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Identifying opportunities for living shorelines using a multi-criteria suitability analysis

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ABSTRACT

The need to develop more sustainable solutions for coastal hazard risk reduction and to protect and restore degraded coastal habitats has led to an increased interest in living shorelines. A barrier to the wider implementation of living shorelines is a lack of guidance on where it is suitable to implement these solutions. We developed a shoreline suitability model to select areas of a representative coastline that would be either suitable for a soft (natural habitats only) or hybrid (natural habitats in combination with hard structures) approaches. We created species distribution models in MaxEnt to predict the potential distribution of 14 coastal species including four seagrasses, one mangrove, three saltmarsh, three shellfish and three dune species. These were combined in a multi-criteria analysis that also accounted for the accommodation (current space in the intertidal) and adaptation space (amount of space between the intertidal and nearest infrastructure) available to implement living shorelines at a 250 m resolution. This was done for the state of Victoria, Australia as a case study location where there is a high percentage of coastal infrastructure reaching the end of its design life. For the Victorian coastline 74% was suitable for hybrid approaches, while 65% was suitable for soft approaches and 4% of the coastline was not suitable for either approach. For the coastline already protected with hard defence structures, 67 and 69% would be suitable for at least one taxa, using a soft or hybrid approach, respectively. The percentage of coastline suitable for soft or hybrid approaches was similar in rural areas, however, suitability for hybrid was greater than soft approaches in urban and built-up areas, which could be due to a combination of habitat suitability and space available on the foreshore. This study has demonstrated how spatial multi-criteria analysis can be adapted to a complex coastal environment and inform more diverse coastal hazard mitigation actions to risk reduction and climate adaptation.

1. Introduction

Globally, growing coastal populations are at an increased risk of erosion and flooding due to climate change driven changes in sea level, and the frequency and/or magnitude of storm events (Neumann et al., 2015). Climate adaptation options to reduce hazard risk to existing coastal infrastructure include protect, accommodate or retreat, with protection being the most commonly used solution in the past (Galili et al., 2019). Protection has resulted in large linear sections of shorelines being armoured with hard defences, such as seawalls and revetments, replacing more than 50% of natural shorelines in some urban coastal areas (Lai et al., 2015; Gittman et al., 2016; Bugnot et al., 2021). Coastal armouring provides a static defence, that has little capacity to adapt to future climate changes without expensive upgrading or rebuilding of structures (Hinkel et al., 2014). Further, the replacement of natural shorelines with an artificial substratum can result in low biodiversity (Chapman, 2003), decreased connectivity of organisms and resources across the land- and seascape (Bishop et al., 2017) and provide greater opportunities for invasion by non-native species (Dafforn, 2017). To address the challenges of an increasingly vulnerable coastal population into the future, it

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is recognised that more diverse solutions are needed to promote resilience (Morris et al., 2020).

Natural ecosystems, such as coastal vegetation, biogenic reefs, and dunes and beaches provide protection from erosion and flooding through wave attenuation, sediment stabilisation and vertical accretion that increases the land height relative to sea level (Duarte et al., 2013; Morris et al., 2018). The replacement of natural ecosystems by armoured shorelines results in losses of the natural coastal protection service. Global losses, driven largely by anthropogenic factors, have been up to 85% for oyster reefs (Beck et al., 2011), and 50% for coral reefs and coastal wetlands (Davidson, 2014; Hoegh-Guldberg, 2014) and up to 48.5% of sandy beaches could face severe erosion by 2100 (Vousdoukas et al., 2020). The need to develop more sustainable interventions for hazard risk reduction, and to protect and restore degraded coastal habitats, has led to an increased interest in nature-based methods that achieve both of these outcomes (Temmerman et al., 2013). Commonly named "living shorelines" or "nature-based coastal defence" (Bilkovic et al., 2017; Morris et al., 2018), these solutions include the rehabilitation of existing degraded habitats, restoration of those historically present, or the creation of new habitats in ecologically suitable areas (hereafter collectively referred to as 'restored'). Living shoreline approaches include restoring natural habitats alone ("soft" approach), or in combination with hard structures that support habitat establishment ("hybrid" approaches) (Morris et al., 2018). Regardless of the method or habitat involved, however, the key aim of living shorelines is to provide the ecological processes and functions that underpin the delivery of the natural coastal defence service (Bilkovic et al., 2017).

There is growing evidence that living shorelines can be a cost-effective and resilient option for coastal protection (Gittman et al., 2014; Gittman and Scyphers, 2017; Smith et al., 2018). However, this is dependent on living shorelines being applied appropriately along the shoreline. Key factors that determine where soft or hybrid approaches can be used is the environmental context and the risk level (Morris et al., 2020), with social factors also contributing to successful implementation (Strain et al., 2022). The environmental context includes the hazard exposure, as well as a suite of other factors that determine whether the area is ecologically suitable for the key species providing coastal defence mechanisms. Soft approaches are often more suited to low-energy coastlines, or areas where remnant habitats remain, while hybrid approaches can be used in higher-energy environments where the hard structure can support the establishment of habitats in the short-term (Morris et al., 2020; Schotanus et al., 2020). Hazards often pose the greatest risk where people are living in close proximity to the coast. Thus, in areas where there is a greater buffer of land between the shoreline and infrastructure, the risk is lower, and these areas are likely to be more suitable for living shorelines (Morris et al., 2020). This is because living shorelines take time to establish, for example a soft approach using mangroves can take 5–10 years to grow, and even longer to reach full maturity (Salmo et al., 2013). Space within the intertidal to shallow subtidal is also required to establish the habitat (hereafter "accommodation space"), and a terrestrial buffer allows for the landward migration or retreat of the habitat (e.g., Davidson-Arnott, 2005) in response to sea level rise (hereafter "adaptation space") (Strain et al., 2022). Where there is limited space between the shoreline and infrastructure and a high population density, increased hazards pose a high risk, and likely require actions that provide coastal protection quicker and accommodate less space, so these areas are more suited to a hybrid approach or not suitable for living shorelines (Sutton-Grier et al., 2015; Morris et al., 2020).

Providing information to land owners and coastal managers on where a soft, hybrid, or hard approach can be effectively used is a key step to the wider use of more diverse risk reduction interventions (Morris et al., 2020). One way that this can be done is through shoreline suitability modelling. A living shoreline suitability model delineates preferred approaches for erosion control across different coastal areas, and has been used in several US Atlantic and Gulf coast states to encourage greater use of nature-based methods (e.g., New Hampshire, Connecticut, Virginia, Florida, Alabama, Louisiana and Texas; (Berman and Rudnicky, 2008; Carey, 2013; Zylberman, 2016; Dobbs et al., 2017; Boland and O'keife, 2018; Balasubramanyam and Howard, 2019; Nunez et al., 2022). These previous models were largely based on that by Berman and Rudnicky (2008) where shorelines were classified as suitable for a soft or hybrid approach or not suitable for living shorelines based on six attributes: fetch; bathymetry; the presence of marsh; the presence of beach; bank condition; and tree canopy. This approach, however, does not account for the potential distribution of the key species providing the defence service as it is only based on their current distribution. Further, it did not include anthropogenic factors, such as the distance between the shoreline and the nearest infrastructure, although this was integrated into later versions (VIMS, 2021). Another effort at shoreline prioritisation for mangrove living shorelines calculated a habitat suitability model based on the hydrodynamic threshold for mangrove persistence (Kibler et al., 2020). While this accounts for the potential distribution of these species based on hydrodynamics, other environmental factors that are important for determining mangrove suitability (e.g., climate and sea temperature) were not included.

Species distribution models (SDMs), also known as habitat suitability or ecological niche models, are a method that can be used to understand the current and potential distribution of native species for coastal erosion management. SDMs relate species' known occurrences to ecologically relevant environmental variables – such as climate, sediment type and elevation or bathymetry – and use this relationship predict the environmental suitability for the species, expanding species information from point locations across the study land- and seascape (Guisan and Zimmermann, 2000; Elith and Leathwick, 2009). SDMs are frequently used to inform various conservation planning and ecological management questions (Guisan et al., 2013), as well as to guide ecologically sensitive land-use planning (Whitehead et al., 2017). Combining information across shoreline characteristics, hazard risk and SDMs could allow us to understand where living shorelines are (1) most needed, (2) feasible to carry out, and (3) which species might be most appropriate to use given the environmental conditions.

In Australia, living shorelines have not been widely used compared to other locations globally, such as the United States and the Netherlands (Morris et al., 2018). However, a growing interest in their use, supported by new policies (e.g., Victorian Marine and Coastal Policy 2020; DELWP, 2020a) that prioritise nature-based over traditional structures where appropriate is resulting in the expansion of on-ground demonstration projects using different habitats and techniques, such as shellfish reefs and hybrid mangrove approaches (Morris et al., 2021a). To better inform the upscaling of living shorelines, in a first for Australia, this study aims to determine which areas of the coastline are: (1) most suitable for a soft solution; (2) most suitable for a hybrid solution; or (3) not suitable for living shorelines, using the state of Victoria as a case study. This state has up to 50% of coastal defence structures that are nearing the end of their design life (DELWP, 2020a), therefore consideration of alternative options is timely. This study also provides a framework for integrating species distribution modelling with a multi-criteria approach to living shoreline suitability modelling. This can be used to better guide the decisions made by coastal managers on what species and techniques could be applied to select suitable areas for applying nature-based defences in other locations around the globe.

Table 1
Information on the study species and their final models. The table gives the number of the unique occurrence records for each species sourced from the Atlas of Living Australia after data cleaning, background group used to correct for observation bias, mean test-AUC (area under the Receiver Operating Characteristic curve) and the number of variables of the final model and the most important variable with the largest permutation importance for each species. The background group indicates the taxa which records were used to sample background points. The benthic group consisted of Mollusca, Arthropoda, Annelida and Echinodermata occurrence points. See Supplementary Material for further model output details.

Scientific name		Common name	Number of occurrence points	Background group	Mean test-AUC (±SE)	Number of variables in final model	Variable with highest permutation importance
Seagrass				Angiosperms and algae			
	Amphibolis antarctica	Wire weed Sea nymph	72		0.968 (0.027)	11	Fetch (39.7)
	Halophila australis	Paddle weed	22		0.972 (0.032)	11	Elevation/bathymetry (68.8)
	Heterozostera nigricaulis	Australian Grass-wrack	109		0.970 (0.023)	11	Annual mean temp. (51.5)
	Zostera muelleri	Eelgrass	46		0.943 (0.017)	11	Elevation/bathymetry (61)
Mangrove				Angiosperms			
	Avicennia marina	Grey mangrove	893		0.902 (0.007)	10	Elevation/bathymetry (48.8)
Saltmarsh				Angiosperms			
	Austrostipa stipoides	Prickly spear-grass Coast spear grass	343		0.933 (0.008)	10	Elevation/bathymetry (36.2)
	Gahnia filum	Chaffy Saw-sedge	614		0.898 (0.004)	10	Mean temp. of the warmest quarter (39.8)
	Tecticornia arbuscula	Shrubby Glasswort	546		0.943 (0.007)	10	Elevation/bathymetry (44.7)
Shellfish				Benthic			
	Mytilus galloprovincialis	Mediterranean Mussel	20		0.905 (0.114)	9	Seasonality of rainfall (56)
	Ostrea angasi	Angasi oyster Mud oyster Flat oyster	28		0.950 (0.033)	9	Fetch (43.5)
	Saccostrea glomerata	Sydney rock oyster	76		0.873 (0.030)	9	Annual rainfall (48)
Dune				Angiosperms			
	Ammophila arenaria	Marram grass European beachgrass	293		0.914 (0.013)	9	Elevation/bathymetry (46.6)
	Spinifex sericeus	Hairy spinifex Beach spinifex	633		0.879 (0.008)	9	Elevation/bathymetry (73.8)
	Thinopyrum junceiforme	Sand couch Sea couch-grass Sea wheatgrass	154		0.950 (0.011)	9	Annual mean temp. (38.8)

2. Methods

2.1. Species distribution models

We modelled species' distributions across the coastal areas of three south-eastern Australian states: New South Wales; Victoria; and South Australia. Although Victoria was the target state for the full living shoreline suitability model, the larger spatial extent for the SDMs was used to increase the number of occurrence records and better capture the environmental range that the species inhabits and therefore improve model performance (Hernandez et al., 2006; Barbet-Massin et al., 2010). We defined the coastal area as a minimum of 8 km from the coastline landward and seaward to include the elevations relevant for the different types of coastal defence approaches considered, extending intermittently to capture areas of interest. In Victoria, the two areas with such an extension were Port Phillip Bay and Lakes Entrance with a buffer of 15 km seawards and 18 km landward respectively. The maximum distance of the coastal buffer was 30 km seaward to include Gulf St Vincent, South Australia. The primary coastal ecosystems that provide natural coastal defence in Victoria are: dunes and beaches; saltmarshes; mangroves; seagrasses; and shellfish reefs (Morris et al., 2021a). We identified 14 species that are the main habitat-formers within these five ecosystems. These included three dune species (*Ammophila arenaria*, *Spinifex sericeus*, and *Thinopyrum junceiforme*), four seagrasses (*Amphibolis antarctica*, *Halophila australis*, *Heterozostera nigricaluis* and *Zostera muelleri*), three shellfish (*Mytilus galloprovincialis*, *Ostra angasi* and *Saccostrea glomerata*), one mangrove (*Avicennia marina*), and three saltmarsh species (*Tecticornia arbuscula*, *Gahnia filum* and *Austrostipa stipoides*; Table 1). For each species, we obtained occurrence points for New South Wales, Victoria and South Australia from the Atlas of Living Australia (ALA) collected between 1970 and 2020 and with a spatial accuracy of less than 250 m.

We compiled spatial data on 14 environmental and topographic variables known to be ecologically relevant for the habitat suitability of coastal species and for which spatial data was available for our study area (see Supplementary Methods and Table S1). These variables described the elevation/bathymetry as a single, continuous variable, slope, primary substrate (% of terrestrial sand, aquatic sand, and aquatic mud) and fetch as a proxy for wave action along the coastline. In the absence of available sea water temperature data for our modelling region, we employed 8 bioclimatic layers (annual average temperature and precipitation, maximum temperature of warmest week and quarter, minimum temperature of coldest week and quarter, and temperature and precipitation seasonality) obtained from ClimMod (Fick and Hijmans, 2017) to represent temperature and seasonality, acknowledging that these may represent distal predictors for the subtidal species.

All variables were projected to VicGrid GDA94 (EPSG:3111) centred on Victoria and resampled to a 250 m resolution using bilinear interpolation from the Raster package (Hijmans, 2020). We undertook all analyses in QGIS (version 3.6.2), R (version 4.0.2; R Core Team, 2021) and RStudio (version 1.3.1073). We tested all variables for collinearity (Dormann et al., 2013). The two pairs of highly correlated variables (Spearman's rank correlation coefficient $> |0.7|$) were the maximum temperature of the warmest week (bio05) with the mean temperature of the warmest quarter (bio10), and the minimum temperature of the coldest week (bio06) with the mean temperature of the coldest quarter (bio11). As no ecological rationale was apparent for the correlated pairs, we explored both alternative models fit with the correlated variables separately.

The models were built using the presence-background modelling program MaxEnt (version 3.4.0, Phillips et al., 2006) through the *dismo* package in R (Hijmans et al., 2017) with default settings. MaxEnt compares the environmental conditions in locations where the species has been observed to those of the entire modelling region (here, coastline across the three states) to fit species' responses to environmental variables and to infer environments most suitable for the species (Phillips et al., 2006; Elith et al., 2011). To map the environmental space of the modelling region, the program samples many locations across the study area, called background points. Biological records from online databases tend to be spatially biased towards easily accessible and/or frequently visited locations, and this may introduce errors to the predicted suitability patterns, overemphasising well surveyed areas (Phillips et al., 2009; Merow et al., 2013; Fithian et al., 2015). To account for such biases, we employed target group sampling of background points (known as "target group background", TGB; Phillips et al., 2009). Instead of random sampling, we used 10,000 species' records from similar taxonomic groups, cleaned as previously described for the modelled species, to represent the environmental gradients of the modelling region. Based on the availability of records in ALA, we created three groups of background points from various taxa: (1) Angiosperm records for modelling dune, saltmarsh, and mangrove species; (2) Angiosperm and algae records for seagrass species; and (3) Mollusca, Arthropoda, Echinodermata, and Annelida records (Benthic group) for modelling shellfish species (Table 1).

We selected the best model across alternative explanatory variable combinations based on the ecological accuracy of the predicted suitability from expert opinion or, when that was unclear, using the MaxEnt calculated validation metrics of test-AUC, regularised training gain and variable importance. These three validation metrics were calculated through a 5-fold cross-validation method, withholding 20% of the presence records as data upon which to test and reduce overfitting. We used the training sensitivity plus specificity threshold (Liu et al., 2011) to define the lower bound of the habitat suitability. To increase model discrimination between purely terrestrial or aquatic species, we clipped the predicted suitability maps to the appropriate realm (terrestrial or aquatic) using the shoreline limit.

2.2. Multi-criteria suitability model

The study area to assess living shoreline suitability was the Victorian coastline, which we separated into 250 m linear segments. Thiessen polygons (also known as Voronoi polygons) were created around each segment and defined the area in which the input variables would be collated. Three variables were used to determine living shoreline suitability: accommodation space; adaptation space; and habitat suitability using the SDMs.

Accommodation space represented the amount of nearshore habitat available for the restoration of coastal ecosystems. It was calculated as the distance (in metres) from the 0 m contour line (using the Australian Height Datum; approximately mean sea level) to the 1 m contour for seagrass, mangrove, saltmarsh, and shellfish species (Nunez et al., 2022) and 0 m to 4 m contour for the dune species averaged at 50 m intervals within a segment (Figure S1). The 4 m contour is the approximate average minimum elevation dune vegetation grows at along the Victorian coast and was also used as a proxy for beach width, which determines dune-building potential (Keijsers et al., 2013). Adaptation space represented the buffer area of land along the coastline and was a proxy for the potential risk of infrastructure to hazards, as well as the space available for habitats to retreat for enhanced resilience (Figure S1). The adaptation space was calculated as the distance (in metres) from the 0 m contour to the nearest impervious surface, and to the nearest 20% incline of slope, with the lesser of the two distance values then applied in the model for all species. Impervious surfaces were identified by combining the Global Man-made Impervious Surface product (Brown de Colstoun et al., 2017) with the urban and built-up areas recognised in the Victorian Landcover Timeseries between 2015–2019 (DELWP, 2020b). Habitat suitability was derived from the SDMs (Figure S2). The Thiessen polygons were clipped to the accommodation space. The maximum habitat suitability within the accommodation space for each species and each Thiessen polygon was assigned to the corresponding line segment.

For accommodation and adaptation space, all values less than five metres in width were applied a value of one metre, the resulting values were log transformed, then rescaled from zero to five (using equation below). This means all accommodation and adaptation space that was less than five metres will be zero after rescaling, indicating less than five metres in width is insufficient to accommodate habitat for living shorelines. The log transformation was necessary to account for the declining marginal nature-based defence benefit from very large areas of accommodation and adaptation space. A value of five metres was chosen based on the authors knowledge of existing living shorelines in temperate Australia, which require a minimum of that space to be implemented (e.g., mangroves in rock fillets, Jenkins and Russell, 2017).

Suitability criteria (mean accommodation space, mean adaptation space, and maximum habitat suitability for each species) were combined to determine the living shoreline suitability for each taxon (seagrass, mangrove, saltmarsh, shellfish, and dunes), along with a combined suitability for all species. Each attribute was scored on a (continuous) scale from zero to five, with zero indicating no suitability and five indicating the highest suitability. To ensure all criteria were on a comparable scale, we applied the following formula:

$$Score_i = ((S_i - \min(S))/(\max(S) - \min(S))) * 5$$

where $Score_i$ is the criteria score for line segment i, S_i is the raw score for the given criterion in segment i, and S is the set of criteria values over all line segments. For the habitat suitability criteria, for each taxon we took the maximum value of the habitat suitability from all species in each taxon for each line segment (or the maximum species value regardless of taxon for the combined suitability). Once each of the criteria (accommodation space, adaptation space, and habitat suitability) were scaled from zero to five, they were summed together with equal weights (1/3 for each criterion).

We then applied threshold values for each criterion. These were values below which the segment was considered to be unsuitable for living shorelines, regardless of the scores in the other criteria. For adaptation and accommodation space, this threshold was any value below 5 m in width (as described above). For habitat suitability, this was segments where all species in a taxon were scored 0 (i.e. absent). In the case of combined suitability, this applied to all species in the study. Segments below the threshold for any criteria were placed in the 'not suitable' category for living shorelines. The remaining values from the composite score (i.e., the sum of the accommodation space, adaptation space and habitat suitability) were quantiled into two categories evenly: the category with the highest scores were deemed suitable for soft approaches, and the category with lower (but still suitable) scores were deemed suitable for hybrid approaches.

Soft approaches were defined as the creation or restoration of the habitat only (e.g., planting of vegetation, reshaping of dune) while hybrid approaches use a structural element in combination with the habitat, often to enhance the habitat establishment and/or persistence (e.g., mangroves behind rock sills, hard substrate placed for shellfish; Fig. 1). As there is a relationship between habitat width and wave attenuation (Shepard et al., 2011), soft approaches were considered more suitable in areas where a greater width of habitat could be created, there was more time for habitat growth that corresponded to a greater accommodation space and there was the highest habitat suitability. Hybrid approaches can be used where there is less space to implement natural approaches alone (Sutton-Grier et al., 2015), the structural component can provide immediate coastal protection while the habitat is establishing (Morris et al., 2021b) and can increase the environmental suitability for habitat establishment (Temmink et al., 2022). The taxa-specific suitability categorisations further indicate which type (seagrass, mangrove, saltmarsh, shellfish, and/or dunes) of living shoreline is suitable within the soft and hybrid categorisations. An overview of the multi-criteria model is provided in Fig. 2.

As different taxa occupy different ecological niches, we also determined the number of taxa suitable for soft or hybrid strategies in each line segment (using a summation across taxa for each segment). We also calculated the number of line segments designated for soft or hybrid approaches that were coincident with urban and rural areas (based on DELWP, 2020b), along with hard protection infrastructure (based on DELWP, 2022). To facilitate this, urban areas and protection infrastructure were linked to the linear segments using the Thiessen polygon method described above.

Finally, we conducted a sensitivity analysis to determine the robustness of our results through alterations in key parameters. These variations include: taking the mean (instead of the maximum) of the habitat suitability value in the Thiessen polygon for each line segment for each species (Simulation 2); taking the mean (instead of the maximum) of the habitat suitability value *across species* for each line segment (Simulation 3); varying the accommodation and adaptation space deemed unsuitable between 1 m (Simulation 4) and 10 m (Simulation 5); and altering the weightings applied when combining criteria to 0.25 each for accommodation and adaptation space, and 0.5 for habitat suitability (rather than equal weights) (Simulation 6). This resulted in six simulations, together with our primary model run (Simulation 1).

3. Results

3.1. Species distribution models

The final models included between 9 and 11 environmental variables depending on the species after testing each collinear variable. Across all species, elevation/bathymetry was the most discriminative variable with the highest average permutation importance (35.4, Table S2, followed by annual temperature (12.4), and fetch (14.2) or maximum temperature of warmest quarter (17.7) for aquatic/intertidal and dune species, respectively. Fetch was the highest contributor to the suitability of coastal areas for seagrass, shellfish, and mangroves (41.5%, 51.3% and 52.4%, respectively). Suitable sites for seagrass were further characterised by substrate with high levels of aquatic sand for all species except for *Zostera muelleri* (18.1%, Table S3), and with high levels of mud for *halophila australis* although noting this species employed fewer than the recommend number of occurrence points ($n = 22$). After fetch, shellfish distributions were also strongly influence by annual precipitation (19.9%), acknowledging that the *Mytilus galloprovincialis* did not display this strong relationship potentially due to too few occurrence points ($n = 20$). For mangroves, slope and precipitation seasonality (12.8% and 12.6%) respectively contributed strongly to the models (Table S3). Habitat suitability for saltmarsh species was driven by somewhat different sets of variables and varied greatly between species, with the variable being related to elevation/bathymetry, slope, fetch, annual temperature and its extremes, as well as precipitation. Elevation/bathymetry (37.2%), upper temperature extremes (21.9%) and levels of terrestrial sand (18.5%) best explained the distribution of dune species.

The performance of the SDMs was generally high, with all cross-validated AUCs being larger than 0.870 (AUC $>$ 0.7 is regarded as a threshold for an informative model, Swets, 1988). Seagrasses showed the highest and most consistence AUC as a group. Two species (*H. australis* and *M. galloprovincialis*) had $<$30 occurrence points, which is less than the minimum recommended to undertake a MaxEnt distribution model. The analysis of the distribution model results for these two species should account for this limitation. Both species were retained in the following multi-criteria suitability model.

3.2. Multi-criteria suitability model

There was a total of 15,001 segments classified as suitable for a soft or hybrid living shoreline approach, or not suitable summarised across all taxa (Fig. 3), and for each taxa separately (Fig. 4). Seventeen percent (15.5–21.5%; range based on the sensitivity analyses, Table 2) of the segments were suitable for one type of taxa using a soft approach, while 10.5% (8.5–11.5%) of segments were suitable for all five taxa using a soft approach (Fig. 5a). For hybrid approaches, 20% (15%–25%) of the segments were suitable for one taxon, while 2.5% (1–2.5%) of the segments were suitable for all five taxa (Fig. 5b). The overlap in the suitability of taxa for soft approaches was greater than hybrid approaches (Fig. 5); overall, 74% (69–81.5%) of the coastline was suitable for hybrid approaches, while 65% (59–72.5%) was suitable for soft approaches (i.e., at least one, and up to five taxa for each segment could be used). Four percent of the coastline was not suitable for either a soft or a hybrid approach for any taxa, indicating a 43% overlap in soft and hybrid approaches where one or more taxa may be suitable for a soft approach, and the remaining suitable taxa a hybrid approach. The results were within 1%–14% of each other for the six simulations (Table 2).

Coastal protection structures were already present for 1562 segments (1%) of the coastline (Fig. 6). Sixty-seven and 69% of

Fig. 1. Examples of hybrid (A, C) and soft (B, D) living shoreline approaches that would be suitable for the Victorian coastline. (A) shellfish reef © Ralph Roob; (B) mangroves within planters © Rebecca Morris; (C) dune plantings © Lee Bradd; and (D) saltmarsh rehabilitation using fencing © Blue Carbon Lab.

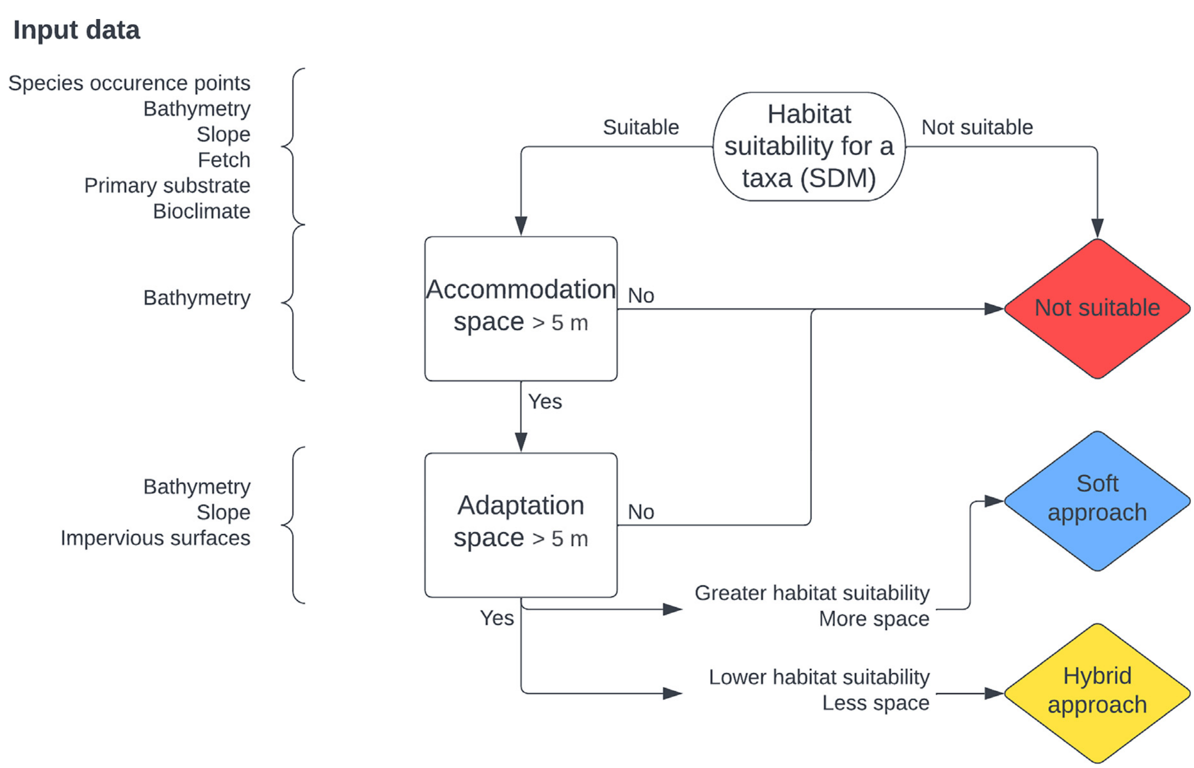

Fig. 2. An overview of the input data and decision tree for the multi-criteria suitability model.

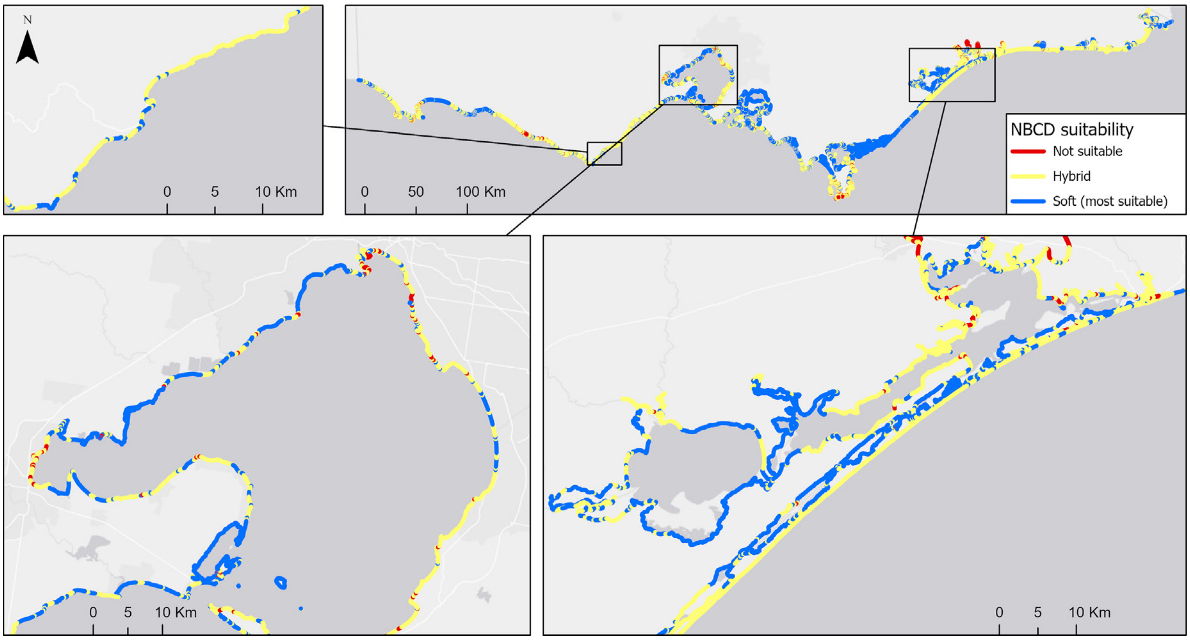

Fig. 3. Suitability analysis for the Victorian coastline (land = light grey; sea = dark grey) identifying areas that are suitable for a soft (blue), hybrid (yellow), or not suitable (red) nature-based approach (NBCD) at a 250 m linear resolution. These results are based on the suitability assessment including all taxa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The percentage of the Victorian coastline 250 m segments not suitable (NS) or suitable for a soft (S) or hybrid (H) approach for 0–5 taxa in the primary model run (simulation 1) and five sensitivity analyses: mean habitat suitability for each species (simulation 2); mean habitat suitability across species (simulation 3); less that 1 m accommodation space as unsuitable (simulation 4); less than 10 m accommodation as unsuitable (simulation 5); and adjusting the variable weights (simulation 6). Note: soft and hybrid approaches are not mutually exclusive among taxa e.g., a segment of coastline could be not suitable for two taxa, suitable for three, two using soft approaches and one using a hybrid approach.

No. taxa	Simulation 1			Simulation 2			Simulation 3			Simulation 4			Simulation 5			Simulation 6		
	NS	H	S	NS	H	S	NS	H	S	NS	H	S	NS	H	S	NS	H	S
0	24	26	35	24	19	27	24	31	39	25	26	32	23	29	41	24	19	27
1	38	20	17	38	24	22	38	15	15	42	17	18	32	25	16	38	24	22
2	26	17	13	26	24	18	26	14	9	27	17	13	22	16	12	26	24	18
3	3	23	13	3	25	16	3	25	12	3	24	14	2	19	11	3	25	16
4	4	12	11	4	7	9	4	14	14	1	14	12	12	10	10	4	7	9
5	4	2	11	4	1	8	4	2	12	2	3	11	9	2	10	4	1	8

the coastline already protected by coastal structures was suitable for a soft and a hybrid approach, respectively. Four percent of the Victorian coastline was considered as "built up" with industrial or commercial development, while 22% was considered "urban" with medium to low density populations (DELWP, 2020b). The remaining 75% of the Victorian coastline was considered rural, including disturbed land, agriculture and natural ecosystems (DELWP, 2020b) where no infrastructure would inhibit the use of natural coastal defences (Fig. 6). In the rural areas, the percent of the coastline suitable for soft approaches (68.5%) was similar to hybrid approaches (70.5%). In urban and built-up areas, however, a greater percentage of the coastline was suitable for hybrid approaches (85 and 80.5%, respectively) compared to soft approaches (56.5 and 51%, respectively). These results were largely robust to the decisions made on the model parameters, with the number of segments suitable for different actions being between 4%–18% of each other (Table 3). An exception to this was the percentage of built-up coastline suitable for soft approaches, which increased when a lower weighting was placed on the accommodation and adaptation space compared to habitat suitability (Table 3).

Table 3
The percentage of segments suitable for at least one taxa for a soft (S) or hybrid (H) approach in the primary model run (simulation 1) and five sensitivity analyses where hard coastal structures are already present, and in rural, urban and built-up areas.

	Coastal structures		Rural		Urban		Built-up	
	Hybrid	Soft	Hybrid	Soft	Hybrid	Soft	Hybrid	Soft
Simulation 1	69	67	70	69	85	57	81	51
Simulation 2	68	69	70	70	86	58	81	53
Simulation 3	66	69	64	65	83	52	80	52
Simulation 4	73	71	70	71	86	60	88	56
Simulation 5	65	61	68	63	82	50	71	41
Simulation 6	75	79	80	74	86	68	77	72

4. Discussion

The aim of this study was to apply a method integrating species distribution modelling with a multi-criteria approach to produce a first assessment of living shoreline suitability for Victoria, Australia to guide future decisions on new or upgraded coastal infrastructure. We found that a substantial proportion of the coastline was suitable for a soft (65%) or hybrid (74%) approach, and that there was some overlap between the use of soft and hybrid approaches for different taxa. There are significant opportunities for consideration of nature-based defences when existing structures reach the end of their design life as living shoreline suitability overlapped coastal structure presence by 67 and 69% for soft and hybrid approaches, respectively. There is greater potential for the use of hybrid approaches, especially

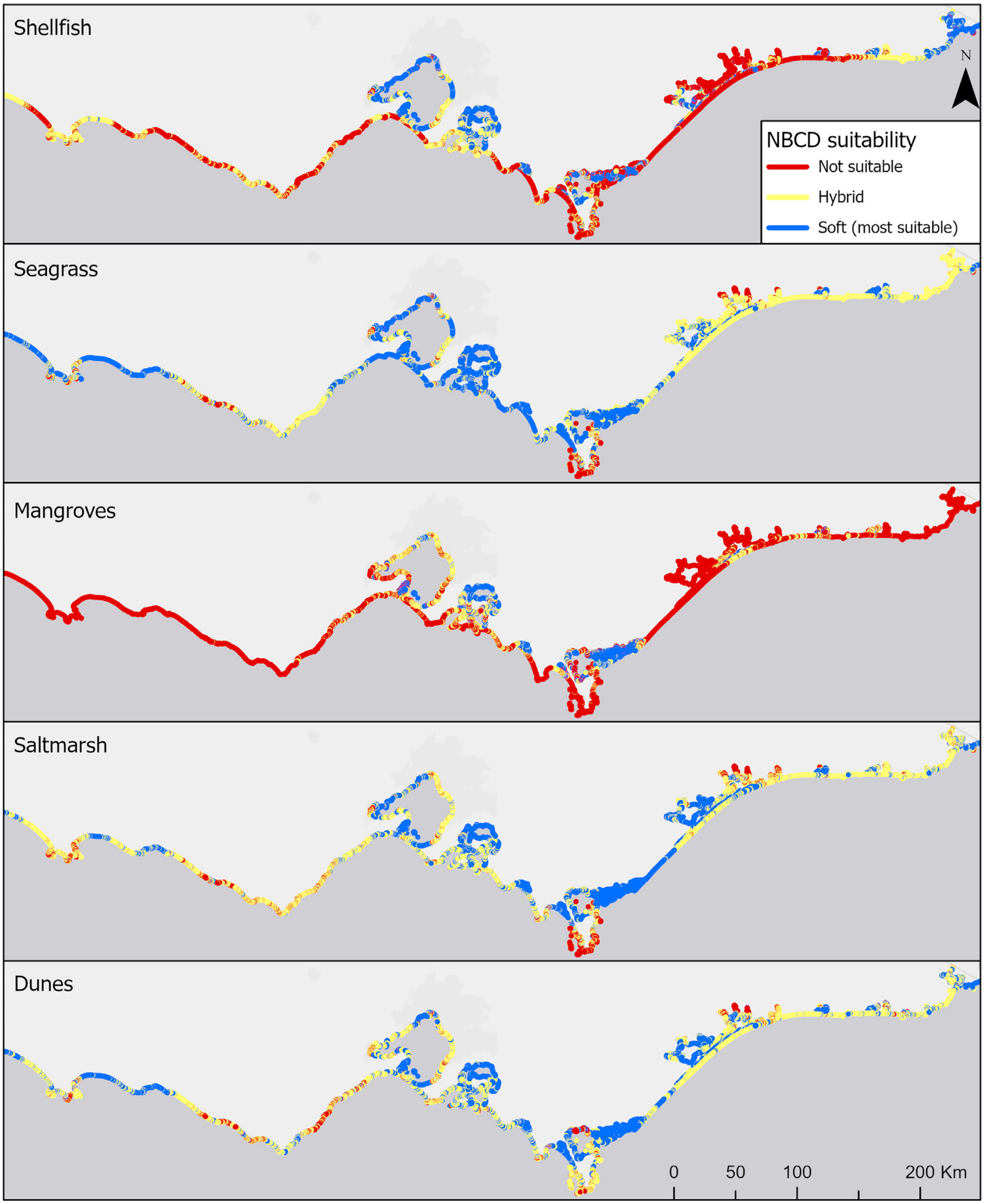

Fig. 4. Suitability analysis for the Victorian coastline (land = light grey; sea = dark grey) identifying areas that are suitable for a soft (blue), hybrid (yellow), or not suitable (red) nature-based approach for five taxa (from top: shellfish; seagrass; mangroves; saltmarsh; dunes) at 250 m linear resolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in urban and built-up areas due to space constraints on the foreshore as infrastructure is situated nearer the coast.

Multi-criteria analyses have been applied to support decisions on the use of living shorelines in the United States. For example, Bezore et al. (2020) used five input datasets to recommend soft or hybrid stabilisation techniques, or areas not suitable for living shorelines along the entire Texas coast. These were elevation/bathymetry, relative exposure risk (based on wind data and fetch), shoreline type (presence of beach, marsh, bank scarp or armouring), shoreline change rate and the proximity to boat channels. Based on these data inputs, five actions were recommended: hybrid stabilisation; retrofit hybrid stabilisation; soft stabilisation; retrofit soft stabilisation; and not suitable for living shorelines. Retrofit was considered to be suitable in areas where there was not already a beach or marsh present, but the other factors were conductive to either a soft or hybrid living shoreline. These areas would therefore need to have these natural systems created or restored. This is similar conceptually to the

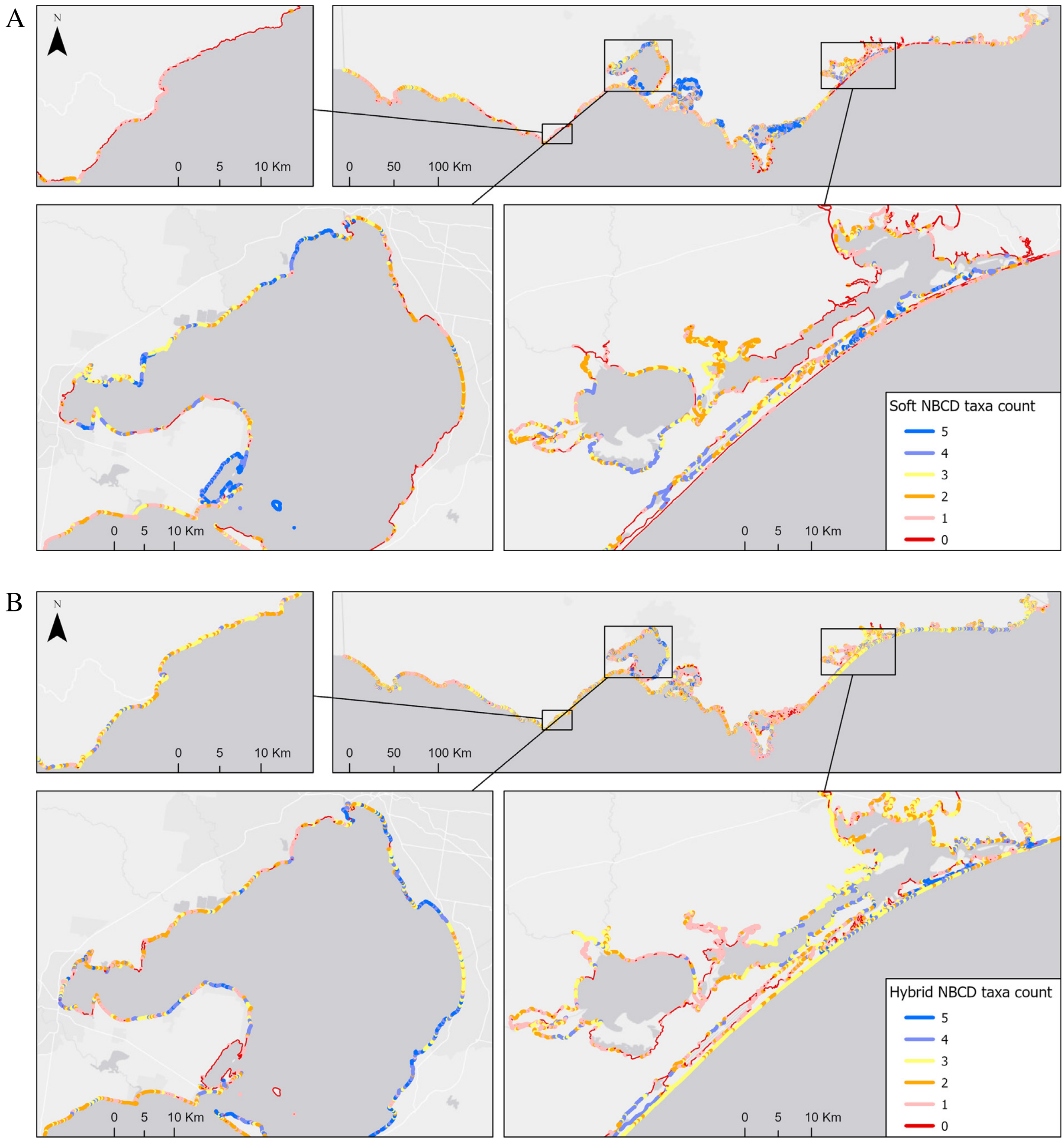

Fig. 5. The number of taxa that can be applied for (A) soft and (B) hybrid living shoreline approaches at 250 m coastline segments of the Victorian Coastline (land = light grey; sea = dark grey).

model we have presented in this paper, however, we used species distribution models to determine thresholds for habitat suitability that help identify locations where each species could be used for soft and hybrid approaches. Using SDMs was a particularly useful approach for Victoria due to the number of species and taxa that could be applied in a living shoreline along this coast.

Species distribution models provide a powerful tool to expand our understanding of species distribution patterns from singular point observations to full landscapes. They provide a cost-efficient option to map the potential habitat suitability for species across large scales or in environments that may otherwise be difficult to survey extensively, providing new opportunities for spatial planning (Elith and Leathwick, 2009; Guisan et al., 2013). However, as with all models, there is unavoidable uncertainty associated to the estimated habitat suitability values. These stem, among others, from the imperfect understanding of species' ecology and its main environmental drivers, biases in observation data that cannot be compensated for, use of proximal environmental explanatory variables or inappropriate spatial scale and differences between alternative modelling approaches (Barry and Elith, 2006; Elith and Leathwick, 2009; Synes and Osborne, 2011). All these factors introduce some level of uncertainty to the spatial extent and relative importance of suitable habitat that may affect decisions based on these data (Muscatello et al., 2021). Modelling species habitats across coastal environments poses further challenges, such as the general poorer availability of data for intertidal and underwater environmental variables and their vertical gradients, and non-trivial technical questions about how to best combine environmental data collected separately

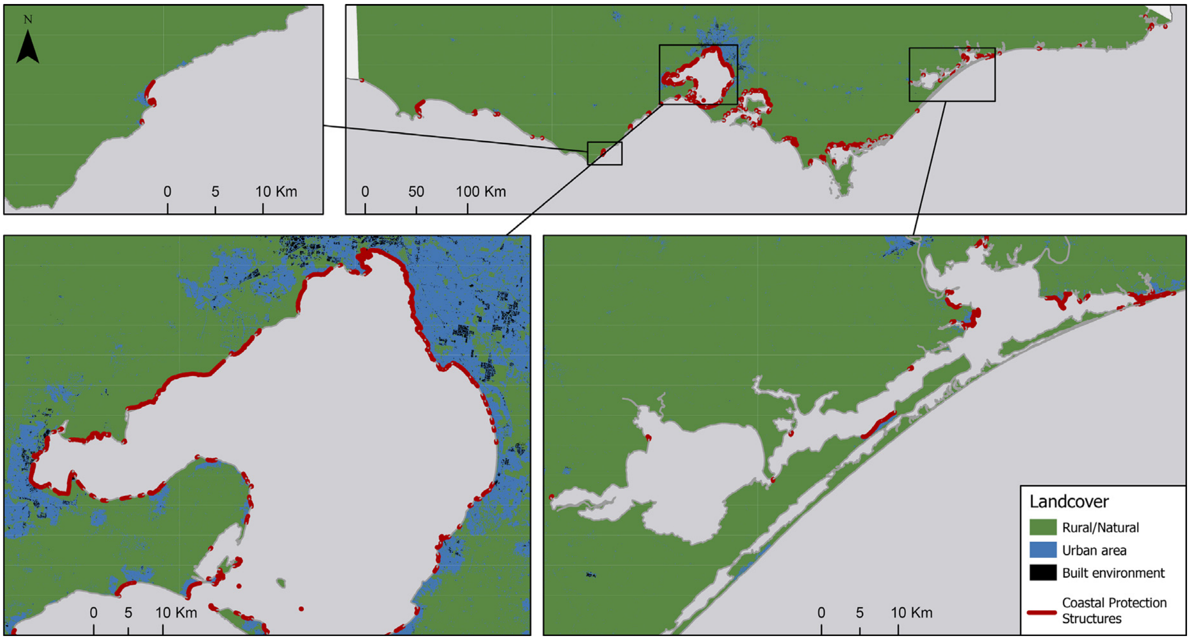

Fig. 6. The distribution of coastal protection structures (red line; DELWP, 2022) and land use categories (DELWP, 2020b): rural and natural (green shading); urban (blue shading); and built environment (black shading). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for terrestrial and marine realms, often across different timescales and using different approaches or measures (Reiss et al., 2011; Melo-Merino et al., 2020). Yet the planning opportunities provided by SDMs are deemed to outweigh their shortcomings (Guisan et al., 2013), particularly given the rapidly growing need for more ecologically sustainable land use planning. The species-specific areas identified as suitable for soft and hybrid approaches in this study should therefore be understood as a broad-level patterns, and the suitability of individual sites and their most optimal approach need to be assessed in more detail in the field. Current species distributions were not available, therefore if one of the habitats is already present at a site then this may just need to be expanded, rehabilitated or a hybrid approach applied to improve resilience.

The percentage of the Victorian coast suitable for living shorelines was comparable to other shorelines globally based on decision support tools. For example 66% of the Chesapeake Bay, Virginia shoreline was suitable for soft approaches (Nunez et al., 2022), while 45% of the Texas coastline was suitable each for soft and hybrid approaches, and only 10% was not suitable for living shorelines (Bezore et al., 2020). A key difference between these previous models and that presented in this paper is the possibility of having multiple actions per 250 m segment, which meant that soft and hybrid options for different taxa could overlap. Different taxa (i.e., seagrass, mangrove, saltmarsh, shellfish reefs and dunes considered here), and indeed even species within different taxa (Fig. 7) can occur under different physical and environmental conditions, which means that they are suited to different areas of the coastline. For example, mangroves in southern Australia are confined to sheltered embayments or estuaries (Lymburner et al., 2020), whereas dunes occur more extensively with greater volumes of sand along the wave-dominated open coasts (Geoscience Australia, 2020). Naturally taxa may co-occur, for example along intertidal gradients. Where there is more than one taxon suitable for a segment, a multi-taxa living shoreline could be considered. For example, shellfish reef living shorelines have been used to increase the resilience of saltmarsh in the United States (Morris et al., 2021b) and to increase the success of dune building and revegetation in Australia (Morris et al., 2021a). This is due to the offshore shellfish reefs reducing hydrodynamic energy and increasing sediment supply in the lee of the reef that can facilitate the establishment of vegetation. Living shorelines that use multiple habitats can provide greater wave attenuation than single habitats (Manis et al., 2015). Multi-taxa or multi-species living shorelines may be more resilient to climate impacts, and for this reason is recommended in restoration projects for habitat recovery (Zabin et al., 2022).

In their model for Chesapeake Bay, Nunez et al. (2022) showed that 61 and 69% of existing bulkhead and revetment, respectively was suitable for a living shoreline treatment. Our model indicated a similar percentage (67 and 69% for soft and hybrid approaches) for existing armouring along Victorian coastlines. In Victoria, a 2018 audit of coastal assets (seawalls, groynes, piers and jetties) estimated that up to 50% had less than 10 years of useful life remaining (DELWP, 2020a). There is therefore a substantial opportunity for implementing living shorelines through decommissioning ageing hard infrastructure when it reaches the end of its design life. A recent example of this has been constructed at Wagonga Inlet, New South Wales where a failing revetment was replaced with banks of low-growing riparian vegetation fronted by an oyster reef (Eurobodalla Shire Council, 2022). In urban and built-up areas, which also had large stretches of already armoured shorelines, hybrid approaches were more frequently suitable than soft approaches due to the space available for construction and/or adaptation. In the sensitivity analyses, decreasing the importance of the accommodation and adaptation space increased the suitability for soft approaches in urbanised areas. The model was generally robust to all the other decisions made (e.g., mean or maximum of species suitability, threshold for accommodation and adaptation space), with little changes to the outputs.

The model presented was made on the best spatially explicit ecological and physical datasets available. Using adaptation space as a proxy for hazard risk (in addition to the space available for the habitat to move back and maintain resilience) does not account for the actual rate of shoreline change along the coast, which was included in previous models in the United States (Bezore et al., 2020; Nunez et al., 2022). The inclusion of these data as they become available, for example through the statewide

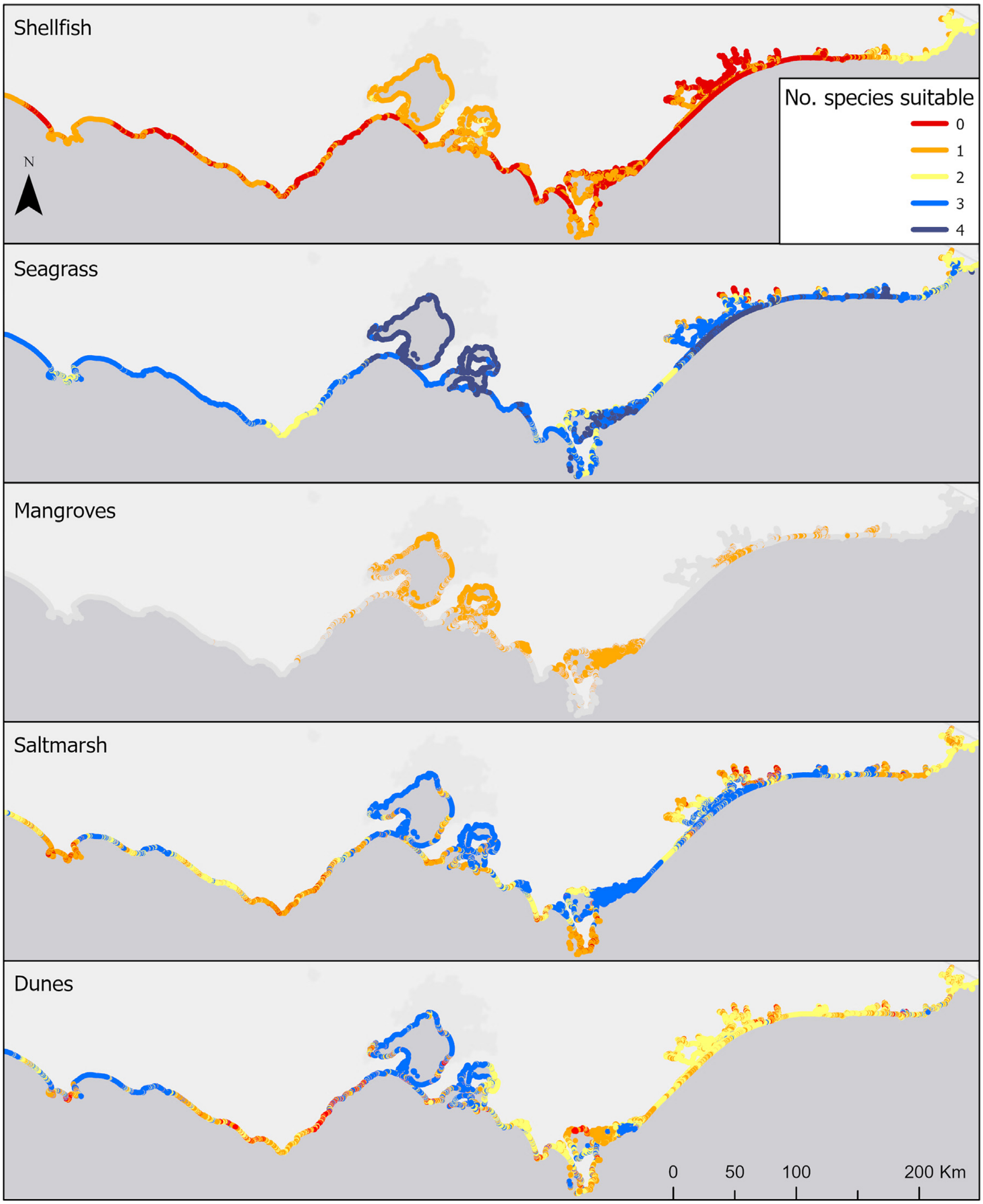

Fig. 7. The number of species within each taxa (shellfish, n = 2; seagrass n = 4; mangrove n = 1; saltmarsh n = 3; and dune n = 3) suitable for a soft or hybrid living shoreline.

coastal hazard assessment currently underway (DELWP, pers. comm.) would allow for better delineation of coastal segments suitable for soft or hybrid approaches. The model recommendations require a site-specific assessment to design and implement an on-ground solution, which would consider the current ecosystems present and the hydrodynamics and sediment transport at the site. Social factors, such as the acceptability of different options (Strain et al., 2022), or competing uses of the coast (e.g., boating or other watercraft, swimming etc.) will also need to be evaluated. The inclusion of climate change projections on species distribution and coastal hazard risk could be an extension to this model, particularly for distributional modelling of species with strong relationships to the bioclimatic variables such as *Gahnia filum*, which would inform adaptation pathway planning (Haasnoot et al., 2019).

4.1. Conclusions

We have presented a novel approach that combines species distribution models with a multi-criteria model to identify best practice approaches to manage coastal hazard risk along a diverse coastline with open-coast and estuarine shoreline types. One of the barriers to living shoreline implementation is a lack of understanding by coastal practitioners on what the available options are and where they can be used (Morris et al., 2022). The model provides a screening tool for local and state governments, consultants and other marine stakeholders to guide decisions around what options to consider for sections of the coastline. A regional-scale model can also be used to inform a more collaborative approach to coastal planning across sites and jurisdictions. The use of living shorelines over traditional hard approaches where suitable delivers multiple advantages through providing an adaptive coastal defence structure with environmental and social co-benefits (Gittman et al., 2014; Morris et al., 2018). The method used is transferable to other locations globally and is flexible to accommodate the geospatial data available in different regions. Shoreline suitability analyses are important tools in overcoming the barriers that are limiting living shoreline application at scale.

CRediT authorship contribution statement

Alys Young: Methodology, Data curation, Formal analysis, Writing – original draft. **Rebecca K. Runting:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Heini Kujala:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Teresa M. Konlechner:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Elisabeth M.A. Strain:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Rebecca L. Morris:** Conceptualization, Methodology, Writing – original draft, Supervision, Funding acquisition.

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.

Data availability

The data are available at https://livingshorelines.shinyapps.io/VicMap/.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2023.102857.

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