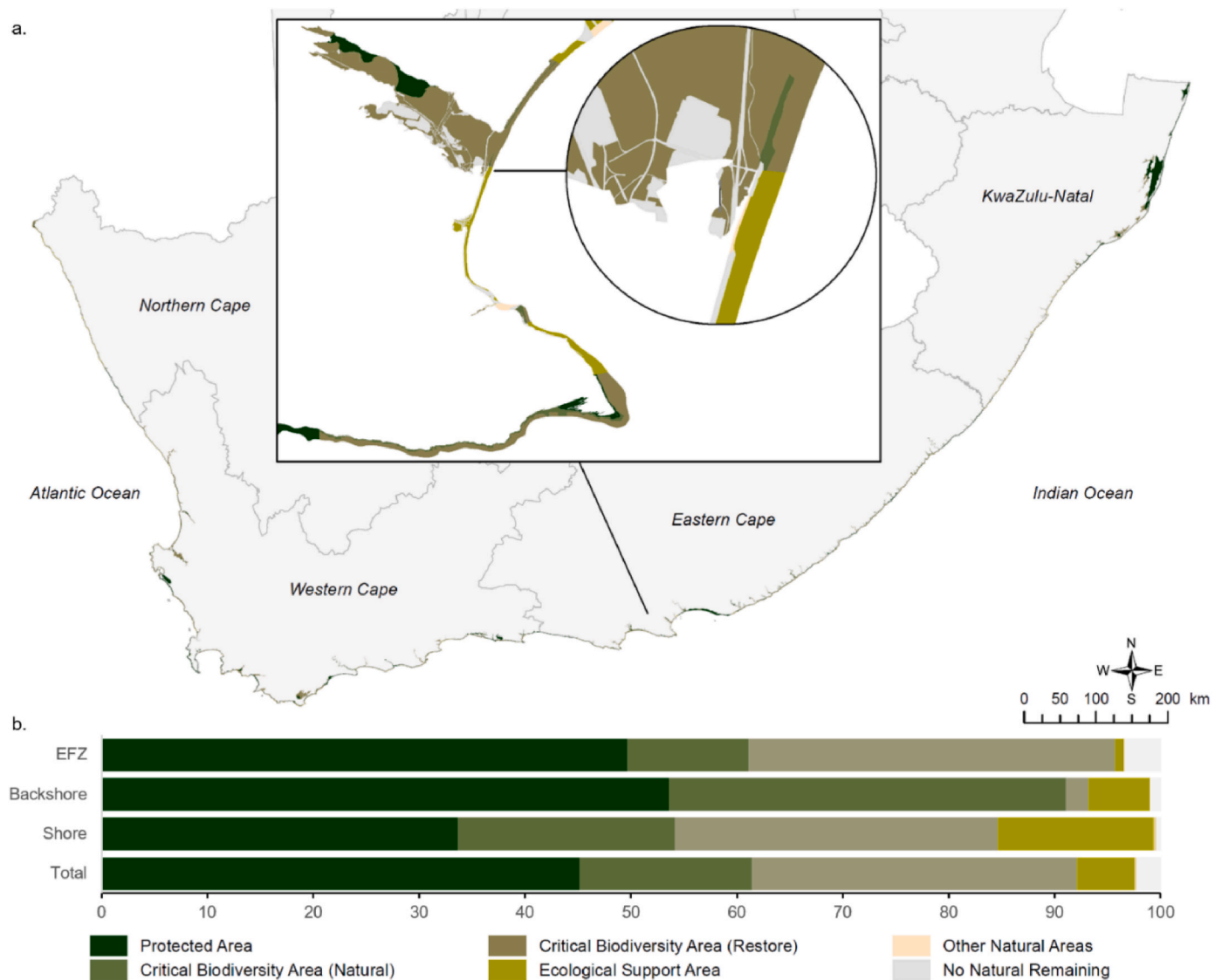


Fig. 6. (a) The biodiversity priority areas in the Map of Critical Biodiversity Areas and Ecological Support Areas for the Seashore and Estuaries (Seashore and Estuary CBA Map) comprise Protected Areas, Critical Biodiversity Areas (Natural and Restore), and Ecological Support Areas, each of which has a specific management objective with associated management recommendations (Table 3). Insets of Gqeberha show the level of detail in the Seashore and Estuary CBA Map (see Table A4 for summary statistics).

the marine data and targets were the same as those used to identify biodiversity priority areas in the NCMSBP (Harris et al. 2022a, 2022b), whereas on land, the existing priorities were developed at a provincial scale, at a higher resolution, and with more locally specific data than are available at a national scale. The provinces also have different planning styles and nuances that we could not replicate in a national prioritisation. Consequently, it was interesting to see that, in some cases, the existing priorities were more connected through the landscape than the coastal priorities were (e.g., in some cases, existing priorities included whole EFZs, whereas the coastal priorities included disconnected upstream and downstream portions thereof).

The disproportionately high selection of foredunes, shores and estuaries relative to the other coastal land and sea areas (in both existing and coastal priorities) reflects the immense biodiversity value of these zones. It is well known that the seashore and estuaries support rich diversity and essential ecological processes, and provide a plethora of ecosystem services that enhance human health and wellbeing (Harris et al., 2014a; Harris and Defeo, 2022). This emphasizes the significance of the recent findings that two-thirds (67.3%) of the seashore and estuarine area in South Africa is in a modified state, and almost two

thirds (62.3%) of the 61 seashore and estuarine ecosystem types are threatened (Harris et al., 2022c). Coastal managers and decision makers need to pay careful attention to this sensitive, impacted and threatened zone that is a national asset at risk. This is especially important in the face of global change, where the seashore and estuaries will bear the brunt of climate-change impacts from sea-level rise and increased storminess. From a biodiversity perspective, rates of endemism in the seashore zone are high in South Africa, e.g., two-thirds of the beach macrofauna are endemic species (Harris et al., 2014a), further emphasising the importance of conserving, restoring, and sustainably managing this connected and important but often-overlooked interface between land and sea. Further, securing and restoring naturally functioning seashores and estuaries has the added benefit of enhancing their capacity to deliver a myriad of other ecosystem services (Harris and Defeo, 2022), including providing a cost-effective natural defence against intensifying flooding and erosion for coastal communities (Narayan et al., 2016).

The Seashore and Estuary CBA Map and related management recommendations lay a foundation for co-ordinated action in the country, regardless of scale or management authority, and provide the basis for

Table 3

Management recommendations for biodiversity priority areas in the Seashore and Estuary CBA Map that are needed in order to maintain the broad management objective of each CBA Map category. (CBA Map = Map of Critical Biodiversity Areas and Ecological Support Areas; see Table A5 for detailed, realm-specific recommendations).

CBA Map category: broad management objective	Activities	Recommendations for management to maintain the broad management objective in each CBA Map category
Protected Areas: As per the management plan Critical Biodiversity Area (Natural): Maintain in a natural to near-natural state	All	As per the management plan and/or gazetted regulations
	Coastal development and land-use change	Avoid any new development or land-use change
	Living resource extraction	Avoid new extractive activities, enforce management regulations (e.g., bag and size limits), and eliminate any illegal extraction
	Non-living resource extraction	Avoid, and eliminate any illegal extraction
	Disruption of biota and biotic processes	Avoid
	Disruption of physical properties and abiotic processes	Avoid
	Pollution (light, noise, chemical, solid waste, sewage)	Avoid
	Invasions by alien species	Monitor to prevent, and eradicate quickly to avoid invasions
	Coastal development and land-use change	Avoid further expansion and intensification of development, relocate infrastructure behind setback lines where possible, and restore degraded habitats preferably using soft engineering practices where needed
	Critical Biodiversity Area (Restore): Improve ecological condition and, in the long term, restore to a natural/near-natural state, or as near to that state as possible. As a minimum, avoid further deterioration in ecological condition and maintain options for future restoration.	Living resource extraction
Non-living resource extraction		Avoid further expansion and intensification of extraction, restore degraded habitats, and eliminate any illegal extraction
Disruption of biota and biotic processes		Reduce activities that cause disruptions or manage activities to mitigate impacts; at the very least avoid further expansion and intensification of disruptions, and restore impacted populations
Disruption of physical properties and abiotic processes		Reduce activities that cause disruptions or manage activities to mitigate impacts; at the very least avoid further expansion and intensification of such activities, and restore degraded habitats preferably using soft engineering practices where needed
Pollution (light, noise, chemical, solid waste, sewage)		Reduce sources of pollution; at the very least avoid further expansion and intensification of pollution sources, and restore polluted habitats
Invasions by alien species		Eradicate or control existing invasive species, and avoid new introductions
Coastal development and land-use change		Avoid further expansion and intensification; needed management interventions should preferably use soft engineering practices than using hard infrastructure
Living resource extraction		Enforce management regulations (e.g., bag and size limits), and eliminate any illegal extraction
Non-living resource extraction		Ensure current extraction is sustainable, encourage rehabilitation where needed, and remove all illegal extractive activities
Disruption of biota and biotic processes		Avoid further expansion and intensification of disruptions
Ecological Support Area: Avoid further deterioration in ecological condition	Disruption of physical properties and abiotic processes	Avoid further expansion and intensification of disruptions
	Pollution (light, noise, chemical, solid waste, sewage)	Avoid further expansion and intensification of pollution
	Invasions by alien species	Control existing invasive species and avoid new introductions

ecosystem-based management across the land-sea interface. They can also guide where to prioritise efforts as South Africa seeks to make progress in the GBF targets for conservation, restoration and sustainable management (CBD, 2022). Although South Africa has >30% protection of the extent of the seashore and estuaries, it is not ecologically representative of all the constituent biodiversity, with 13 (21.3%) ecosystem types having <5% of their extent protected, and five (8.2%) ecosystem types without any protection (Harris et al., 2022c). To meet Target 3 (30% of areas protected in representative networks by 2030) for this zone, South Africa can secure prioritised portions of the CBA Natural category. Further, the proportion of the seashore and estuaries comprising the CBA Restore category is 30.7%, providing managers and decision makers with a set of priority areas for restoration to meet Target 2 (30% of degraded areas under restoration by 2030) for the land-sea interface, which could be refined further with local high-resolution data.

Because the spatial prioritisation included threatened species,

securing and restoring the CBAs can contribute to making progress towards Target 4 (halting human-induced extinctions, and significantly reducing extinction risk). Where these threatened species depend on multiple realms, it highlights even further the importance of doing cross-realm assessments and planning for achieving this GBF target. Implementing the proposed management recommendations will assist with meeting Target 5 (regarding sustainable harvesting), Target 6 (regarding eliminating and controlling biological invasions), and Target 7 (regarding reducing pollution). Finally, between including features such as ecological infrastructure (e.g., for coastal protection) and carbon habitats (for climate-change mitigation) in the spatial prioritisation, and the proposed management actions (e.g., to maintain the littoral active zone intact, protect freshwater flow requirements), progress can also be made towards Target 8 (regarding minimizing impacts of climate change). South Africa is thus well positioned to make progress in the GBF long-term Goals A and B for 2050 (CBD, 2022).

We also recognise that the seashore and estuaries are intensively used areas given their associated goods and services, and as is reflected in the ecological condition of this zone (Harris et al., 2022c). This does mean that there are strong social considerations that need to be accounted for when managing these systems, especially regarding the livelihoods of small-scale fishers who often depend on living resource extraction (Clark et al., 2002). Both Target 1 and 3 in the GBF highlight the importance of “respecting the rights of indigenous peoples and local communities”. Management actions should benefit biodiversity but also should not further disadvantage vulnerable communities.

4.2. Recommendations for countries embarking on applied cross-realm planning in the coastal zone

Our recommendations for cross-realm biodiversity planning when there are established, separate land-based and marine planning and implementation processes are first to identify and, where needed, co-develop cross-realm biodiversity datasets to represent species distributions, ecological processes, cross-realm connectivity, ecological infrastructure, and any other relevant features that need to be accounted for in both land-based and marine plans. Examples, with methods, include: land-sea run-off and ocean dispersal modelling (Tulloch et al., 2021); catchment modelling (Álvarez-Romero et al., 2016); within- and between-realm connectivity modelling (Beger et al. 2010a, 2010b; Hermoso et al., 2021); species distribution modelling (Harris et al., 2014a); and ecological infrastructure mapping (Perschke et al., 2023). Planners from the different realms could share these data and use the same targets to ensure the cross-realm features are adequately secured throughout their extent. Co-developing such datasets and targets will most likely require expert input. A key foundational dataset underpinning land-sea planning is a seamless, cross-realm map of ecosystem types for the coastal zone (Harris et al., 2019). In South Africa, for example, this map has been the catalyst that has unlocked cross-realm biodiversity assessment (Harris et al., 2022c) and planning (this study) in the country, and has provided a set of land-sea boundaries for all to use (Harris et al., 2019). A key lesson in spatial prioritisation in South Africa has been not to wait for perfect data or processes but rather to start with the best available information, build on it by prioritising and filling research and data gaps over time, and learning across iterations and from the community of practice in biodiversity planning (Botts et al., 2019). We therefore encourage others to start with the information available, and iteratively improve the spatial prioritisation over time.

Second, we recommend identifying a portfolio of coastal priority areas to which planners can try to align. Planning at finer scales than national will likely refine these priorities by allowing smaller planning units, and more locally relevant biodiversity and cost data of higher resolution to be used (e.g., Holness et al., 2022). Third, given that the seashore is often poorly included at the edge of land-based and marine plans, which also effectively splits the littoral active zone (dune, beach, and surf) that is a single geomorphic unit (Harris et al., 2019), it is highly recommended to do a dedicated prioritisation for this zone. Estuaries are fundamentally linked to the seashore through their critical coastal processes (e.g., sediment replenishment) and biodiversity patterns, and thus need to be included as well. The output can then be split between the land-based and marine plans, but will seamlessly align when the plans are merged, and management actions will all contribute to a common goal and coherent prioritisation. If there is scope for land-based and marine planners and experts to work together in a broader area, that may be preferable, otherwise the priorities in the seashore and estuaries can be used to seed cross-realm alignment upstream and downstream.

In terms of technical recommendations, our coastal analysis comprised >1000 features, almost 500 000 planning units, and took >60 h to run; it's one of the largest, most computationally intensive Marxan analyses undertaken in South Africa to date. However, if the objective is specifically to develop or advance a Seashore and Estuary CBA Map (or similar spatial prioritisations used by other countries for

conservation and sustainable management), then the planning domain can be reduced in size, allowing more data layers to be included and the algorithm to run in a shorter time. Planning unit delineation and design is also crucial in land-sea planning because automatically generated lattices (e.g., hexagons or grids) do not work well. At the very least, a line representing the land-sea boundary (e.g., dunebase as a decadal-scale high water mark; Harris et al., 2019) is essential to integrate into the planning units. Ideally, boundaries for the shores and EFZs should also be included to ensure proper inclusion of these features. It is highly recommended that cross-shore planning units are used for the seashore (similar to Harris et al., 2014b) to avoid post-hoc rationalisation of the priority area boundaries, as we had to do. Similarly, within estuaries, planning units could include zones that are sensible from an ecological and management perspective. For example, having zones within estuaries that contain ports that distinguish between the operational port area and other parts of the estuary that have high biodiversity value and still need to be managed appropriately. In other cases, making the whole EFZ a single planning unit could be a sensible approach, particularly where the systems are very small. This will help to ensure appropriate selection and identification of biodiversity priority areas, and will reduce the need for post-hoc processing and alignment.

4.3. Way forward

One aspect of our analysis that was very apparent when comparing the existing and coastal priorities is that although we included a large set of data across all realms that covered the whole planning domain, this was not enough to ensure land-sea connectivity in the final selection. Beger et al. (2010a) provide an excellent framework for identifying different types of cross-realm connectivity, and these kinds of data and applications are needed in the next version of the coastal prioritisation and Seashore and Estuary CBA Map. For example, it could be useful to identify nodes and corridors of connectivity through the landscape and seascape using programmes such as LinkageMapper (Hermoso et al., 2021; McRae and Kavanagh, 2011) or Conefor (Saura and Torne, 2009), and/or using MarxanConnect (Daigle et al., 2020) to strengthen connectivity in the portfolio of selected sites. We used an initial set of data on cross-realm species, ecological processes, and ecological infrastructure. Identifying and creating more of these kinds of data that need to be co-developed between land-based and marine planners and coastal experts, following the methods and approaches noted in Section 4.2, is a priority for the next version of the coastal prioritisation and Seashore and Estuary CBA Map. Where managers and other coastal stakeholders and knowledge-holders have spatial information to contribute (both for the biodiversity and cost layers), this too would add significant value.

4.4. Conclusion

Coastal zones, especially the seashore and estuaries, have immense biodiversity, social and economic value. Consequently, they have high priority for conservation and sustainable management, but are also generally highly impacted and threatened spaces, and in a state of ecological decline. Given how intensely coasts are experiencing (and will experience) climate-change-related impacts, they cannot be separately considered in land-based and marine planning any longer. Fully recognising the administrative and governance constraints in the real world, planners working in the different realms need to overcome these challenges together. We propose that (1) building shared cross-realm datasets with associated targets, (2) identifying broad coastal priorities that can be refined at higher resolution in the different realms, and (3) developing a seashore and estuary ‘seam’ of biodiversity priority areas with a coherent set of management recommendations can all help to better integrate cross-realm biodiversity effectively into separate land-based and marine planning and implementation processes. It can make an important contribution to the foundation for integrated coastal zone management, and for prioritising areas for conservation,

sustainable development, and restoration. In turn, this can help countries make progress towards the targets outlined in the GBF (CBD, 2022) and the Sustainable Development Goals, and help secure coasts as the diverse and inspiring spaces we experience today for generations to come.

CRediT authorship contribution statement

Linda R. Harris: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lara van Niekerk:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Stephen D. Holness:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Kerry J. Sink:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Andrew L. Skowno:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Anisha Dayaram:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Heidi van Deventer:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Nancy Job:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Stephen J. Lambert:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Janine B. Adams:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jacqueline L. Raw:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Taryn Riddin:** Writing – review & editing, Methodology, Investigation, Conceptualization. **C. Fiona MacKay:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Myriam J. Perschke:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2025.107586>.

Data availability

The map of coastal priorities is available at: <https://doi.org/10.6084/m9.figshare.22463890.v1> and the Seashore and Estuary CBA Map is available at <https://doi.org/10.6084/m9.figshare.22461901.v1>.

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