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Scenario planning from the bottom up: supporting inclusive and ecosystem-based approaches to marine spatial planning

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Countries attempting to grow their ocean economies are encouraged to adopt the internationally recognised processes of marine spatial planning. Marine spatial planning encourages inclusive and sustainable management of ocean resources and spaces. However, producing a marine spatial plan that is considered socially inclusive and follows an ecosystem-based or sustainable approach is complicated and complex. Decision makers need to integrate the various needs, interests and knowledge from numerous sectors and stakeholders, which are often incompatible and competing for space to promote growth in socio-economic wealth and environmental health. Using decision support tools to produce future scenarios that explore the potential outcomes of decision-making is an excellent way to integrate large amounts of information into easily understood temporal and spatial outputs. Building scenarios, if developed through a bottom-up process (i.e., involving stakeholders from the start and throughout the process), can provide a platform that can promote the sharing and integration of different types of knowledge, thus producing more equitable and sustainable area-based plans. Here, we present a systematic method and use the prioritizR with zones tool to produce zoning scenarios for a high biodiversity-high human use bay (Algoa Bay) in South Africa. We show how win-win scenarios for ocean health and socio-economic priorities can be developed, from the bottom up, in an inclusive, ecosystem-based and transparent manner.

All sectors of society benefit from the various goods and services provided by the world's oceans and coasts, for example, through sustenance, cultural, religious or commercial interests[1]. Many coastal regions, however, are focusing on developing their ocean economies, which is placing increased pressure on marine ecosystems and the services they provide. These pressures include overexploitation of marine resources, pollution, ocean noise, alien introductions, disease and habitat destruction, as well as indirect pressures from climate change. The impacts of these pressures can change the state of marine ecosystems, risking the potential for long-term benefits[2–5]. To support sustainable development, marine spatial planning (MSP) has emerged as an ecosystem-based approach to ocean governance and is rapidly being adopted by countries globally[6–9]. MSP is intended to be a cooperative process to develop a sustainable blue economy (i.e., sustainable ocean development) by achieving ecological, economic and social goals, integrating sectors and government agencies, applying adaptive management and reducing conflicts through iterative input from all affected sectors and stakeholders[10]. Here, we acknowledge that the term 'blue economy' has been critiqued by authors such as Voyer et al.[11] and Germond-Duret et al.[12]. These authors argue that the term is being used in competing and often conflicting ways, by including certain stakeholders and excluding others, and negatively impacting both environmental and social sustainability.

Globally, the importance of growing the blue economy using MSP has been recognized and is being reinforced by initiatives and commitments of the United Nations (UN) such as the 17 Agenda 2030 Sustainable Development Goals, the Decade of Ocean Science for Sustainable Development (2021-2030) and the Treaty for Marine Biodiversity of Areas Beyond National Jurisdiction (2023). Current MSP approaches have, however, been

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critiqued by many authors for not addressing power imbalances[13], prioritizing economic objectives over environmental or social ones[14,15], having superficial stakeholder participation processes[14,16] and providing limited adaptive capacity[17], for example. Therefore, developing a clear understanding of the interdependence among environmental, economic and socio-cultural dimensions becomes key when growing a sustainable and long-lasting blue economy[18]. To address these concerns, we aimed to develop a marine spatial plan for Algoa Bay that was inclusive, collaborative and followed an ecosystem-based approach. A spatial plan that is developed through a bottom-up process, encouraging participation from all affected stakeholders throughout the process, including non-commercial groups such as local and traditional affected parties, can benefit from various positive consequences. Inclusivity throughout the MSP process can lead to a more comprehensive understanding of diverse knowledge systems (e.g., refs. 19–22), build trust among participants and enhance compliance and/or stewardship and thus sustainability of agreements (e.g., refs. 23–25) as well as reduce current or avoid future conflict among ocean users (e.g., refs. 26). However, the effects of inclusiveness are not uniformly positive; in some cases, it can also lead to delays, increased conflict, or superficial engagement if not managed effectively[27,28].

South Africa has a large exclusive economic zone (~1.5 million km^2) and the national government has embarked on an economic development program to grow its blue economy through Operation Phakisa[29]. Launched in 2014, Operation Phakisa aims to fast-track the implementation of actions that would unlock the economic potential of the country's ocean and is supported as one of the solutions to resolve the 'triple threat' of high levels of unemployment, poverty and inequality in South Africa[30]. However, some have criticized the 'big results fast' methodology of Operation Phakisa, noting that it is failing to incorporate values and views of local communities because public participation and knowledge sharing has been severely inadequate[31–33]. This has already led to mistrust and a lack of buy-in into the process, given that local communities have experienced the process as inequitable and biased towards the commercial sectors such as fishing and mining[33,34].

In 2018, the MSP Act No. 16 of 2018 was gazetted[35] and came into force in April 2021. The Act established the regulatory framework for equitable and fair designation and use of space in the maritime domain for South Africa. As the lead authority of the MSP process in the country, the Department of Forestry, Fisheries and the Environment (DFFE) is responsible for facilitating collaboration with all authorities that have a spatial presence in the marine environment. As such, the DFFE chairs the Marine Spatial Planning National Working Group (MSP-WG, established in 2015). The MSP-WG is composed of members from departments responsible for defense, energy, environmental affairs, fisheries, mineral resources planning, monitoring and evaluation, public enterprises, science and technology, telecommunications, tourism, transport, rural development, land affairs and marine cultural heritage through the South African Heritage Resources Agency. No civil society representatives are included in this group, including local or Indigenous knowledge holders or academics with the data and expertise to contribute most to the MSP process (see Reed and Lombard[36] for suggestions of how civil society could be formally incorporated into this process).

In 2017, a community of practice (CoP) was established, the 'Algoa Bay Project', to pilot the MSP process in a high-use bay situated in the Southern Area (one of four defined marine areas)[37]. The CoP aimed to develop appropriate locally relevant methods and products to inform the MSP process and was initially funded by the National Research Foundation (South African public funds) with additional funding raised for the second phase of the CoP (see funding statement). The Algoa Bay Project consists of researchers with transdisciplinary expertise gained from working in the Bay and fosters a diverse, equitable and inclusive approach to MSP[21]. Algoa Bay was chosen as a pilot site to explore the legislative, biophysical and socio-economic practicalities involved in developing a marine area plan because the site has the longest-standing biophysical monitoring along the country's shoreline and has well-established port infrastructure with diverse recreational and sport activities that attract local and international tourists[37]. Supplementary Note 1 provides a detailed description of marine activities and current area-based conservation measures within the bay.

Following the principles of the MSP process stipulated both internationally[10] and nationally (MSP Act), to conduct a transparent cross-sectoral planning process, the initial phase of the project identified and collected spatial data from Algoa Bay's marine stakeholders. This included approaching typical ocean users such as the tourism, fisheries, research and recreation sectors[38] as well as individuals from different cultural groups within the local and Indigenous communities in the bay to understand how the ocean is important to them[19,20]. The Algoa Bay Project's MSP process differs from the National process in that it is co-developed with stakeholders from the start, rather than including stakeholders merely to comment on government documents. National legislation does provide text indicating that stakeholders should be meaningfully consulted from the outset, but this has not been implemented in the unfolding national MSP process to date[34].

Using data collected from and curated by stakeholders, the Algoa Bay project paid specific attention to two of the six foundational principles of MSP highlighted by Reimer et al.[39]: i.e., the MSP process should be 'strategic' and 'participatory'. This implies that the process should be inclusive and should actively engage stakeholders during the development and implementation stages, while also being 'evidence-based' and reliant on the best available scientific information, including various forms of knowledge systems and priorities. This is a difficult task because the evidence-based approach is rooted in specialist knowledge gained through experience and/or tertiary education and is often tied to complex data analyses, which is beyond the knowledge of different stakeholders.

To integrate inclusive participation and the scientific method, decision-support tools have become indispensable to the MSP process by assisting stakeholders and decision makers to consider different options and the consequent trade-offs to sector-based interests[9,40,41]. These tools aim to visualize the consequences of ocean use decisions over time, space or both, and to simulate a greater understanding among stakeholders. This leads to cohesive discussions and increased participation in decision-making, ultimately leading to shared ownership, stewardship and co-management options and subsequently implementation of MSP. To this end, the Algoa Bay Project developed the 'Algoa Bay Marine Systems Analysis Tool' or MSAT, a System Dynamics Model (SDM) used to explore trends over time and the underlying feedback effects between marine uses and the environment[42]. The structure of the MSAT model was compiled from expert opinion through stakeholder engagement processes, including representatives from academia, business, civil society and municipal and government officials. The tool is publicly available online (https://exchange.iseesystems.com/public/esteevermeulen/the-algoa-marine-systems-analysis-tool-algoamsat-user-interface) and allows any user to explore how different combinations of cross-sectoral management interventions can impact the socio-economic dimensions of the blue economy in the Bay and the sustainability of the marine environment over time. The MSAT was built with a bottom-up participatory process with stakeholders and therefore represents a participatory, trade-off and predictive modeling tool that can be used within the MSP process to investigate the outcomes of different scenarios[40].

MSP is a complex and complicated process that must consider the needs of numerous and diverse ocean users to create a management plan that is considered inclusive, and it is recommended to follow an ecosystem-based approach to promote sustainability[10,43]. Producing scenarios of how management decisions will unfold is an excellent way to integrate and package vast amounts of data and knowledge from various stakeholders into interpretable outputs that can support decision-making and coherence among stakeholders. One of the main aims of the Algoa Bay Project was to complement the temporal MSAT decision-support tool with an equally rigorous spatial decision-support tool to integrate socio-cultural connections and sustainable development in a spatial zonation of ocean users. Here, we use a systematic-site prioritization tool, prioritizR[44], to develop four zoning scenarios for the Bay, in an effort to understand the spatial limitations of human uses. We attempt to provide insight into how ocean space can be zoned to foster ocean health that considers the interconnected social-ecological systems. We do this by incorporating spatial layers of commercially valuable activities (e.g., living and non-living resource extraction) with spatial layers that were collated during the initial stage of the Algoa Bay Project, which show the distribution of biodiversity, nature-friendly human activities[38] and areas important to local and traditional communities[19,20].

Systematic-site prioritization is closely synonymous with 'systematic conservation planning' (SCP), which aims to identify representative, well-connected networks of priority sites for biodiversity protection while minimizing a cost[45]. Systematic-site prioritization tools, such as prioritizR[44] or Marxan with Zones (Marzone[46]), identify representative spatially defined zones for multiple marine uses (e.g., refs. 47–49). Various attributes within a site-prioritization algorithm can be altered to meet different objectives and thus produce scenario zonation maps that can be used during stakeholder engagement as well as provide evidence-based support to final zonation maps. South Africa has long used SCP to identify and support the designation of candidate sites for marine protected areas (MPAs)[38,50–52]. SCP has subsequently been used to delineate Ecologically and Biologically Significant Areas[53] and priority areas for shark and ray conservation[54] to contribute to further expansion of South Africa's MPA estate. However, the current MSP Framework in South Africa[55,56] does not suggest using the same or similar methodology for the zonation schemes within its marine area plans, even though the methodology has been used as a successful support tool for zoning plans elsewhere[57,58]. This may be due to the complexity of analyses or that the methods and tools are viewed as a 'black box' (i.e., complex analyses, whose inner workings are hidden or not easy to understand). This study thus aims to increase transparency of the algorithm's inner workings, key assumptions and parameters by providing a detailed step-by-step guide on how scenario zoning plans are created within prioritizR. The method specifically allows for an inclusive and participatory approach by developing different scenarios to explore the complex trade-offs that decision makers face.

Results

Spatial zoning solutions for the four zoning scenarios we developed for Algoa Bay using the prioritizR tool[44] are shown in Fig. 1. By altering various attributes in prioritizR's algorithm (see 'Methods'), we explored scenarios based on different levels of the three axes of environmental health, sustainability of governance and the level of socio-economic prosperity. Two scenarios were biased toward allocating more space to economically beneficial activities such as tourism, fisheries and mining (i.e., the Business as Usual and Empty Bay scenarios), one scenario was biased towards allocating more space toward conservation and cultural/heritage needs (i.e., the Untouched Paradise scenario) and one scenario allocated space to all activities without bias (i.e., the Bay of Plenty scenario). To further investigate spatial allocation, zoning scenarios were run with and without the mandatory allocation of planning units (PUs) to a zone.

Scenario zoning schemes for Algoa Bay

By altering feature targets, feature layers, permitting or restricting mining and/or ship-to-ship bunkering activities, the four zoning scenarios showed strikingly different marine zonation in Algoa Bay (Fig. 1). For example, the area allocated to the conservation priority zone decreased as targets of extractive activities (such as mining and fishing) increased through the scenarios from Untouched Paradise, to Bay of Plenty and to Business as Usual (Fig. 2). In the Empty Bay scenario, where the current MPAs were removed from the solution, more space was allocated to the conservation priority zone compared with other scenarios, even though biodiversity features received lower targets compared with other feature layers (Fig. 2). However, the area allocated to the conservation priority zone in the Empty Bay scenario was less than the area of the current MPAs in the Bay. Through the scenarios, as more preference was given to human activities, the zones became more fragmented (indicated by a lower aggregation index; Fig. 3a, c) and less costly (as determined by the cost layer per zone, the cost of assigning a planning unit to a zone), except for the commercial fisheries zone (Fig. 3b, d).

Mandatory versus non-mandatory allocation of planning units to zones

In the two zoning scenarios, Untouched Paradise and Bay of Plenty, not all planning units had to be allocated to a zone for features to meet their targets, resulting in unallocated areas of 558 $km^2$and 1432 km^2, respectively (Figs. 1 and 2). However, in the Business as Usual and Empty Bay scenarios, almost all planning units had to be allocated to zones, with only 24 km^2 and 2 km^2 area remaining unallocated, respectively (Figs. 1 and 2). The Bay of Plenty zoning scenario had the most unallocated area even though this scenario included equitable target setting for all features and included the current MPAs as well as current ship-to-ship bunkering and mariculture areas (Fig. 1). All other zoning scenarios were biased towards allocating more area to certain zones as higher targets were set for either biodiversity and cultural heritage, or towards commercially beneficial activities. For the Untouched Paradise and Empty Bay zoning scenarios, the algorithm had more area available to allocate to different zones to meet feature layer targets, as ship-to-ship bunkering and MPAs were not locked into their solutions, respectively. However, regardless of more space being available, the algorithm still required more area to meet these scenarios targets, as less area remained unallocated compared with that of the Bay of Plenty zoning scenario (Fig. 2). The Bay of Plenty scenario had the most unallocated area (Fig. 2) and high aggregation scores for all zones (Fig. 3). This indicates that when scenarios bias their zoning towards certain activities (by awarding higher targets toward either biodiversity and cultural heritage or commercially rewarding activities) there will be higher competition for space in the Bay compared with when an equitable and ecosystem-based approach is taken to create a zoning scheme.

Discussion

Creating a zoning scheme in MSP is both complex and complicated. It requires decision makers to consider the spatial extent and distribution of numerous activities and integrate knowledge from a diverse array of stakeholders to spatially zone these activities. If national[55,56] and international[10] guidelines for MSP are adhered to, this zonation must be considered inclusive across various stakeholder groups as well as promote sustainable development by incorporating an ecosystem-based approach. This study demonstrates how developing zoning scenarios using the spatial decision-support tool, prioritizR[44], can consider and integrate a large data set (142 spatial layers) and explore different stakeholder interests by producing single-layer outputs that are driven by different narratives. By complementing the temporal decision-support tool, 'Algoa Bay Marine Systems Analysis Tool', created by Vermeulen-Miltz et al.[42], this study shows the potential of decision-support tools to enable inclusive stakeholder input and involvement during the decision-making process of MSP by increasing transparency and encouraging informed engagement. The zoning scenarios presented here provide the insight that the entire planning area does not need to be zoned to inclusive and ecosystem-based targets (i.e., the Bay of Plenty zoning scenario). Additionally, in scenarios that emphasize extractive use (i.e., the Business as Usual and Empty Bay scenarios), space is more contested and there is no room for development of new sectors (e.g., renewable energy) or growth of present sectors.

The Bay of Plenty zoning scenario, resulting from an attempt to 'fairly' divide the marine space among users, allows each ocean use to meet its spatial requirement. This provides evidence that, in the context of this study, if marine spatial plans deviate from the Business as Usual scenario, they can result in 'win-win' scenarios that are inclusive, environmentally sustainable and economically rewarding. To further explore this, we present two 'extreme' scenarios, Empty Bay and Untouched Paradise, representing potential zoning plans if exploiting the bay for economic gain is undertaken unsustainably or if conserving the bay is prioritized with no economic growth plan, respectively. These 'extreme' scenarios exhibit the potential

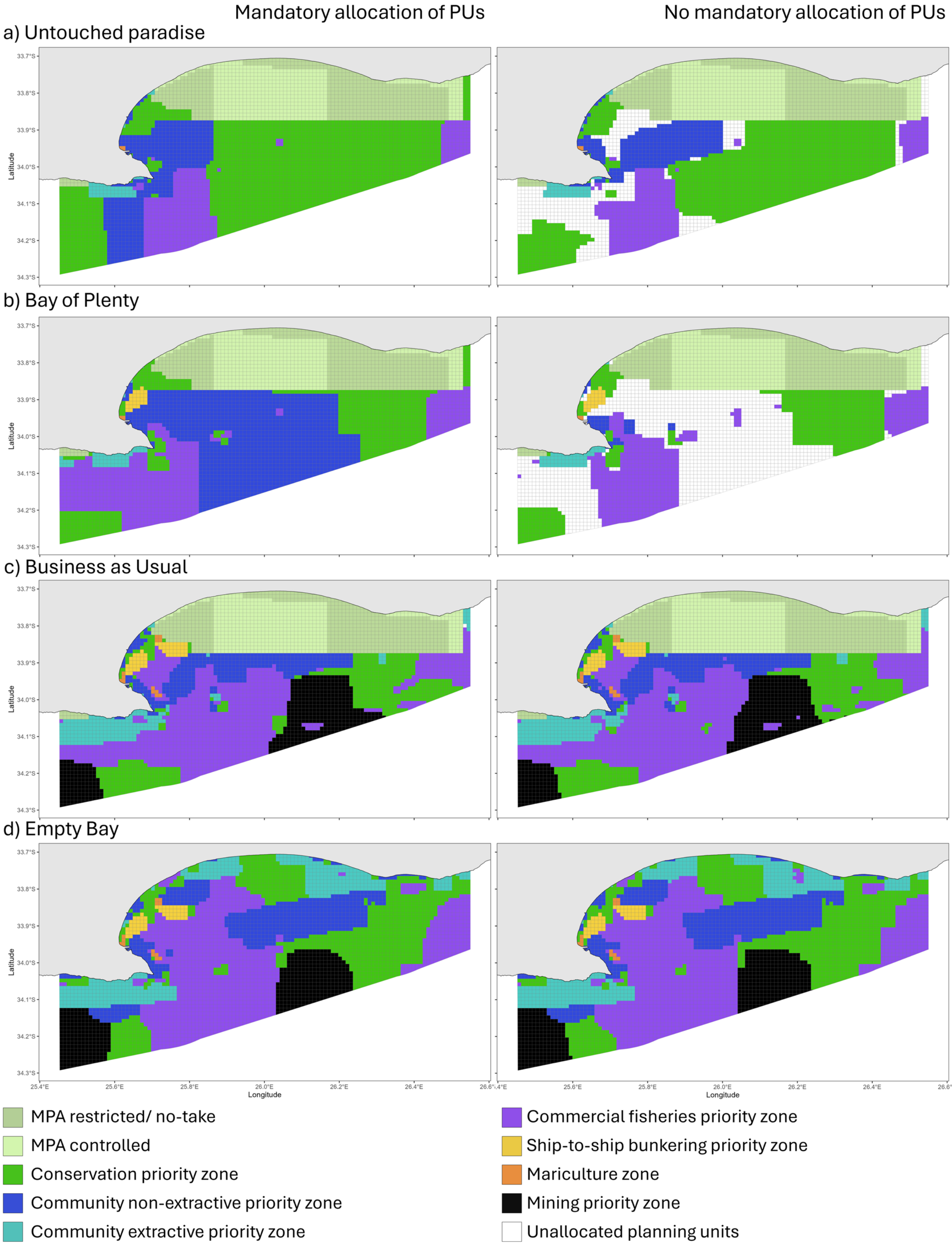

Fig. 1 | Potential zonation scenarios for Algoa Bay, South Africa. Solutions of prioritizR zoning prioirtization analyses for four zoning scenarios. a Untouched Paradise, **b** Bay of Plenty, **c** Business as Usual, and **d** Empty Bay, with (left) and without (right) mandatory allocation of planning units (PUs) to a zone within the prioritization problem.

losses in ocean use to stakeholders if the development of a marine spatial plan does not follow an inclusive and participatory approach. These scenarios illustrate how spatial decision-support tools, like prioritizR, can be utilized during the marine spatial planning process to integrate and distill large amounts of quantitative data with qualitative storylines into 'easy-to-understand' visualizations. These visualizations can facilitate discussion and cohesion among ocean users as well as encourage participation of more diverse stakeholders.

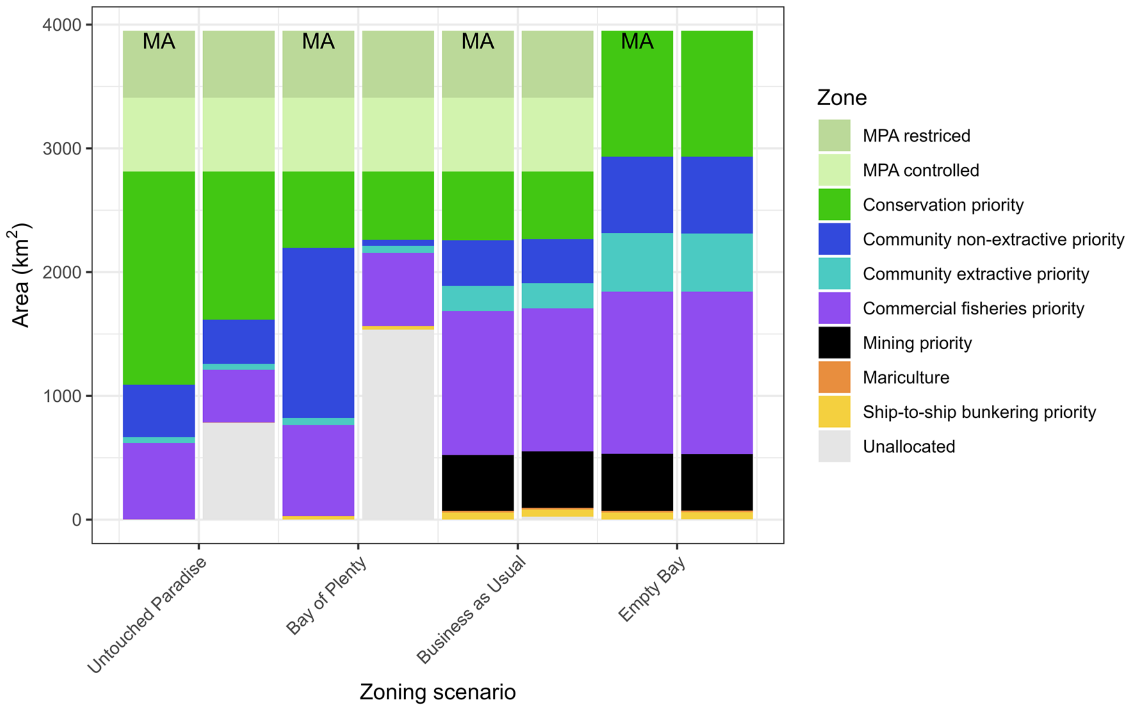

Fig. 2 | Area of zones in potential zonation scenarios for Algoa Bay, South Africa. Area of zones for four zoning scenarios: Untouched Paradise, Bay of Plenty, Business as Usual and Empty Bay, with (MA) and without mandatory allocation of planning units to a zone within the prioritization problem.

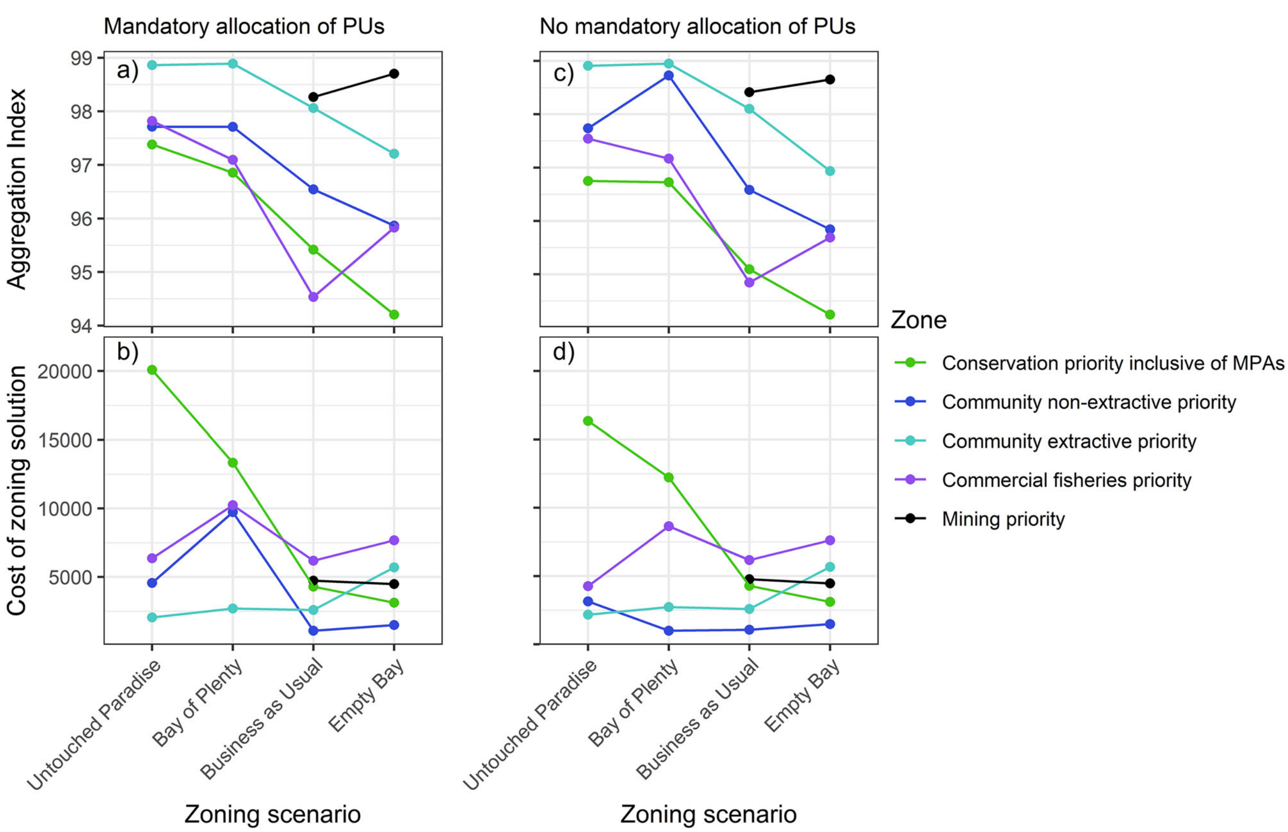

Fig. 3 | Aggregation index and total cost of zoning planning units (PUs) to a zone in potential zonation scenarios for Algoa Bay, South Africa. Aggregation index (ranging from 0–100, disaggregated to aggregated, respectively) and total cost of zoning PUs to a zone for each zone for four zoning scenarios with (**a**, **b**) and without (**c**, **d**) mandatory allocation of PUs to a zone, respectively. Cost is explained in the 'Methods' section: development of scenarios and Cost layer, and refers to the user-defined cost of assigning each planning unit to a zone.

In all four zoning scenarios, targets specified for each feature layer were met, albeit with or without mandatory allocation of planning units to a zone. However, as marine activities increased through the scenarios, the complexity of zoning scenarios increased, leading to greater fragmentation and complexity of zones, as was found by Mazor et al.[59]. A zoning scheme that consists of multiple fragmented zones, each permitting or prohibiting certain activities, will be difficult, if not impossible, to implement and regulate. Furthermore, the large amount of unallocated area in the Untouched Paradise and Bay of Plenty scenarios (that had no mandatory allocation of planning units) should caution planners to avoid trying to zone entire marine areas. Instead, this 'unzoned area' can be zoned as a 'Future Development Zone' that can be allocated to emerging marine activities (such as renewable energy). In practice, as outlined by South African[55,56] and international[10] frameworks, MSP processes should not be static but should be subject to monitoring and evaluation to allow for adaptive management and improvements over time[60,61].

Both this study and the system dynamics model (i.e., a temporal decision-support tool) for Algoa Bay by Vermeulen-Miltz et al.[42] modeled four future scenarios of the Bay following similar axes to develop the scenarios, i.e., socio-economic wealth/prosperity, environmental health, and governance for sustainability. Here, the most equal, inclusive or best 'win-win' scenario, the Bay of Plenty, attempted to 'fairly' divide the marine space between biodiversity features and human activities by setting area-based targets following Holness et al.[38]. This 'winning' scenario followed the narrative of an ecosystem-based approach to grow the blue economy, within a governance regime that supports sustainable use of the environment and allocates space among all ocean users equally. The equivalent scenario in Vermuelen-Miltz et al.[42] was the Sea of Plenty. Similarly, this scenario included ocean governance for sustainability and followed an ecosystem-based approach. It surfaced as the best ('win-win') scenario because it showed the highest socio-economic gains as well as the best marine health over the study's 40-year projection, with many socio-economic gains being directly correlated with healthy ecosystems (e.g., increased mariculture yields, fish biomass and tourist numbers). Together, the temporal decision-support tools of Vermeulen-Miltz et al.[42] and the spatial decision-support tool presented here, are powerful tools for understanding the consequences of decision-making and how governance can shape the future. The result of either product is useful as a standalone, where the zoning spatial decision-support tool lends itself to understanding spatial limitations, and the system dynamics model highlights future economic gains, a strong driving tool behind decision-making in MSP, especially in Global South countries[62]. By supplying easily understood economic information and projections, scenarios can inform and support decision-making allowing ecological and socio-economic goals to be met. Future work should build on existing examples of spatial-temporal coupling of models for decision-making (see refs. 63–66). Coupled models can allow planners to consider the impacts of zonation schemes on environmental and socio-economic well-being, and the ecosystem services provided by healthy environments[67] (Orolowitz et al. (submitted)).

Spatial decision-support tools, such as Marzone or prioritizR are sensitive to input data, feature targets and cost layers[67–70]. Although Algoa Bay is very well sampled with respect to environmental parameters, social, cultural and economic parameters were more difficult to source and presented a limitation to our study. In addition, we had to alter some of the data sets to conform to the spatial regulations put in place in 2019 by the declaration of the Addo MPA (for more detail see 'Methods' and Supplementary Note 1) and the no-take area for the small-pelagic fisheries put in place in 2023 to protect African penguins[71]. However, rather than discouraging planners from using spatial models when data are imperfect, we encourage planners to develop scenarios with available data that are transparently and explicitly incorporated into scenarios. No matter the data quality, scenarios are very effective at starting conversations and exploring options across diverse stakeholder groups[72]. By increasing the transparency of input data and parametrization of spatial decision-support tools, effectively removing the black box, diverse stakeholders are able to interpret the resulting maps (e.g., ref. 49). Transparency also increases the legitimacy of the spatial decision-support tool among stakeholders and encourages them to provide data so they are not 'forgotten' within the site selection procedure[69]. To demonstrate the value of contributing data and knowledge to stakeholders, planners can produce scenarios with and without certain data. For example, Kockel et al.[68] used Marzone[73] to investigate potential sites for new MPAs. They presented three zoning scenarios that incorporated various levels of data set completeness for small-scale fisheries. The data poor scenarios showed how small-scale fishers would incur inequitable costs in the MPA design compared with scenarios that incorporated high quality data collected through stakeholder participation workshops. Although spatial zoning tools are not expected to produce a final solution[74], by allowing for stakeholder participation in scenario development, greater understanding of zoning outcomes can be reached across border audiences[58], leading to large areas of agreement and more effective implementation of marine spatial plans[75].

Depending on the goals and objectives of different zoning scenarios, important information can be provided to planners to allow for the evaluation of trade-offs, synergies and conflicts between activities. Both prioritizR and Marzone decision-support tools have been successfully used to inform final zonation maps (Grenadine islands[76]; St. Kitts and Nevis[57]; Malaysia[58]) and their potential to inform the MSP process is increasingly being shown in academic studies[49,59,67,68,77–80]. Despite their usefulness in MSP processes, zoning scenarios require the analysis of large quantities of heterogeneous, multi-sourced and spatially explicit data. Tools such as prioritizR can be used to collate these large data sets and integrate them in a way that produces zoning maps that meet users objectives and are easier to digest and understand compared to being confronted with the raw data alone. Resulting scenario zoning maps are an ideal discussion tool to weigh trade-offs and help end users by providing a systematic and defendable result that can support decision-making[40,41,49,81].

A zoning scheme that is developed concurrently with a defensible, systematic approach and genuine and effective public and stakeholder engagement can facilitate an integrated MSP that can enable effective implementation. The next steps of the national MSP process in South Africa will be to incorporate all information in the draft marine sector plans to produce the first of four marine area plans in 2025. These marine area plans will consist of general development guidelines, sector development guidelines and a zoning scheme[55,56]. In South Africa, the MSP process of collating spatial data, understanding various sectors objectives, future growth goals as well as synergies and conflicts between sectors is already far progressed. A National MSP Data and Information Report has been published (detailing how various sectors are using the South African marine space[82]) and draft marine sector plans (detailing national development objectives, priorities and spatial interests of each marine sector[83]) are currently under review following public comment. However, it is unclear how the Marine Spatial Planning National Working Group (MSP-WG) intends to collate all these data and objectives into a comprehensive zoning scheme. South Africa has a long history of using systematic conservation planning to identify priority sites for conservation, e.g., conservation plans/ MPA design[50–52,84], sharks and rays[54], and identifying Ecologically and Biologically Significant Areas[53]. Here we show the value of using a similar tool to produce zoning scenarios for the MSP process and recommend that a similar approach is used to produce the marine area plans for South Africa.

An equitable and ecosystem-based MSP process requires integration of knowledge across disciplines (e.g., policy and science), sectors and power structures within the affected communities[75,85–88]. Integration is facilitated through stakeholder engagement at various intervals throughout the MSP process. Using traditional and local knowledge from those who are frequently using the marine space, including commercial, subsistence and recreational fishers, tourist operators, as well as those using the space for religious, spiritual or recreational purposes can provide different perspectives and invaluable knowledge about the marine environment which can complement and should inform the knowledge and practice of coastal managing authorities and researchers[74]. A bottom-up approach to MSP that

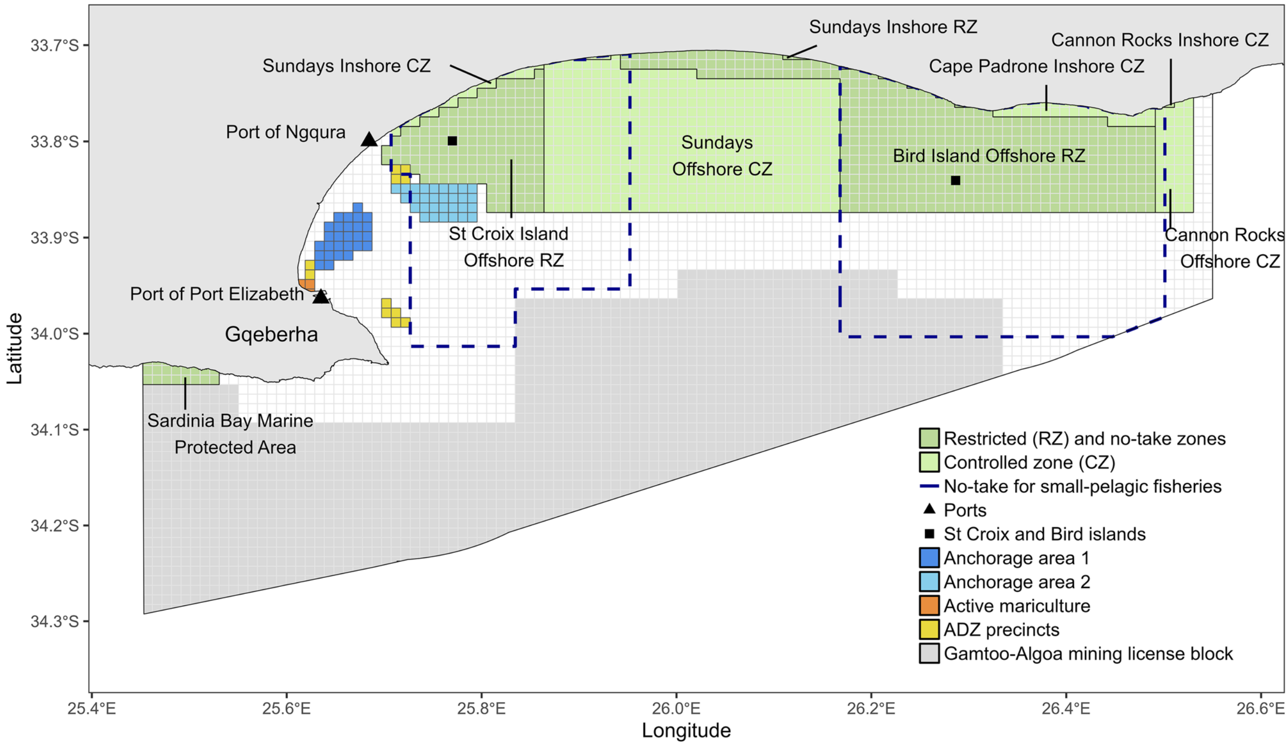

Fig. 4 | The planning domain with key features shown. The planning domain used for zoning scenarios in Algoa Bay, South Africa, is divided into 1 km^2 planning units. Key features and names of the marine management areas of the Addo Elephant National Park Marine Protected Area (shaded in green) are illustrated. The Aquaculture Development Zone (ADZ) precincts are areas zoned for future mariculture by the Department of Forestry, Fisheries and the Environment.

is inclusive and ecosystem-based and seeks to include and collaborate with all stakeholders, from government to civil society and grassroots groups, is both possible and necessary if we are to support the UN Sustainable Development Goals in a time of rapid climate change, increased environmental destruction, human rights abuses and economic uncertainty.

In conclusion, we have provided evidence that using decision-support tools to explore scenarios of ocean use can integrate large amounts of spatial data and stakeholder input to produce relatively easily understood outputs (i.e., maps). Once inputs of a prioritizR algorithm have been collated, it is relatively easy and quick to adjust and produce scenarios that are guided by stakeholder input. These scenario outputs are a powerful tool, and even though they are not final marine spatial plans, they can guide the decision-making process and increase the inclusivity of stakeholders and transparency of the process.

Methods

We used the spatial decision-support tool, prioritizR[44], to explore four zoning scenarios for Algoa Bay. PrioritizR with multiple zones is a systematic-site prioritization tool that allocates a user-defined proportion of features or activities to several user-defined zones at the lowest possible cost. Here, the proportion of features (i.e., feature targets) allocated to zones was altered to create the four zoning scenarios: two scenarios were biased toward allocating more space to economically beneficial activities such as tourism, fisheries and mining (i.e., the Business as Usual and Empty Bay scenarios), one scenario was biased towards allocating more space toward conservation and cultural/heritage needs (i.e., the Untouched Paradise scenario) and one scenario allocated space to all activities without bias (i.e., the Bay of Plenty scenario). We explain the creation of the inputs needed to run a prioritizR algorithm (i.e., zones, cost layer and feature target development) and how these inputs were altered to create zoning scenarios.

All spatial manipulation and analyses were conducted in the R statistical environment (R version 4.3.3[89]). Code and data are available in the GitHub repository: https://github.com/Tegan151/AlgoaBayZoningScenarios. Analyses described hereafter were performed with data projected in the Africa Equal-Area Conic projection.

Planning domain

Using Marxan software[46], Holness et al.[38] developed a systematic conservation plan for biodiversity conservation and nature-based activities in Algoa Bay. To facilitate the transfer of their spatial layers to our analysis, we used the same planning domain and planning units. The planning domain extended 150 km along the shore from Sardinia Bay to Cannon Rocks and was divided into 4108 x 1 km^2 planning units (Fig. 4). The landward extent of the planning domain follows the dune base[90] and extends to the outer edge of the territorial sea, 12 NM offshore[91].

Collation of spatial data

A total of 142 spatially explicit data layers (referred to henceforth as 'feature layers') of marine biodiversity and human activities were collated (Table 1). Feature layers of commercial, subsistence and recreational fishing, active mariculture, transport and related activities, biodiversity features and non-extractive recreational activities were sourced from Holness et al.[38], who collated the data from various sources including published information, expert mapping by local and scientific stakeholders and the National Biodiversity Assessment 2018[92]. Supplementary Tables 1 and 2 provide details of the data sources and maps of data layers. In addition to data provided by Holness et al.[38], we sourced spatial layers of the mining license block, legal precincts for mariculture, dredge dumping areas, ballast water discharge areas, waste-water outfall points and a military practice area (Table 1). To assign these spatial layers to the 1 km^2 planning units, the spatial polygon was intersected with the planning units using the st_intersection function within the sf R package[93,94]. If the areas of the resulting intersected planning units were >50% of the original planning units' area, the activity was assigned as being present in that planning unit (i.e., a value of 100). Values of all feature layers (e.g., fishing effort) were scaled between 0 and 100.

Table 1 | Summary of human activities and biodiversity features that were included in the systematic-site prioritizations that zoned various marine uses in Algoa Bay, South Africa, in four future scenarios

Features (*n*)	Description	Data source	Zone allocation
Human activity features (50)			
Commercial fisheries (5)	Intensity and distribution of commercial longline, shark longline, small pelagic, squid and inshore bottom trawling fisheries.	Holness et al.[38]	Commercial fishing priority zone
Subsistence and small-scale fishing (6)	Areas of value/importance for livelihood and subsistence are divided into four layers to represent community distribution across the bay (4)	Strand et al. (in review) See Supplementary Note 1 for more details.	Community extractive priority zone
	Areas used by small-scale fishers; this fishing requires a permit, which specifies catch limits (1).	Strand et al. (in review) See Supplementary Note 1 for more details.	Community extractive priority zone
	Subsistence fishing intensity (1).	Holness et al.[38]	Commercial fishing priority zone
Culturally significant areas (13)	Areas of cultural value/importance for heritage (3), learning (4) and spiritual means (2) are divided into four layers to represent community distribution across the bay.	Strand et al. (in review) See Supplementary Note 1 for more details.	Community non-extractive priority zone
	Positions of shipwrecks, ancient fish traps, shell middens and other archeological areas of importance (4).	Holness et al.[38]	
Extractive recreational activities (5)	Recreational fishing areas (fishing from kayaks and ski boats), recreational spear fishing areas, shore fishing areas, and shore competition fishing areas	Holness et al.[38]	Community extractive priority zone
Non-extractive recreational activities (17)	Popular bird and whale watching (2), boating (2), open water swimming (1), surf-ski (1), stand-up paddle boarding (1), kiteboarding (1), surfing (1), lifesaving competitions and training (1) and beach going (1) areas and shark cage diving (1) and scuba diving (1) site(s).	Holness et al.[38]	Community non-extractive priority zone
	Areas of cultural value/ importance for recreational use divided into four layers to represent community distribution across the bay (4).	Strand et al. (in review) See Supplementary Note 1 for more details.	
Potential areas for mining exploration and extraction (1)	The Algoa-Gamtoos license block for oil and gas exploration and extraction	Digitized from the South African Petroleum Agency (PASA) online geoportal (https://www.petroleumagencysa.com/)	Mining priority zone
Current and proposed mariculture (2)	Active mariculture	Holness et al.[38]	Mariculture zone
	Legal precincts for mariculture	Digitized from Massie et al.[105]	
Ship-to-ship bunkering areas (1)	Anchorage areas	Holness et al.[38]	Anchorage areas were used in zonation as a proxy for the ship-to-ship bunkering priority zone
Biodiversity features (83)			
Shorebird and seabird distributions (14)	Damara tern nesting and feeding sites, swift tern breeding sites and Roseate tern, Antarctic and other tern roosting sites (6).	Holness et al.[38]	Conservation priority zone
	Coastal bird species richness and abundance from the South African Bird Atlas Project (SABAP2) (2).	Holness et al.[38]	
	Colonies, and relative presence and core areas used at sea by African penguins and Cape gannets (6).	Holness et al.[38]	
Whale and dolphin distribution (8)	Distribution of bottlenose, common and humpback dolphins, Bryde's, minke, and southern right whales and orcas.	Holness et al.[38]	
Ecosystem types (18)	National classification of coastal and marine ecosystem types (16).	National Biodiversity Assessment (NBA) 2018[92]	
	Fine-scale reef distribution (1).	Holness et al.[38]	
	Abalone-supporting reefs (1).	Holness et al.[38]	
Fish (27)	Distribution of 25 common linefish species (25).	Holness et al.[38]	
	Important recruitment and nursery areas (2).	Holness et al.[38]	
Turtles (1)	Turtle sightings.	Holness et al.[38]	
Sharks and rays (12)	Distribution of Zambezi, pyjama, shy, dusky, smooth-hound, spotted gully, hammerhead, ragged tooth, bronze whaler, white sharks, and eagle, bull, blue and diamond rays.	Holness et al.[38]	
Squid (2)	Important squid spawning and nesting areas.	Holness et al.[38]	

Table 1 (continued) | Summary of human activities and biodiversity features that were included in the systematic-site prioritizations that zoned various marine uses in Algoa Bay, South Africa, in four future scenarios

Features (*n*)	Description	Data source	Zone allocation
High priority biological areas (1)	Resulting biodiversity priority areas in Algoa Bay highlighted in a systematic conservation planning analysis by Holness et al.[38].	Holness et al.[38] (Fig. 2b)	
Area-based management tools in Algoa Bay (2)			
Marine Protected Areas	Addo Elephant National Park (controlled and restricted) and Sardinia Bay (no-take) Marine Protected areas	Digitization of Government Gazetted delineated protected[96]	Biodiversity priority zone
No-take areas for commercial small-pelagic fisheries	No take zones for small-pelagic fisheries around African penguin breeding colonies implemented in 2023.	Provided by Birdlife South Africa	Not used for zonation
Layers used for construction of cost layers only (7)			
Waste outlets (1)	Waste-water outfall points in Algoa Bay	Nelson Mandela Bay Municipality	
Military practise area (1)	Area used for military training operations by the South African Navy within the Algoa Bay	SANHO.	
Other (1)	Map of cumulative intensity of 31 activities and pressures, such as waste-water outfalls, coastal development, coastal disturbance, alien invasive species, and industrial fisheries.	National Biodiversity Assessment (NBA) 2018[92].	
Transport and related activities (4)	Shipping intensity (1) and lanes (1)	Holness et al.[38]	
	Dredge dumping (1) and ballast water discharge (1) areas	South African Navy Hydrographic Office (SANHO).	

For more details on data and their sources, see the Supplementary Table 1.

To include socio-cultural and heritage information, the following feature layers were developed: (1) livelihood, work, subsistence; (2) spiritual and/or religious connections; (3) recreational uses, fun and family time; (4) learning and knowledge; and (5) cultural heritage and history. These features were mapped by Strand et al. (in review) using a participatory community mapping approach during stakeholder engagement workshops with local and Indigenous people residing in Algoa Bay. Strand et al. (in review) co-created the types of categories of socio-cultural and heritage features to map. They did this with local and Indigenous stakeholders by discussing the main themes emerging from transect walks, arts-based participatory research in the form of in-situ photovoice and digital storytelling, collaborative workshops and semi-structured interviews collated during their previous research[13,19]. To account for accessibility to areas by different communities across the bay, these five feature layers were subdivided into four sub-feature layers determined by their geographic locations: (1) western extent of planning domain to the port of Port Elizabeth, (2) port of Port Elizabeth to the port of Ngqura, (3) port of Ngqura to Colchester, and (4) Colchester to eastern extent of planning domain (Supplementary Tables 1 and 2). Offshore areas within the livelihood, work, and subsistence feature layer were extracted and included as a separate feature layer and included as a separate 'small-scale fishery' layer. Small-scale fishers make a small profit from their catch and were thus separated from the livelihood, work and subsistence feature layer (Mia Strand, pers. comm.). Changes to spatial layers after the declaration of the Addo Elephant National Park Marine Protected Area in 2019.

Data collection for the analysis by Holness et al.[38] and the National Biodiversity Assessment 2018[92] occurred before the establishment of the Addo MPA[95]. The MPA is divided into eight marine (three restricted and five controlled zones, Fig. 1) and three estuary management areas (two restricted and one controlled) that restrict or allow certain activities[96]. In general, no person may fish or attempt to fish in restricted zones, and no diving is allowed in the Sunday's inshore and Bird Island offshore restricted zones (Fig. 4). Fishing with a permit is allowed in the Addo MPA controlled zones, with the exception of fishing from a vessel in the Sundays inshore and Cape Padrone inshore control zones (Fig. 4). It was not possible to source data for some human activities, such as commercial, small-scale and subsistence fisheries and diving, after the Addo MPA was declared, thus these activities were removed from within the boundaries of the Addo MPA zones which now restrict them (Supplementary Table 2).

The distribution of commercial fisheries intensities across the Bay was calculated using Vessel Monitoring System (VMS) and/or logbook data, assigning intensity of use per planning unit between 0 and 100[97], with the exception of the small-pelagic fishery feature layer, which is an interpolated spatial layer of catches scaled between 0 and 100[92]. To simulate displaced fishing intensity after the declaration of the Addo MPA, fishing intensity was extrapolated to planning units outside of the MPA's restricted areas (Supplementary Table 2) by allocating all planning units of a feature layer within a prohibited a value of zero and then applying Eq. (1) to calculate the extrapolated value of each planning unit ($PU_{extrapolated}$).

$$PU_{extrapolated} = PU_{revised}\left(\sum PU_{original} / \sum PU_{MPA}\right) \tag{1}$$

Where: $PU_{revised}$ is the value of a planning unit once all planning units that are no longer allowed in the Addo MPA have been allocated a value of zero, $\Sigma PU_{original}$ is the sum of the original planning unit values before the allocation of zero to those values no longer allowed in the Addo MPA and ΣPU_{MPA} is the sum of the original planning unit values that were allocated a zero within the Addo MPA.

In addition, no-take zones for the commercial small-pelagic fishery were declared for 10 years around the two African penguin *Spheniscus demersus* colonies on St Croix and Bird islands in Algoa Bay to reduce potential predator-fisheries resource competition (Fig. 4 and Supplementary Note 1[71,98]). To account for the no-take zones for the small-pelagic fishery, the commercial small-pelagic feature layer was further altered, using the formula above, to remove this fishery from the newly formed no-take areas.

Zone types

Seven types of zones were defined for this study, and each planning unit can be attributed to only one type of zone by the prioritization algorithm. Following the 'National Framework for Marine Spatial Planning in South

Table 2 | The types of zones and their primary use defined for Algoa Bay

No.	Zone	Primary use	Example
1	Conservation priority zone	Conservation and protection of biodiversity and related ecosystem health, as well as the functioning of ecosystem services.	Reefs, penguin foraging areas, fish nurseries.
2	Non-extractive community priority zone	Non-extractive activities that have little impact on ecosystem health. Areas of socio-cultural importance identified by Indigenous and local co-researchers are also included (Strand et al. In Review).	Recreational and tourism activities such as boating, whale and bird watching, water sports, scuba diving, and shark cage diving and sites of historical artifacts. Socio-cultural areas include those important for heritage, spiritual activities and learning.
3	Extractive community priority zone:	Non-commercial extractive activities. To avoid potential competition for resources, commercial fisheries are not prioritized in this zone (although recreational and subsistence fishing is predominantly onshore whereas commercial fisheries are predominantly offshore).	Recreational and subsistence fishing
4	Commercial fisheries priority zone	Fisheries working for a profit, i.e., commercial and small-scale fishing	Small-pelagic fishery
5	Mining priority zone	Mining exploration and extraction	
6	Ship-to-ship bunkering priority zone	Anchorage areas were used as a proxy for this zone. Although anchorage areas exist in the bay, within the prioritization algorithm, these areas were not zoned because many of the feature layers overlap with them. However, depending on the scenario (defined below), anchorage area one, or areas one and two, were locked into the solution as a proxy for bunkering.	
7	Mariculture exclusive zone	Mariculture (exclusively)	Bivalves

Africa'[56], zones were named after their primary use (i.e., the activity that is given priority in a particular zone) or their exclusive use. A zone may allow activities (consent-use activities) that do not impede the primary use, and it may also prohibit certain activities that conflict with the primary (prohibited use activities). Table 2 lists the zones defined for this study. Each feature layer was assigned to a zone type based on its primary use (Tables 1 and 2). Zones which may potentially allow additional consent uses have a 'priority zone' included within their naming to indicate that the zone may allow certain other consent uses. Consent and prohibited uses of each zone should be included in the management regulations of each zone and determined with appropriate stakeholders.

Scenarios are future projections used to explore the consequences of management decisions made today. Vermeulen-Miltz et al.[42] developed a systems dynamics model (MSAT) to explore the consequences of decisions made for the management of Algoa Bay along three axes: one represents a continuum from good to bad ocean health, indicating whether ecosystems and biodiversity are thriving or dying; another represents good to bad ocean wealth, indicating the potential financial gain from the bay through industry and tourism; and the third represents good to bad governance, indicating whether sustainable governance practices such as an ecosystem-based approach are implemented or not. They describe four scenarios placed at different extremes of these axes; the 'Sea of Plenty' and 'Dead man's Chest' scenarios result when management is at the 'good', or 'bad' end of all three axes, respectively. In-between scenarios result from management practices placed at different positions along the axes. The MSAT produces 'behavior over time graphs' that are useful for exploring the values, over time, of variables of interest to the system (e.g., income from mariculture), but the models are not spatially explicit. In order to investigate the consequences of different spatial zoning scenarios for the bay, we used the same three axes as Vermuelen-Miltz et al.[42] and developed four similar zoning scenarios: the 'Bay of Plenty' and 'Empty Bay' scenarios are at the 'good' or 'bad' extremes of all three axes, respectively, and the 'Business as Usual' and 'Untouched Paradise' are two alternatives (Fig. 5 and Table 3).

Development of zoning scenarios

Human activities in Algoa Bay were zoned with prioritizR R package[44]. PrioritizR is similar to the commonly used Marxan with Zones or Marzone[73] software, but differs in that it uses integer linear programming and exact solvers to produce a single optimal solution (rather than a set of near-optimal solutions as produced by Marxan). By using prioritizR's minimum set objective function to solve prioritization problems, solutions reflect the minimum set of planning units that meet or exceed targets, while minimizing the costs associated with the planning units selected, where:

- Targets are the user-defined proportion of each feature layer to be represented within a zone in the final zonation solution. To reduce analytical complexity, targets were set to be met exclusively by one zone type. Features were allocated to zones based on the zone's priority use (Fig. 6).
- A cost is a spatial layer representing the actual or surrogate cost of assigning a planning unit to a zone, for example, the potential loss of catches by fisheries when a no-take zone is introduced[80]. PrioritizR uses one spatial layer of cost per zone.

Zone development. Within prioritizR, inputs for zones one to five (Table 2) were relatively straightforward, that is each zone had targets for each feature layer defined and a cost layer assigned. However, for zones 6 and 7 (ship-to-ship bunkering and mariculture), the existing legally designated (anchorage areas) or proposed zones (proposed Aquaculture Development Zone (ADZ) precincts) for these activities were used (see Supplementary Note 1). Within prioritizR, to account for planning units a-priori as belonging to zones, the planning units can be 'locked-out' of all other zones thus making these planning units unavailable for these zones. However, prioritizR's algorithm prefers the user to delete planning units that are not available for solving the zonation problem, but we did not wish to present maps with any planning units deleted. Rather, we chose to combine these activities in a sixth zone and 'locked in' the planning units to represent the presence of these activities in the zone's solution. A cost layer was created for this zone by assigning a cost of one to the 'locked in' planning units, and all other planning units received a cost of 100).

The existing Sardinia and Addo MPAs are already zoned for the conservation and protection of biodiversity and were therefore locked into the conservation priority zone. They are represented in results as MPAs, and any additional planning units needed for the biodiversity targets to be met are presented as the conservation priority zone. However, the management regulations of the Sardinia and Addo MPAs allow many non-extractive activities and the controlled zones of the Addo MPA allow fishing activities with a permit. Therefore, many of

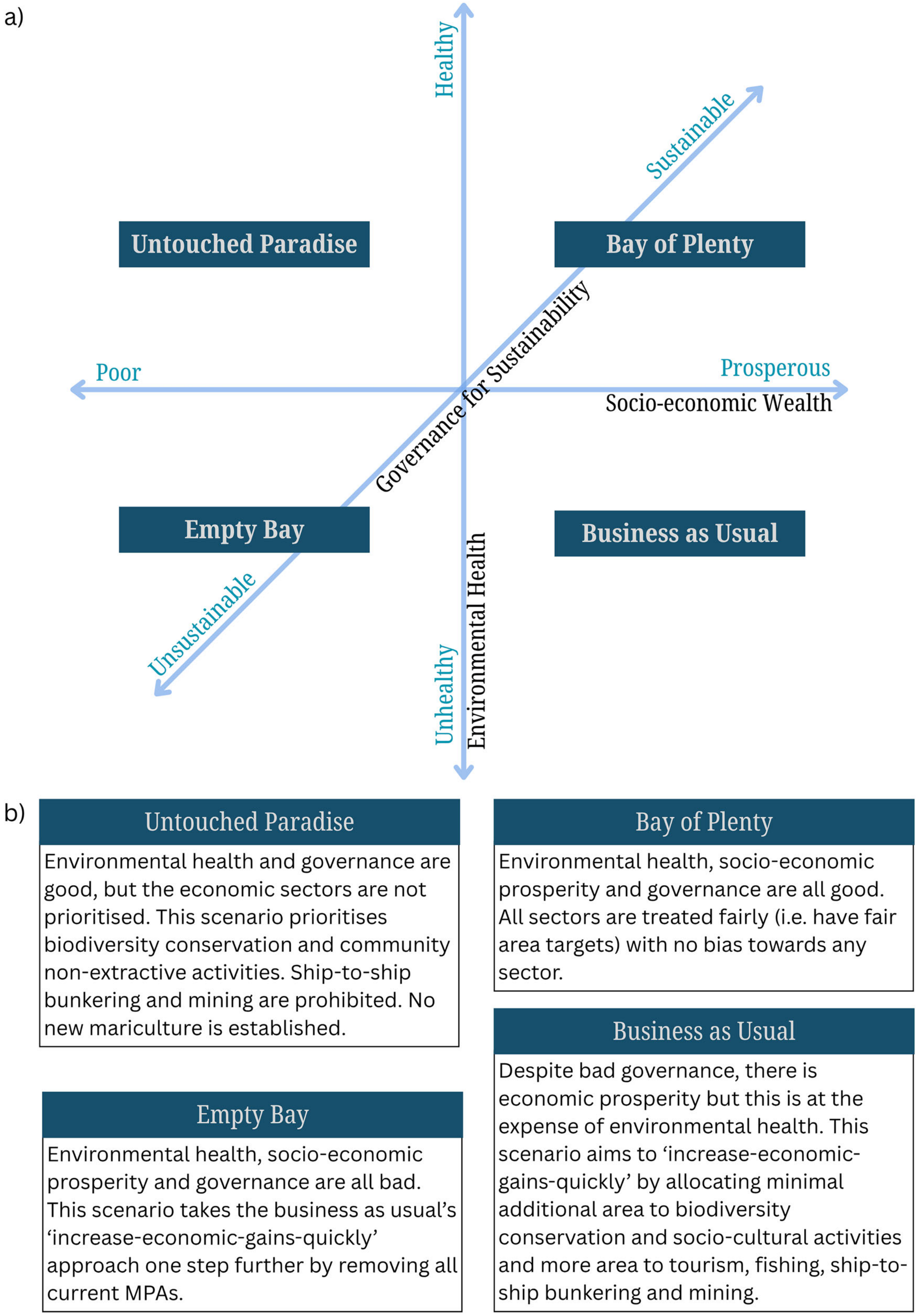

Fig. 5 | Schematic and brief narratives of four zoning scenarios for Algoa Bay, South Africa. a Schematic and **b** brief narratives of four zoning scenarios for Algoa Bay, guided by environmental health, socio-economic prosperity and governance aspects. Detailed narratives are provided in Table 3.

the feature layers that overlapped with the MPAs are already present as 'consent uses' in these MPAs (Supplementary Table 2). To account for this, the proportion of a feature layer's target that was met in the MPA was taken into account so that the feature was not overrepresented in the final scenario run of prioritizR.

Scenario and target development

Scenarios were implemented by changing which zones to include, altering targets of feature layers, increasing or decreasing the size of the ship-to-ship bunkering and mariculture zones or including a mining priority zone (Fig. 6).

Table 3 | Detailed narratives of the four zoning scenarios defined for Algoa Bay

Scenario	Narrative
Bay of Plenty	A MSP approach is embraced by the governance of the bay and the aim is to unlock the blue economy, sustainably. To show fairness to all sectors, targets for all human activities and biodiversity spatial layers are set following the same area-based rule described in Holness et al.[38]. The declared no-take zones and MPAs are still active and ship-to-ship bunkering continues to occur in anchorage area 1. By allocating space fairly to all sectors in the bay, all sectors benefit from the marine space. Fish are harvested sustainably; the bay's ecosystems are functioning well and there is an increase in socio-economic wealth and prosperity owing to the healthy environment. Following a precautionary approach, mining is not permitted in the bay.
Business as Usual	Governance has not embraced a MSP approach but instead has focused on growing the blue economy. There is an increase in ship-to-ship bunkering licenses, more fishing rights or higher total allowable catch limits are set, mining exploration and extraction is occurring, mariculture increases and efforts are made to increase income from tourism activities. Although the priority has moved away from conserving biodiversity and socio-cultural activities, the declared no-take zones and MPAs are still active. Environmental health degrades and socio-economic wealth/ prosperity initially increases but then decreases because this management regime runs the risk of collapsing fish stocks and reduces the potential of tourism as the esthetic value of the environment declines with its health.
Empty Bay	Conserving the bay's biodiversity is no longer an objective in this scenario. The current MPA is deemed to restrict other sectors and is deproclaimed. In addition, the 'unlocking the blue economy' goal for the 'business as usual' scenario is followed. Commercial industries that do not rely on the health of the environment, such as mining and ship-to-ship bunkering, benefit from this management regime, however, as fish stocks and environmental health decline, other socio-economic wealth/prosperity activities such as tourism and cultural activities decline rapidly.
Untouched paradise	The governance of the bay is no longer interested in increasing the economy of the bay and is instead only interested in protecting its biodiversity. In this scenario, biodiversity features and socio-cultural activities receive priority over all other uses of the bay. All ship-to-ship bunkering and mining activities are restricted from occurring in the bay, and all fishing and mariculture activities are kept to a minimum. Although locals enjoy the esthetic and peace of an untouched marine space, the economic influx from tourism, fishing and other activities is drastically reduced.

For the two scenarios where environmental health is low because of bad governance (Empty Bay) or a focus on economic growth dominates (Business as Usual, Fig. 5), a mining priority zone was included in the prioritization, both anchorage areas were zoned for ship-to-ship bunkering and current as well as ADZ precincts for mariculture were locked into the solution (Figs. 4 and 6). Based on the Kunming-Montreal Global Biodiversity Framework 30 x 30 conservation target[99], which aims to have 30% of the ocean and land protected by area-based management tools such as MPAs by 2030, biodiversity feature layers had a 30% target. In line with this international agreement, we chose a minimum target of 30% for biodiversity feature layers. Similarly, cultural/heritage feature layers also had a target of 30% because we viewed them more similar to biodiversity layers than to commercial and 'profitable' feature layers. Commercial and small-scale fisheries, as well as both types of recreation (i.e., non-extractive and extractive), had a 60% target, double that of the biodiversity and cultural/ heritage features, because of their role in direct income generation. However, for the Empty Bay scenario (which ignores current MPAs), a solution could not be reached with these targets so they were reduced to 25% and 50%, respectively. The Empty Bay scenario did not use the extrapolated feature layers to account for the restriction of activities in the Addo MPA (see section '*Changes to spatial layers due to the declaration of the Addo Elephant National Park Marine Protected Area in 2019*').

In the scenario that focuses on environmental health (Untouched Paradise), a target of 60% was used for the biodiversity, non-extractive recreational and culture/heritage features, and a lower 30% target was used for extractive activities such as recreational, commercial and small-scale fishing (Fig. 6). This scenario also excluded ship-to-ship bunkering activities from the bay and allowed only the existing mariculture zone with no expansion into the ADZ precincts (Fig. 6).

The fourth scenario (Bay of Plenty) assumes good governance and aims to zone the bay for both environmental and socio-economic health. In an attempt to set targets fairly or equitably for all features, the area-based targets developed by Holness et al.[38] were used. Area-based targets are based on the extent of a feature, with lower targets assigned to features with larger area coverage and vice versa and consider the intensity of the activity per planning unit. We refer to this as a feature's Area x Activity value (AA_v), and it is calculated with Eq. (2).

$$AAv = \sum (PUarea \cdot PUvalue) \tag{2}$$

where PU_{area} is the area (in km^2) of each planning unit in which the feature occurs, and PU_{value} is the intensity of the activity in the planning unit (e.g., fishing intensity or at-sea distribution of African penguins, etc.). For features that are just a distribution map of where a feature is present or absent (e.g., non-extractive recreational activities such as boating areas) the PU_{value} is 100 for each planning unit in which that feature occurs and AA_v for that feature will simply be equal to its total area. Targets were then calculated as follows, using an additive process: 60% of the first 1000 AA_v; 50% of the next 1000–5000 AA_v; 40% of the next 5000–10,000 AA_v; 30% of the next 10,000–50,000 AA_v and 20% of areas greater than 50,000 AA_v. With this process, feature layers with small distributions receive higher proportional targets (because they are likely at greater risk than widely distributed features), and for feature layers with intensities, targets can be met in areas where the activity is concentrated.

Cost layers. To avoid potential spatial conflicts among human activities, a synergy-conflict matrix was developed to define which activities were compatible, compatible but at a cost, or not compatible, with the objectives of each zone (Table 4). Scores of 0, 0.5 or 1 were allocated, respectively, guided by the compatibility of activities as indicated by the different marine sectors within the National Data and Information Report for Marine Spatial Planning produced for South Africa[82]. For each zone, each feature layer was weighted by this compatibility score. All layers were then summed and rescaled between 0 and 100 to create a zone-specific cost layer. To avoid assigning a zero cost to any planning unit, we added one (+1) to each planning unit's cost value. Equation (3) was used to scale cost layers between 0 and 100.

$$Cost_{scaled} = \left(\frac{Cost_{pu} - Min}{Max - Min}\right) \cdot 100 + 1 \tag{3}$$

Where: $Cost_{scaled}$ is the new scaled value of a planning unit in a cost layer, $Cost_{PU}$ is the original value of the planning unit in the cost layer, and Min and Max are the minimum or maximum value of all cost layers in a scenario, respectively.

Mandatory allocation of planning units. Whether it is mandatory to allocate a planning unit to a zone can be set within the prioritization algorithm of prioritizR[44]. Therefore, all zoning scenarios were run with and without the mandatory allocation of planning units to investigate what influence this may have on the final zonation product.

Boundary penalty. As fragmented zones consisting of one or a few planning units are not conducive to the enforcement of regulations and management, a boundary penalty was used to avoid overly fragmented zones. The optimal boundary penalty of each scenario was sought based

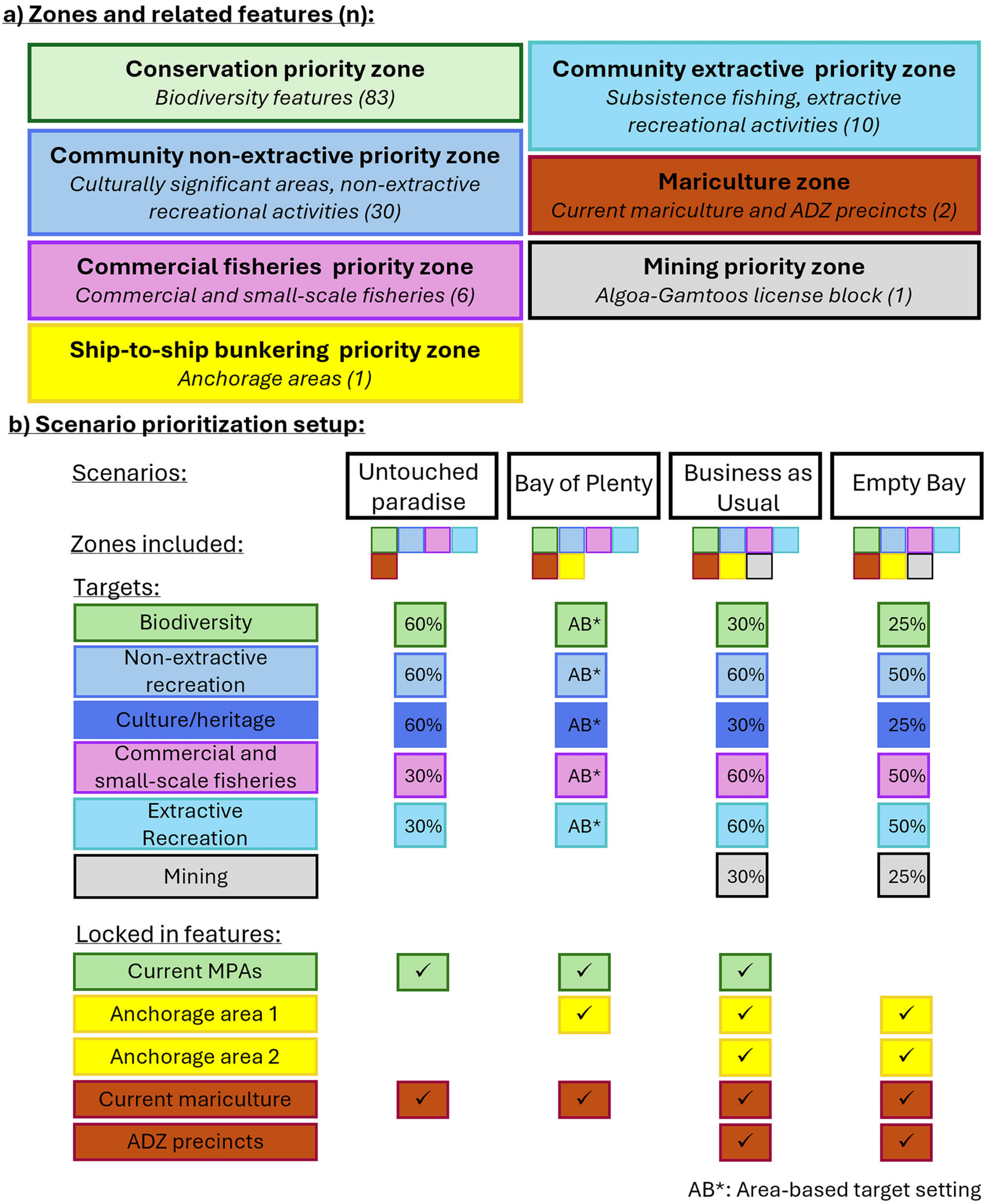

Fig. 6 | Graphic description of the prioritization setup of four scenarios. a Zones and **b** graphical description of the prioritization setup for four zoning scenarios for Algoa Bay, South Africa.

on iterations of prioritizations with a 10-fold increases in the boundary penalty between 0 and 0.1 and identified as the inflection point in the trade-off curve between the total cost and sum of perimeters of the solutions' zones, following the methods described by Ardron et al.[100]. However, these values were inadequate to identify each scenario's optimal boundary length value and therefore additional iterations with values between 0.13 and 0.01 at 0.015 intervals were run. The inflection points in the total cost and sum of perimeter trade-off plots were identified using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method[101] using R package topsis[102]. For trade-off curves and optimal boundary values, see Supplementary Fig. 2.

Table 4 | Synergy-conflict matrix between biodiversity and human-use features and the five zones used in zoning scenarios for Algoa Bay, South Africa

Features	Zones: Conservation priority zone	Community non-extractive priority zone	Community extractive priority zone	Commercial fisheries priority zone	Mining priority zone
Biodiversity features	Compatible	Compatible	Compatible but with a cost	Compatible but with a cost	Compatible but with a cost
Mining exploration and extraction	Not compatible	Compatible but with a cost	Compatible but with a cost	Compatible but with a cost	Compatible
Anchorage areas	Not compatible	Not compatible	Not compatible	Not compatible	Not compatible
Shipping lanes and intensity	Not compatible	Compatible but with a cost	Compatible but with a cost	Compatible but with a cost	Compatible but with a cost
Dredge dumping	Not compatible	Compatible	Not compatible	Not compatible	Compatible but with a cost
Ballast water discharge	Not compatible	Compatible	Not compatible	Not compatible	Compatible but with a cost
Mariculture	Not compatible	Not compatible	Not compatible	Not compatible	Not compatible
Commercial fishing	Not compatible	Not compatible	Compatible but with a cost	Compatible	Compatible but with a cost
Recreational fishing	Not compatible	Not compatible	Compatible	Compatible but with a cost	Compatible but with a cost
Small-scale and subsistence fisheries	Not compatible	Not compatible	Compatible	Compatible but with a cost	Compatible but with a cost
Recreational non-extractive activities	Compatible but with a cost	Compatible	Compatible	Compatible but with a cost	Compatible but with a cost
Historical sites *	Compatible but with a cost	Compatible	Compatible	Compatible but with a cost	Compatible but with a cost
Socio-cultural and heritage **	Compatible but with a cost	Compatible	Compatible	Compatible but with a cost	Compatible but with a cost
Cumulative impact assessment map	Not compatible	Compatible	Compatible	Compatible	Compatible
Waste discharge outfalls	Not compatible	Not compatible	Compatible but with a cost	Compatible but with a cost	Compatible
Military practice areas	Compatible	Compatible but with a cost	Compatible but with a cost	Compatible but with a cost	Compatible

* Inclusive of fish traps, shell middens and shipwrecks

** Inclusive of learning, spiritual, heritage and recreation

Not compatible

Compatible but with a cost

Compatible

Within each zone, different categories of features are scored as compatible, compatible but with a cost, or not compatible with the zone's objectives. Scores were allocated based on sector-specific information given for compatible and conflicting activities (DFFE 2021). These scores were used to weight the spatial layers of the different activities before summing all layers to create a cost layer for each zone. A cost layer was created for a 6th zone that combined the mariculture and ship-to-ship zones (Zone 6 and 7), see section 'Zone development' for more detail.

Comparison of scenarios

Zoning scenarios were compared with each other using three indices:

1. The total cost of each zone within a zoning scenario, i.e., the sum of costs to assign a planning unit to a zone.
2. The total area that each zone covers in a zoning scenario is in km^2.
3. The aggregation index[103] of each zone per zoning scenario was calculated with the R package landscapemetrics[104]. The aggregation index, ranging between 0 and 100, is calculated as the ratio of actual edge to the total amount of edge possible and indicates maximal disaggregation (0; planning units assigned to a zone share no edges) and maximal

aggregation of a zone (100; all planning units assigned to a zone share an edge).

Data availability

Code and data are available in the GitHub repository: https://github.com/Tegan151/AlgoaBayZoningScenarios.

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T.C.K.: writing—original draft, methodology and formal analysis. H.T.: writing—review and editing, data collation, project administration. A.L.: writing—review and editing, data collation. B.S.: conceptualization, supervision, writing—review and editing, fund raising. M.S.: writing—review and editing, data collation. N.R.: writing—review and editing, data collation. J.B.: writing—review and editing, conceptualization. R.B.: writing—review and editing, conceptualization. L.N.: writing—review and editing, methodology. A.T.L.: conceptualization, supervision, writing—review and editing, fund raising, project management.

Competing interests

The authors declare no competing interests.

Additional information

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