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Assessing the coastal protection services of natural mangrove forests and artificial rock revetments

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ABSTRACT

Coastal flooding and erosion cause significant social and economic impacts, globally. There is a growing interest in using natural habitats such as mangroves to defend coastlines. The protective services of mangroves, however, have not been assessed in the same rigorous engineering and socio-economic terms as rock revetments, and therefore are often overlooked by coastal managers. We used field measurements, a social science survey and economic valuation to compare the coastal protection services of mangroves and rock revetments, at five locations across Victoria, Australia. The results showed, in sheltered locations, both mangroves and rock revetments attenuated waves, however, the wave attenuation (per metre) of rock revetments was greater than mangroves, at two of the five locations. Only a small proportion of the survey respondents had observed flooding or erosion in their suburb but most agreed that mangroves provide important coastal protection benefits. Coastal landowners visited areas with mangroves more often than the public but were less likely to worry about the links between climate change and coastal erosion and flooding, or to agree that the coast was well protected with existing artificial coastal infrastructure, than other respondents. There were much higher up-front costs associated with building rock revetments, than planting mangroves, but rock revetments required less land than mangroves. Mangroves covered a larger area and averted more damages than rock revetments. Coastal managers and policy makers will have more success in advocating for nature-based solutions for coastal protection, if they are implemented in locations where they are eco-engineering and socio-economically acceptable options for climate change adaptation.

1. Introduction

Coastal zones are experiencing rapid population growth, land conversion and increasing urbanisation (McGranahan et al., 2007; Merkens et al., 2018). At present, it is estimated that 40% of the human population live within 100 km of the coastline (UN, 2017). In many countries population growth is higher in coastal than non-coastal areas (UN, 2017). This trend is exposing coastal populations and assets to a wide range of climate change-induced hazards, resulting from sea level rise and increases in the magnitude and/or frequency of extreme storm events (Neumann et al., 2015). Hence, there is an urgent social and economic need to develop cost-effective and adaptive strategies for coastal defence (Sutton-Grier et al., 2015).

Traditional methods for protecting coastal communities include seawalls, rock revetments and groynes (collectively referred to as artificial coastal infrastructure). However, these structures are expensive to build and maintain. Part of this cost is because artificial coastal infrastructure is non-adaptive - it must be upgraded, repaired, and rebuilt in response to a changing climate (Morris et al., 2020; Schoonees et al., 2019). In Victoria, Australia, alone it is estimated that approximately 50% of the existing artificial coastal defence structures will need to be rebuilt and upgraded to protect coastal communities from the threats of flooding and erosion, in the next 10 years (DELWP, 2020). Artificial coastal infrastructures also have high environmental and social costs when they replace natural coastal habitats (for example, dunes and beaches, mangroves, and saltmarshes) and sever the transition zone between terrestrial and marine systems (Bishop et al., 2017) and human access to natural shorelines (Strain et al., 2019a).

There is increasing interest in understanding the role of natural habitats in coastal defence along with their benefits for biodiversity, fisheries, and tourism (Temmerman et al., 2013). Vegetated habitats, including mangroves, can protect the coast against flooding and erosion, from sea level rise and storm surge (Guannel et al., 2016). Their vertical structure can attenuate waves and reduce water levels, and their roots

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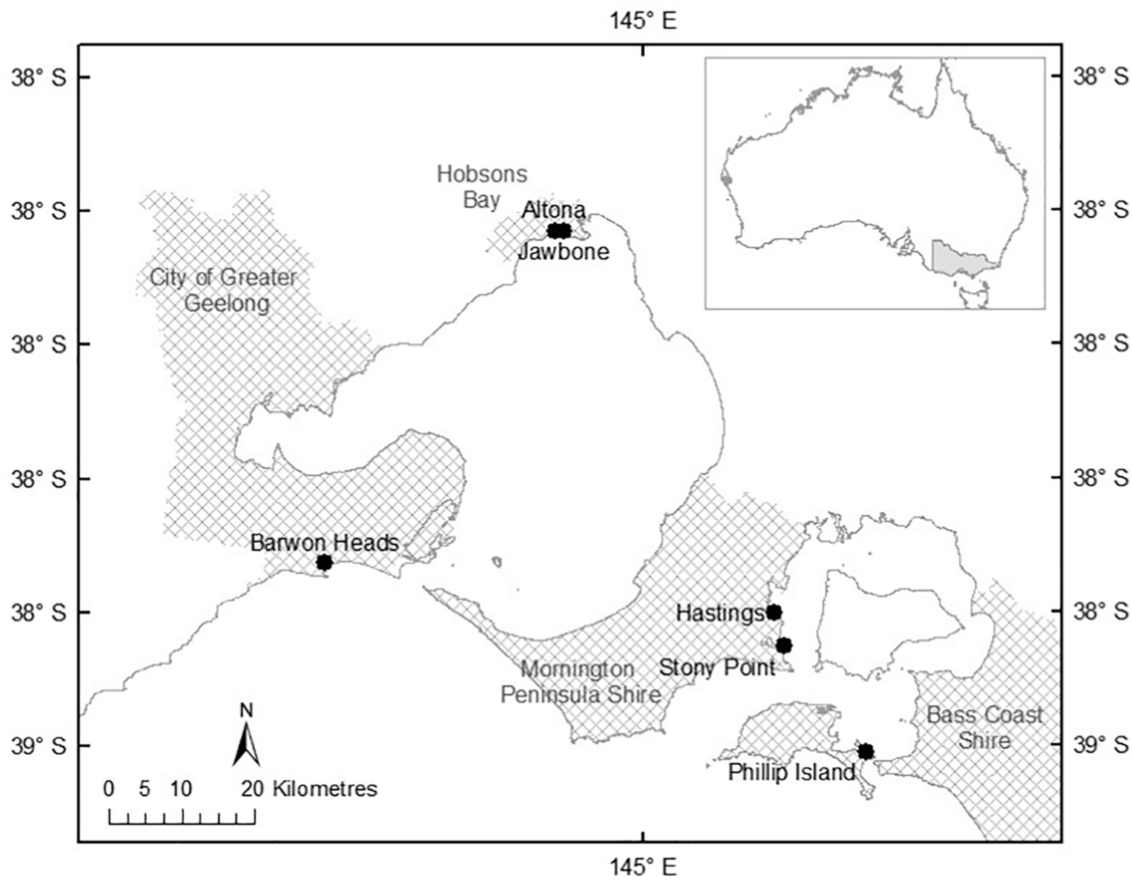

Fig. 1. Map of the locations wave sensors were deployed at mangroves and rock revetments (black circles) and the local government areas (grey hatch) targeted for the social science surveys in Victoria, Australia.

capture sediment and limit erosion (Horstman et al., 2014; Marois and Mitsch, 2015; Montgomery et al., 2018). The importance of mangroves in coastal defence, however, depends on the site characteristics and the local hazard context (Spalding et al., 2014). Currently, there is limited information on the coastal protection benefits of mangroves relative to artificial coastal infrastructure (Morris et al., 2018; Narayan et al., 2016), particularly for mangroves located in temperate areas. Hence, further study is required to determine under what ecological and environmental conditions mangroves can provide comparable coastal protection services to artificial coastal infrastructure (Pontee et al., 20178; Sutton-Grier et al., 2015).

This gap in the literature exists largely because mangroves and artificial structures have different mechanisms for providing coastal defence services (Morris et al., 2021a). Both mangroves and artificial coastal infrastructures can attenuate waves, but mangrove forests are made of individual trees that create roughness, which can cause dissipation of wave energy as the flow interacts with the roughness (Morris et al., 2021a). In contrast, artificial coastal infrastructures such as rock revetments can be made with permeable materials which absorb the wave energy or impermeable materials for seawalls, that reflect the wave energy (Schoonees et al., 2019). Moreover, mangroves require tidal inundation, which assuming the density and nature of vegetation does not change along the wave propagation trajectory, means that the wave dissipation rate is constant across the width of the forest whereas rock revetments or seawalls form a fixed vertical or sloping barrier against inundation which can enhance the initial wave set heights, and means that much of the wave energy is either dissipated or reflected at the toe of the structure (Schoonees et al., 2019). These issues must be considered when comparing the wave attenuation of mangroves and artificial coastal infrastructure.

Globally, mangroves have suffered dramatic declines, hampering the provision of their coastal protection services (Polidoro et al., 2010). Much of this loss is related to modification of coastal landscapes and shorelines for human development, aquaculture, or resource use (Thomas et al., 2017). Hence, coastal policies need to protect, and also take into account, the coastal protection benefits of mangroves (Gray et al., 2014; Morris et al., 2020; Scyphers et al., 2015). Current policies advocating for the use of mangroves and other vegetative habitats as a standard approach for coastal protection are limited to a few key locations (such as Maryland's Living Shorelines Act, 2008, USA; and the Victorian Marine and Coastal Policy, 2020; Schoonees et al., 2019). The lack of evidence-based support and public understanding have been identified as potential barriers for the uptake of vegetative habitats as a coastal protection strategy or policy (Seddon et al., 2020). Previous studies have addressed how concern for coastal hazards and support for coastal protection options varies among stakeholder groups, according to their past experiences (Gray et al., 2017; Scyphers et al., 2015). However, these studies are limited to a few key locations across the USA, and further research is required to determine whether coastal landowners in other locations are similarly concerned about coastal hazards, and the types of options that can be used for coastal protection.

One of the greatest challenges for policy makers and coastal managers is the limited knowledge about the expected benefits and costs of building and maintaining mangroves to achieve coastal protection services relative to the more commonly used artificial coastal infrastructures (Sutton-Grier et al., 2015). Given there are few studies that have made comparisons between the effectiveness of existing natural and traditional defences in attenuating waves or public opinion of these

Table 1
Summary of the wave measurements for mangrove forests and rock revetments for each of the five locations.

Measure	Barwon Heads		Williamstown		Hastings		Phillip Island		Stony Point	
	Mangrove	Rock revetment	Mangrove	Rock revetment	Mangrove	Rock revetment	Mangrove	Rock revetment	Mangrove	Rock revetment
Sample period	18/09/18–24/09/18	30/09/18–07/10/18	14/08/18–26/08/18	13/10/18–25/10/18	23/11/18–29/11/18	8/11/18–14/11/18	11/10/18–25/10/18	26/10/18–1/11/18	20/10/18–26/10/18	20/10/18–26/10/18
Tidal range (m)	0.97	1.30	0.55	0.50	2.09	2.23	1.93	2.33	1.29	1.29
Maximum elevation AHD (m)	0.80	0.41	−0.10	−0.84	−0.36	0.02	0.01	0.35	−0.03	0.56
Significant wave height in metres (mean/max)	0.03/0.06	0.01/0.01	0.03/0.29	0.11/0.44	0.12/0.40	0.03/0.10	0.01/0.02	0.04/0.11	0.08/0.13	0.04/0.05
Depth in meters (average across the two RBRs)	0.84	0.48	0.34	0.36	1.63	1.09	0.86	0.85	1.33	0.56
K_t (mean/range)	0.53 (0.41 0.60)	0.90 (0.77 1.03)	1.05 (0.29 4.61)	1.17 (0.68 2.63)	0.20 (0.02 0.42)	0.35 (0.17 0.65)	0.16 (0.08 0.28)	0.99 (0.58 1.51)	0.37 (0.22 0.52)	0.92 (0.80 1.25)
K_d (mean/range)	−0.02 (-0.03 −0.02)	−0.08 (-0.17 −0.02)	−0.01 (-0.04 0.05)	−0.01 (-0.97 0.16)	−0.03 (-0.07 −0.02)	−0.25 (-0.39 −0.09)	−0.02 (-0.03 −0.02)	−0.01 (-0.20 0.15)	−0.01 (-0.02 −0.01)	0.01 (-0.13 0.13)

options, it is unsurprising there is also a lack of data for site-specific cost-benefit comparisons (Ferrario et al., 2014; Narayan et al., 2016). This is widely regarded as one of the most significant barriers to the uptake of natural habitats as coastal defence options in coastal adaption strategies and policies (Narayan et al., 2016) and also prevents coastal managers from advocating for mangrove plantings or other nature-based solutions when considering coastal defence options.

In this study, we integrate the information about the costs of mangrove plantings with rock revetment building projects, to address these gaps and improve understanding of how and where temperate mangroves, in Victoria, Australia may be viable options for providing coastal protection services. Specifically, we use a multidisciplinary approach (eco-engineering, social science and economics) to compare the use of natural mangroves and rock revetments for coastal protection, at five locations across Port Phillip and Western Port Bay in Victoria, Australia (Fig. 1). The focus of our study was on rock revetments rather than other types of coastal infrastructure because these structures attenuate waves similarly to mangroves, are located in the intertidal zone and have distinct management/policy interventions used to protect the coastal from erosion and flooding (Morris et al 2020, DELWP 2020). We hypothesized that: 1) mangroves and rock revetments would attenuate waves; 2) but that rock revetments would be more effective at attenuating waves over smaller distances. Furthermore, we predicted that: 3) older people who own coastal properties would be more likely to have observed flooding and erosion in their suburb and to visit nearby natural mangroves or rock revetments than other respondents; and 4) highly-educated, younger people and coastal landowners would be more likely to agree that climate change will result in increasing risk of coastal hazards, that mangroves and rock revetments provide important coastal protection benefits and less likely to agree that the coast is already well protected with existing artificial coastal infrastructure. Finally, we expected that 5) planting mangroves would be a more cost-effective solution for coastal protection than constructing rock revetments. The implications of our findings for coastal policy makers and managers are discussed.

2. Methods

2.1. Eco-engineering data

The effectiveness of natural mangroves and rock revetments at providing coastal protection was compared through assessing their wave transmission. The wave measurements were conducted at five locations (Barwon Heads, Williamstown, Hastings, Phillip Island and Stony Point), across three estuaries in Victoria, Australia (Fig. 1). These five locations were chosen as they have mangrove forests in close proximity to rock revetments (<1 km). The tides at these locations are semi-diurnal with a mean tidal range of 0.5–2.33 m, during the sampling period (Table 1). The Victorian mangrove forests occupy the most southerly and highest latitude locations for mangroves across the globe. The mangroves (*Avicenna marina*) are relatively short (maximum 1.5 m height) and they occupy sheltered areas along the coast.

Wave loggers (RBR®solo D wave; hereafter RBR) were deployed for approx. seven days at each location between August 2018 and November 2018; deployment of the RBRs was linked to king tides to maximize the inundation duration of the treatments, and therefore the number of data points collected (Table 1). At each location, four RBRs were deployed, one RBR was directly placed in front (offshore) of the mangrove forest or rock revetment and the other two RBRs were placed either directly behind (onshore) the mangrove forest, or at the high tide mark (onshore) of the rock revetment (Supplementary S1). The RBRs were attached, approx. 0.05 m above the seabed, with cable ties to star pickets. The RBRs were programmed using the Ruskin software (v1.13.12; wave frequency = 4 Hz; duration = 2048, burst rate = 20 minutes) to collect wave data (significant wave height, H_s, in metres and associated period, T, in seconds). The waves were primarily assumed to be wind driven.

During retrieval of the RBRs, crest height of the rock revetments, and the along shore distance (width) and the distance between the onshore to offshore RBRs (length) of the mangrove forests and rock revetments were measured using a REACH RS + Real Time Kinematic GPS unit. The RTK-GPS was connected to a 2.0 m GPS Survey/Prism Monopole, allowing for a 2.085 m offset height correction, and the Networked Transport of RTCM via Internet Protocol (NTRIP) was used to provide base data from satellites. The RTK point data (WGS84 Ellipsoid) were converted to Australian Height Datum (AHD) using the AusGeoid program and the AUSGeoid09 V1.01 grid. The density of mangrove adults, saplings and seedlings were estimated from quadrats (2 × 3 m for adults and saplings and 1 × 1 m for seedlings), which were sampled at 10 m intervals, along the width of the mangrove forest.

The wave attenuation of the mangrove forests and rock revetments at each location were calculated based on the methods proposed by Ysebaert et al. (2011), Haynes (2018) and Morris et al. (2021b), (see Supplementary S2 for full details). In brief, we calculated the wave transmission coefficient which is the ratio of measured to predicted wave height, accounting for shoaling on wave height, through the change in depth between the offshore and onshore RBRs:

$K_t = (H_s/H_{s\_pred})$.

where H_s is the recorded wave height and $H_{s\ pred}$ is the predicted wave height at the onshore RBR (Morris et al., 2021b). The wave transmission coefficient accounts for potential changes in wave height due to shoaling, but not other processes, such as rugosity and refraction. Wave attenuation is caused by the energy dissipation generated by the mangroves or rock revetments (Ysebaert et al., 2011). Using the wave transmission co-efficient we calculated how the wave attenuation of the mangrove forests and rock revetments at each location declined as a function of distance (i.e. wave decay per m):

$K_d = \ln(K_t)/x$.

where × is the distance between the onshore and offshore RBR (Ysebaert et al., 2011). The data was recorded every twenty-minutes for water depth, significant wave height, wave period and the decay coefficient, during high tide when the RBRs were underwater and all processing was done in MATLAB (MathWorks, 1996). A two-way ANOVA (type III sum of squares) was used to test the effects of mangrove forests and rock revetments (fixed, 2 levels), and site (fixed, 5 levels) on wave attenuation (K_t, K_d).

2.2. Social science data

The survey assessed the perceptions of landowners (living up to two streets away from the coast) and the public (all other participants), across Victoria. It used both targeted (landowners) and convenience sampling (public) to capture the responses of stakeholder groups (Kemper et al., 2003). The survey was distributed online to people 18 years of age or over, and participants were recruited through mailing lists (Melbourne Water, Hobsons Bay City Council, City of Greater Geelong Council, and Bass Coast Shire Council), or in person (using a tablet or paper copy of the questionnaire) at street locations, shopping malls, private businesses and open houses at five locations (Altona, Geelong, Hastings, Grantville and Lang Lang) and through the post at six locations (90 surveys sent to landowners and 200 to the public at Altona, Barwon Heads, Geelong, Hastings, Grantville and Lang Lang), (Fig. 1). All respondents were provided with access to the plain language statement (ethics approval reference number **1852769.1** University of Melbourne, Australia) before agreeing to undertake the survey (Supplementary S3).

The survey was made available online through Surveymonkey (www.surveymonkey.com) between 11/05/2018 and 11/05/2019 or on paper copies through the post. The survey required approximately 10–15 minutes to complete and included 26 questions. In this study, eight questions were used in the analyses (Supplementary S4). The survey included questions with binary (yes or no), 5-point Likert scales (e.g. daily, monthly, not sure, rarely or never or a lot, some, a little, never or not sure) and open answers. This mixture of responses allowed for nuance and the ability to explore multiple perspectives. Participation in the survey was voluntary and without incentive. All incomplete online surveys were excluded from the analyses.

Generalised linear models with a binomial distribution (GLMs) were used to test the effects of stakeholder group (fixed, 2 levels = coastal landowner or public), and age (fixed, 6 levels = 18–24, 25–34, 35–44, 45–54, 55–64 or + 65) on the respondent's experiences of flooding or erosion in their suburb (yes or no). The effects of stakeholder group and age were then tested on respondent's frequency of use of mangroves and rock revetments for recreational activities (5-point Likert scale = daily, monthly, rarely or never) using ordinal regression models (ORMs). Similarly, GLMs or ORMs were used to test the effects of stakeholder group (as above), age bracket (as above), and education level (fixed, 4 levels = did not go to school or primary, secondary, TAFE or vocational, university) on respondents' perceptions of the links between climate change and rising sea levels (5-point Likert scale = strongly agree, agree, not sure, disagree or strongly disagree), increasing storminess, flooding and erosion, level of worry about these issues, belief that the coast is already well protected with existing artificial coastal infrastructure (5-point Likert scale = a lot, a little, not sure, some, not at all), and that mangroves and rock revetments provided coastal protection benefits (yes or no).

2.3. Economic data

To provide a direct comparison of the value of natural mangroves with rock revetments, we calculated the costs of planting mangroves (Melbourne Water, 2013), the construction costs of building rock revetments (www.delwp.vic.gov.au) and the amount of property damage averted by the mangrove forest or rock revetment, at each of the five locations. The density of mangrove seeds and seedlings required to plant each location (1–6 plants, 0% losses), (Melbourne Water, 2013) and the approximate costs of the materials and labour required to construct rock revetments (www.delwp.vic.gov.au), were estimated from restoration and building projects, undertaken across Victoria.

The amount of damage averted by the mangroves and rock revetments, was calculated based on the approach of Kompas et al. (2021), using Victorian digital and spatial data for 88 land-use classes and more than 240 subregions (see Supplementary S5 for full details). The calculations were based on assumption that both the mangroves and rock revetments will provide complete protection to properties, infrastructure, and other environmental assets such as parks, from sea level rise and storm surge, as determined by our measurements of wave attenuation. The sea level rise projection was derived from the Victorian Coastal Inundation Dataset, which modelled the extent of land subject to coastal inundation through time for RCP6.0 climate change scenarios (Department of Environment Victoria, 2020). At each of the five locations, the economic costs of sea level rise and storm tides were projected for 2040 and 2100, using standard GIS methodology and MATLAB (MathWorks, 1996) modelling techniques. The model was dynamic and included both the relationship between land or house prices over time and a 3% and 5% discount rate for environmental and portfolio assets respectively. We used a lower discount rate for the environmental assets than property or infrastructure because of their intergenerational benefits (Costanza et al. 2021). The calibration of sea level rise per year was consistent with the only available spatial data set for coastal Victoria, indicating a 0.2 m rise by 2040 or 0.82 m rise by 2100, under scenario RCP6.0. The values of the properties in each location were estimated based on the values of residential and rural land (Allhomes, 2020), along with ABS (2020) and BITRE (2020) data. The value of public assets was calculated based on hedonic pricing mechanisms (Kompas et al. 2021) or price-transfer function values (Stoceckl et al., 2020). The non-market value of direct-use, indirect-use, option and non-use values for recreational areas, social infrastructure and residential and non-residential properties were derived from the ecosystems service values calculated by Van der Ploeg et al. (2010). All prices were adjusted based on the category of use (residential, commercial, industrial, manufacturing, public facilities) and surrounding land costs for each location. The assets layers were constructed by Stoceckl et al. (2020). The amount of damage averted by the mangrove forest or rock revetment, for each of the five locations was calculated by multiplying the total cost (economic and non-market) by the area occupied by the mangrove forest or rock revetment. The area of the mangroves or rock revetments were calculated from the REACH RS + Real Time Kinematic GPS unit measurements (see section 2.1 for full details). All-monetary values were standardised by using the appropriate Consumer Price Index (CPI) inflator indices and converting the inflated costs to 2019 AUD $ (https://www.rba.gov.au/calculator/annualDecimal.html). All costs are presented on a per m^2 basis.

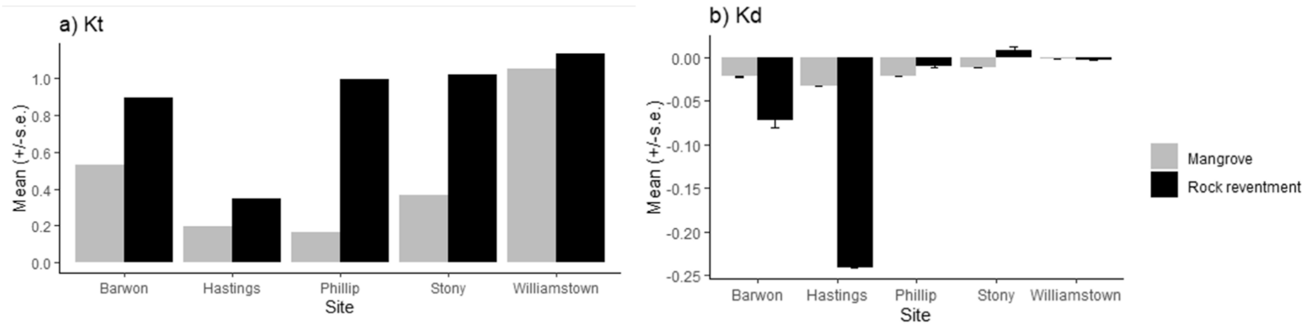

Fig. 2. Mean (±SE) wave attenuation for mangrove forests (grey) and rock revetments (black) between (a) an offshore and onshore RBR (Transmission coefficient (K_t) values below 1 indicate a reduction in wave height, whereas values above 1 indicate an increase in wave height); and (b) an offshore and onshore RBR per metre (Decay coefficient (K_d) values below 0 indicate a reduction in wave height, whereas values above 0 indicate an increase in wave height) at five locations (Barwon = Barwon Heads, Phillip = Phillip Island and Stony = Stony Point) across Victoria, Australia. The increases in wave height for both mangrove forest and rock revetment in Williamstown and for the rock revetment in Stony Point were likely linked to processes not measured in this study, including the presence of rocky reefs and/or refraction.

Table 2
Socio-economic characteristics of respondents, and census data for Victoria.

Characteristic	Survey respondents (%)	Victoria (%)	Williamstown (%)	Mornington Peninsula (%)
Gender				
Female	56.0	49.1	50.9	51.7
Male	42.0	50.9	49.1	48.3
Age bracket				
>18	NA	24.3	18.4	23.2
18–24	6.0	7.0	5.8	4.8
25–34	3.4	14.3	14.7	8.7
35–44	14.0	14.5	15.2	12.1
45–54	16.0	13.6	14.2	13.7
55–64	20.0	11.4	11.6	13.6
65+	**35.4**	**14.2**	**14.8**	**24.6**
Education bracket				
Primary school	1.4	1.0	1.3	8.5
Secondary school	20.0	15.9	15.9	13.8
Tafe or vocational training	20.0	23.6	22.3	29.5
University	**54.7**	**24.3**	**26.1**	**17.2**
I prefer not to answer	2.0	10.0	9.2	10.7
Income				
Household income median	$1000 - $1999 per week	$1.419 per week	$1,567 per week	$1,276 per week

3. Results

3.1. Wave attenuation of mangroves and rock revetments

The average significant wave heights recorded at the five locations, during the study period were 0.01 to 0.12 m, with maximum heights of 0.01 to 0.29 m (Table 1). There was a significant difference in the transmission and decay coefficient from the off- to onshore RBRs between the mangroves and rock revetment treatments at all sites (Fig. 2, Supplementary S6). At all sites, the wave attenuation between the on- and offshore RBRs (transmission coefficient), was greater in the mangroves than the rock revetments (Fig. 2; Supplementary S5). In contrast, the wave attenuation per m (decay coefficient) was greater at the rock revetments relative to the mangroves at Barwon Heads and Hastings but there were no detectable differences between the mangrove forests or rock revetments at Phillip Island, Stony Point and Williamstown (Fig. 2; Supplementary S6). The site with greatest mangrove forest length (Hastings) had the greatest wave attenuation potential per m (decay coefficient) (Fig. 2; Supplementary S6).

3.2. Coastal landowner and public perceptions and use of mangroves and rock revetments

In total, 149 people completed the survey (with 65 responses from coastal landowners and 84 responses from the public). Of the 149 participants, 42% completed the survey online and 22% returned the survey through the post. This number of responses is comparable to other public perceptions studies on coastal protection issues (Evans et al., 2017; Kienker et al., 2018; Morris et al., 2016; Strain et al., 2018).

There were approximately equal numbers of males and females surveyed, with the most common age category +65 years, education bracket bachelor's or higher degree, and household income bracket $1000–1999 per week (Table 2). The percentage of males and females surveyed and the median income per week were comparable to equivalent census data (Table 2). In contrast, the percentage of highly educated people with a bachelor or postgraduate degree, that were aged +65, were overrepresented relative to the equivalent census data (Table 2).

The survey indicated that only a small proportion of people surveyed had observed erosion (0.27) or flooding (0.30) on their property or in their suburb. The results also showed that the coastal landowners were more likely to use the mangrove forests for recreational activities than the other respondents (Table 3, Supplementary S7). However, contrary to our predictions, the proportion of people that had observed flooding and erosion or that used the rock revetments was unrelated to whether they lived on the coast or their age (Table 3, Supplementary S7).

The respondents' perceptions of climate change were influenced by whether they lived on the coast, education level and age bracket (Fig. 3; Table 3; Supplementary S8). Overall, the older respondents were less likely to agree or strongly agree with the statements 'Climate change will

Table 3
Effect size (odds ratio and two sided 95% confidence interval) for the relationships between stakeholder group (coastal property owners or public) and age bracket on: a) experience of coastal erosion (yes or no), b) experience of coastal flooding (yes or no), c) use of mangrove forests for recreational purposes (daily to never), d) use of rock revetments for recreational purposes (daily to never) and relationships between stakeholder group, and age and education bracket on people's perceptions that; e) climate change will result in rising sea levels (strongly disagree to strongly agree), f) climate change will result in increasing storminess (strongly disagree to strongly agree), g) climate change is linked to coastal flooding and erosion (a lot to not at all) h) level of worry about the links between climate change and coastal flooding and erosion (a lot to not at all), i) coast is already protected by artificial coastal infrastructure (yes or no), j) mangrove provide coastal protection benefits (yes or no) and k) rock revetments provide coastal protection benefits (yes or no). Significant relationships (where confidence intervals do not overlap 1) are indicated in bold print (see Supplementary S7–S8 for full details).

Characteristic	a) Experience of erosion	b) Experience of flooding	c) Use of mangrove forests	d) Use of rock revetments	e) Climate change results in rising sea levels	f) Climate change results in increasing storminess	g) Links between climate change and flooding and erosion	h) Level of worry about the links between climate change and flooding and erosion	i) Protected from coastal erosion and flooding	j) Mangroves provide coastal protection benefits	k) Rock revetments provide coastal protection benefits
Stakeholder group	0.761 (0.319 1.777)	1.276 (0.603 2.708)	**4.503 (2.310 8.997)**	1.872 (0.993 3.567)	0.649 (-1.192 0.329)	0.655 (-1.189 0.343)	0.478 (-1.769 0.237)	**−0.224 (-2.223 −0.793)**	**0.105 (0.016 0.422)**	0.492 (0.160 1.478)	**0.221 (0.095 0.489)**
Age bracket	1.008 (0.762 1.352)	1.039 (0.804 1.358)	0.827 (0.677 1.008)	0.898 (0.731 1.101)	**−0.649 (-0.756 −0.139)**	**−0.723 (-0.634 −0.043)**	1.111 (-0.209 0.413)	**−0.890 (-0.666 −0.336)**	0.744 (0.453 1.188)	1.121 (0.702 1.759)	1.254 (0.897 1.774)
Education bracket	NA	NA	NA	NA	1.414 (-0.106 0.794)	1.132 (-0.369 0.599)	**1.749 (0.062 1.063)**	**1.541 0.022 0.844)**	**0.432 (0.214 0.838)**	0.974 (0.472 1.831)	0.625 (0.348 1.049)

result in rising sea levels' and 'Climate change will result in increasing storminess' than younger people. Similarly, the older respondents and coastal landowners were less likely to be 'Worried about the links between climate change and coastal flooding and erosion' than younger people and those living further from the coast (Fig. 3; Table 3; Supplementary S8). In contrast, the highly educated people were more likely to be 'Worried about the links between climate change and coastal flooding and erosion' and to have thought about the statement 'Have you thought much about the links between climate change, coastal erosion and flooding before today?' than others (Fig. 3; Table 3; Supplementary S8).

Only a small proportion of the people surveyed (0.12) thought that the coastline was well protected from flooding and erosion with existing artificial coastal infrastructure. However, most respondents agreed that mangroves (0.87) and rock revetments (0.72) can provide coastal protection benefits. The coastal landowners and highly educated respondents were less likely to agree that the coastline was well protected, relative to the other respondents (Table 3; Supplementary S8). The coastal landowners were also less likely to think that rock revetments can provide coastal protection benefits compared with the other respondents (Supplementary S8). There were, however, no detectable effects of age on the respondents' attitudes towards coastal protection (Supplementary S8).

3.3. *Costs of planting mangroves, constructing rock revetments and damages averted by existing mangroves and rock revetments.*

Across the five locations, the total cost (economic and non-market) of sea level rise was \$4.12 to \$122.00 million AUD per km^2, by 2040 and \$15.5 to \$333.9 million AUD per km^2, by 2100 (Table 4). The costs of planting mangroves ranged between \$3.35 and \$39.5 AUD, per m^2 (Table 4), and the costs of constructing rock revetments ranged between \$200 and \$5,000 AUD, per m^2 (Table 4). The total avoided damage costs of the mangroves ranged between \$0.001 and \$70.70 million per m^2 AUD, whereas the avoided damage costs of the rock revetments ranged between \$0.001 and \$8.21 million per m^2 AUD (Table 4). On average the upfront cost of planting mangroves was significantly lower than constructing rock revetments, but the rock revetments required less land than mangroves to achieve the same wave attenuation benefits (Table 4). At all locations, the area occupied and therefore the total averted damages of the mangroves were greater than the rock revetments (Table 4).

4. Discussion

4.1. *Comparing the coastal protection services of mangrove forests and rock revetments*

We provide the first direct comparison of natural mangrove forests and rock revetments in attenuating waves, at five locations across Victoria, Australia. Our results extend the results from previous meta-analyses (Ferrario et al., 2014; Morris et al., 2018; Narayan et al., 2016; Shepard et al., 2011) by measuring the effectiveness of mangroves and rock revetments in attenuating waves, under the same environmental conditions. We showed that, with small to moderate incoming waves (significant wave heights < 0.30 m), both mangroves and rock revetments attenuated waves at four of the five sites. However, in terms of wave attenuation per metre, rock revetments outperformed mangroves at two of the five locations. These results could be explained by differences in rock revetment slope or design between locations which influences their ability to attenuate and/or refract wave energy (Schoonees et al., 2019). Overall, these results provide further evidence that, in some sheltered locations, both mangroves and rock revetments can attenuate waves and provide important coastal protection services (Morris et al., 2018; Narayan et al., 2016). Further research is required to determine the applicability of our findings to other types of artificial coastal infrastructure and wave conditions.

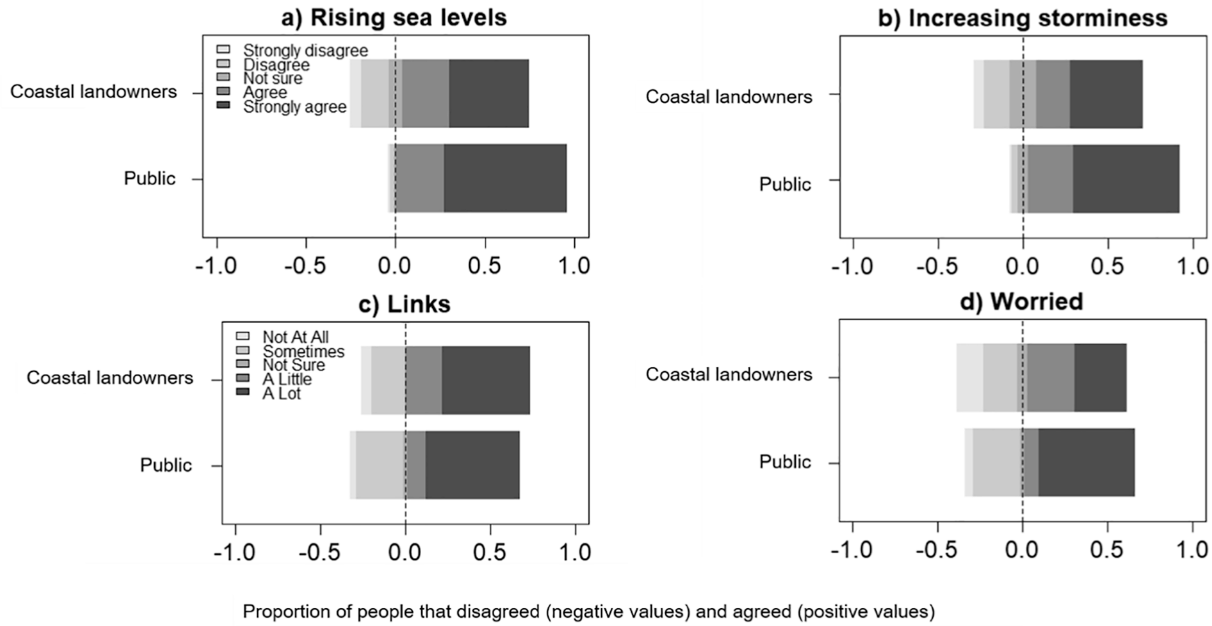

Fig. 3. Relationships between stakeholder group (coastal landowners or public) and their perception that: a) climate change will result in rising sea levels (strongly disagree to strongly agree); b) climate change will result in increasing storminess (strongly disagree to strongly agree); c) whether they had thought about the links between climate change and coastal erosion and flooding (a lot to not at all) and d) whether they were worried about the links between climate change and coastal erosion and flooding (a lot to not at all). The dotted vertical line shows the neutral position (not sure).

We also demonstrated that environmental conditions at each of the five locations had a significant influence on the degree of wave attenuation provided by the mangroves. For instance, the locations with greater mangrove forest length and higher elevation had a positive influence on wave attenuation. Within a location, the wave attenuation of vegetated habitats can also vary spatially across their width (Shepard et al., 2011). Studies have highlighted the importance of understanding how the vegetation characteristics and flow dynamics influence the ability of vegetated habitats to attenuate waves (Armitage et al., 2019; Sánchez-Núñez et al., 2019). Hence, to better quantify the benefits of natural temperate mangroves in protecting coastal communities into the future, much greater emphasis needs to be placed on understanding the effectiveness and spatial variability of this coastal vegetation in attenuating waves and accumulating sediment, under a range of wave climates and over larger spatial and temporal scales (Sánchez-Núñez et al., 2019).

When managing coastal hazards, it is important to consider engineering and socio-economic factors (Arkema et al., 2017). In Australia coastal communities are often dominated by older people (Gurran, 2008; MacKenzie, 2020) who can be more vulnerable to coastal hazards, because they are slower to respond and recover from extreme weather events, such as flooding (Arkema et al., 2013; MacKenzie, 2020). We found that coastal landowners were more likely to use mangroves for recreational activities such as fishing, bird watching and walking, than other respondents. However, contrary to our hypotheses, the proportion of people that had observed coastal flooding and erosion was unrelated to whether they lived on the coast, or their age. Moreover, the older coastal residents were less likely to be concerned about the links between the changing climate, and the increasing risk of coastal flooding and erosion than the other respondents surveyed. This is because in our study location many coastal residents still question the validity of sea level rise predictions (Barnett et al., 2014; Graham and Barnett, 2017) and do not believe erosion and flooding pose a significant risk to the coastal zone either currently or in future (DELWP unpublished). This knowledge gap means that policy makers cannot develop a dialogue with coastal communities around adaptation strategies, based on shared knowledge or belief in climate change, but rather must rely on other social or environmental triggers (e.g. flooding or erosion events) (Barnett et al., 2014; Graham and Barnett, 2017).

In contrast, very few of the people surveyed, including the coastal landowners, thought that the coastline was already well protected from flooding and erosion with existing artificial coastal infrastructure. Research has demonstrated that coastal landowner preferences for different types of adaptation strategies are influenced by the perceived benefits of the different options in mitigating coastal hazards (Karrasch et al., 2014), their exposure to risks (Gray et al., 2017) and other socio-economic factors (Han and Kuhlicke, 2019). In some areas, coastal landowners prefer artificial structures because they are perceived as more durable and less costly than maintaining natural solutions (Scyphers et al., 2015), whereas in other locations vegetated habitats are more desirable because of concerns that built coastal infrastructure can aggravate the intensity of the impacts from coastal hazards (Peterson et al., 2019) as well as a lack of trust that structures will be properly maintained (Touili et al., 2014). In our study, a similar proportion of coastal landowners and other respondents thought that mangroves were important habitats for coastal protection, but a higher proportion of the public thought rock revetments provide significant coastal protection services, compared with the coastal landowners. These results suggest that in some locations coastal landowners, consider mangroves the more desireable options for providing coastal protection services than rock revetments (Gray et al., 2017; Smith et al., 2017). However, semi-structured interviews with 25 residents from one location surveyed in this study (Grantville) have highlighted more mixed views with participants only selecting specific sites where mangrove plantings were the preferred option for coastal defence purposes (DELWP unpublished). Hence further research with participatory mapping is required to identify key sites, in which mangrove plantings can be used as socially acceptable climate adaption tools (Strain et al., 2019b).

In this study we combined two types of non-probabilistic sampling – including purposive sampling for coastal landowners and convenience sampling for the public, to provide crucial insights into what people think about coastal erosion and flooding, and the use of mangroves and rock revetments in providing coastal protection and recreational benefits. These sampling methods are used to capture cost-effective data

Table 4
The costs of sea level rise (SLR) by 2040 or 2100, for each location and characteristics, total averted damages costs for either mangrove forests or rock revetments, at each of the five locations. The costs of planting mangrove seeds (1–6: $3.35–20.1) or seedlings (1–6: $6.65–39.5) were obtained from https://seagrass.com.au.

Location	Cost of SLR (2020, 2100)	Mangroves				Rock revetments			
	Market and non-market ($ million/ km^2)	Density of plants (m^2)	Onshore to offshore length (m)	Along shore width (m)	Averted damages costs (million/ m^2)	Crest height ADH (m)	Onshore length (m)	Cost of building including rocks (m^2) https://www.delwp.vic.gov.au	Averted damages costs (million/ m^2)
Barwon Heads	Market: 11.98, 32.50 Non-market: 0.71, 10.04	Adults: 0.39 Saplings: 5.00 Seedlings: 0.00 Total: 5.39	271.00	28.99	0.01–0.33	1.772	40.6	$200	0.001–0.003
Williamstown	Market: 22.76, 181.52 Non-market: 4.81, 37.56	Adults: 0.28 Saplings: 0.06 Seedlings: 0.00 Total: 0.34	468.70	21.95	6.23–49.47	2.553	381.91	$5,000	0.59–4.69
Hastings	Market: 11.98, 326.94 Non-market 1.24, 12.95	Adults: 0.43 Saplings: 0.17 Seedlings: 3.60 Total: 4.20	3650.00	57.00	25.4–70.7	2.932	605.83	$5,000	0.22–0.61
Phillip Island	Market: 3.36, 9.51 Non-market: 4.14, 6.04	Adults: 0.06 Saplings: 0.56 Seedlings: 0.00 Total: 0.62	450.00	87.95	0.17–0.62	2.045	112.23	$5,000	0.01–0.03
Stony Point	Market: 120.98, 326.94 Non-market: 1.24, 12.95	Adults: 0.58 Saplings: 0.58 Seedlings: 0.90 Total: 2.06	1430.00	93.00	16.26–45.2	2.647	98.12	$2,000	2.95–8.21

which can be used in the early stages of decision-making, raising awareness of the marine environment, and identifying any differences in perspective among key stakeholder groups (e.g. Kienker et al., 2018; Strain et al., 2018), however it can be difficult to get a representative population sample. To assess this, we compared the data collected via the survey to equivalent census information collected across Victoria and in two of the five locations. We found the proportion of males and females and their average household income per year did not differ from census information but the percentage of highly educated people with a university degree, and the age groups of 65 + were overrepresented relative to the census data. These biases may be due to several reasons, such as the relatively small sample size, the survey's non-inclusion of people under 18 years and a greater interest in the subject by more educated people (Strain et al., 2019a). Alternatively, there could be fundamental differences in the socio-economic characteristics of coastal landowners relative to suburban or state-wide populations. Further study with greater social diversity and using a range of methods is required to distinguish between these possibilities. Irrespective, our results provide important information about some of the key individual level characteristics that influence people's use and preferences for different types of coastal defence strategies.

Based on our analyses and recent studies by the insurance industry (Narayan et al., 2019; Pelayo et al., 2020; Reguero et al., 2020), we found that mangroves are cost effective alternatives to rock revetments for risk reduction and adaptation. In most locations, the natural mangrove forests delivered wave attenuation benefits that were comparable or greater than rock revetments. The upfront costs of planting mangroves are also significantly cheaper than building rock revetments. The coastal area and hence the damages averted by mangroves to coastal properties from sea level rise and storm surge, under current conditions was greater than the rock revetments. Moreover, vegetated habitats such as mangrove provide other ecosystems services of economic importance such as biodiversity, fisheries, and tourism, not considered in this study. However, planted mangroves forests require more coastal land than rock revetments and there is greater uncertainty about how many mangroves need to be planted and how long it will take to achieve the desired coastal protection benefits. Our findings are consistent with recent analyses from the insurance industry on the economics of climate adaptation (Narayan et al., 2019; Pelayo et al., 2020; Reguero et al., 2020). These studies examined the costs and benefits of mangroves and artificial structures for coastal risk reduction and adaptation (Narayan et al., 2019; Pelayo et al., 2020; Reguero et al., 2020). They found that natural mangroves provide significant flood damage reduction benefits to coastal communities in multiple locations and conditions, where there is sufficient coastal land for the forests to persist and retreat with rising sea levels (Narayan et al., 2019; Pelayo et al., 2020; Reguero et al., 2020). This suggests, planting mangroves may not be a viable solution for coastal protection in areas which are heavily populated or where immediate interventions are required and supports the need for a decision support framework considering nature-based solutions in coastal planning and management (Morris et al. 2020).

4.2. Conclusions

Sea level rise and the increasing severity of storm surge are two of the most significant climate change threats to the Australian economy (Australia Climate Council, 2020). Adapting to these threats, requires both structural and policy-based strategies to be implemented, which reduce the risks of flooding and erosion while simultaneously increasing any beneficial opportunities, for coastal communities (Dedekorkut-Howes et al., 2020). Our study provides new insights into the eco-engineering, and social-economic benefits and limitations of using natural mangroves, and rock revetments for coastal protection services. We highlight the important role that temperate mangrove forests play in attenuating waves, averting damages, and providing spaces for recreational activities for coastal communities in addition to their known ecosystem services, through enhanced biodiversity, fisheries productivity, and carbon sequestration. However, we also identified that many older coastal residents do not perceive the links between climate change and the increased risk of flooding and erosion. We suggest policy makers and coastal managers will achieve the greatest benefits by focusing on identifying priority sites for mangrove conservation and restoration based on both eco-engineering and socio-economic characteristics, to promote the use of nature-based solutions for climate change adaptation. Such future climate adaption efforts can be more effectively planned and prioritised if guided by a full cost-benefit analysis of coastal protection alternatives that includes both natural and planted mangroves (Ferrario et al., 2014; Morris et al., 2018) and primary valuation of the full suite of ecosystem services provided by mangrove forests and rock revetments.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jaya Kelvin reports financial support was provided by Deakin University.

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Appendix A. Supplementary data

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