Ecological Economics 194 (2022) 107349

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Estimating the costs and benefits of protecting a coastal amenity from climate change-related hazards: Nature based solutions via oyster reef restoration versus grey infrastructure

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ARTICLE INFO

JEL classification:
Q26
Q51
Q54
Q57

Keywords:
Coastal Amenity
Native Oyster Reef Restoration
Travel Cost Model
Nature Based Solutions
Grey Infrastructure

ABSTRACT

This paper examines the recreational use values associated with a coastal walking trail under threat from increased episodes of storm surges and coastal erosion, and the cost of alternative grey and nature based infrastructure options that could protect it. These options involve restoring an oyster reef bar that would act as a natural breakwater versus an impermeable revetment. The results of an on-site survey of users of the amenity and a negative binomial travel cost model demonstrate that the coastal trail has considerable recreational use value to local communities. In terms of a cost benefit analysis it was found that both protection options resulted in a positive net benefit over a 20 year time horizon but the nature based solution had a benefit cost ratio multiple times larger than the grey infrastructure alternative. The conclusions of the analysis remain valid under sensitivity analysis. The results suggest a compelling case for embedding nature based solutions in climate adaption and flood management planning for low lying coastal areas where recreational resources are under threat as it can be not only more cost effective but may also offer other ecosystem benefits to coastal communities.

1. Introduction

It is widely acknowledged that climate change-related events such as extreme heatwaves, droughts, wildfires and flooding are having an increasingly negative impact worldwide (Dumenu and Obeng, 2016; Reckien et al., 2017). Consequently, there is a strong motivation to develop means of reducing the risks associated with climate change events on infrastructures, communities and society as a whole. The costs associated with storm surges and rising sea levels in low lying coastal areas have also been increasing in recent years and are likely to rise even further in the future due to a projected increase in the severity and frequency of extreme weather events (Tol, 2018). In the absence of adaptation, the IPCC (2019) forecasts that more intense and frequent 'extreme sea level' events, together with trends in coastal development will lead to an expected increase in annual flood damages globally by 2–3 orders of magnitude by 2100. Therefore, in line with the implementation of the UN Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015) and the EU 2021 Adaptation Strategy (EC, 2021), policy makers will need to pay much closer attention to the role of coastal flooding and damage preventative actions.

Risk reducing options for coastal communities may include hard engineering solutions (referred to as grey infrastructure), Nature Based Solutions (NBS[1]) (Ghofrani et al., 2017; Evans et al., 2019; Zandersen et al., 2021) or hybrid solutions involving an element of both (Hill, 2015; Cohen-Shacham et al., 2016). It has also been suggested that the managed retreat of homes and infrastructure under threat through relocation may be the most appropriate policy response for low-lying coastal communities which cannot afford to invest in long-term protection strategies (Alexander et al., 2012). One form of NBS - active ecosystem restoration - is seen as an increasingly important intervention to counteract the degradation of marine and coastal ecosystems and to assist in climate change adaptation (Jacob et al., 2018; Chen et al., 2020; Bayraktarov et al., 2020).

In this paper, the estimated use values associated with a coastal

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[1] The International Union for the Conservation of Nature (IUCN) defines NBS as "actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016).

https://doi.org/10.1016/j.ecolecon.2022.107349
Received 31 March 2021; Received in revised form 4 January 2022; Accepted 7 January 2022
Available online 18 January 2022

walking trail vulnerable to climate related events are compared to the costs of ensuring its continued existence either via hard engineering solutions or through the restoration of a protective oyster reef bar. This comparison also facilitates the demonstration of the cost effectiveness of NBS for climate adaptation compare to the grey alterative – information that is needed for climate adaptation and flood management planning. In particular, the use value associated with a coastal waking trail amenity on the west coast of Ireland that is under constant threat from storm surges is examined. The costs associated with protecting the recreational amenity from erosion and storm damages by building a hard barrier in the form of a revetment/seawall along the coastal trail versus the costs of the NBS of a restored oyster reef running adjacent to the walking trail are examined.

As discussed by Collier and Bourke (2020) NBS to date is a relatively unfamiliar term in both terrestrial and marine Irish planning and management policy. However the concept of NBS is now central in the European Green Deal which calls for systemic solutions for restoring biodiversity and ecosystem services, and for delivering tangible benefits for biodiversity and climate change mitigation and adaptation (EC, 2019). The concept also has a prominent position in the EU Adaptation Strategy as well as within the EU Biodiversity Strategy via its EU Nature Restoration Plan. These policy drivers should support the increased uptake of restorative NBS and all member states are likely to incorporate these options much more in marine policy formation in the coming decades.

While it has been noted that evidence to date on the costs and benefits of coastal nature based and grey solutions in climate change adaptation is limited (Kok et al., 2021) a small number of studies do exist that either compare the effectiveness of the protection alternatives or examine the costs of the alternative approaches or examine the benefits of NBS. Morris et al. (2018) reviewed evidence for the effectiveness of NBS for coastal protection (saltmarshes, sea grass beds, mangroves, etc.) versus the alternative grey solutions of breakwaters and seawalls. The evidence from this study concluded that restored coral reefs, mangroves and sand dunes can be as effective in protecting the shoreline as artificially engineered protective structures. Elsewhere, in a comparison of the costs of nature-based coastal defence projects and hard engineered structures, Narayan et al. (2016) show that coastal habitats such as saltmarshes and mangroves can be a more cost effective solution than a submerged breakwater for reducing wave heights and providing shoreline protection.

More recently Deely and Hynes, 2020 estimated the willingness to pay of residents of the Carlingford Lough Catchment in Northern Ireland's for a NBS project as opposed to a grey infrastructure project in which both projects provide the same level of flood protection. The study found that the average respondent was less likely to pick the status quo option if presented with a NBS to flooding. However the authors point out that if an individual lived in a recognised flood prone area within the catchment there was no statistical difference in the preference for a NBS or grey alternative. Despite these aforementioned studies, research where the monetary costs and benefits of NBS versus grey alternatives are compared is still limited. This study attempts to provide additional information to fill that gap by addressing the research question: 'What are the costs and benefits of NBS versus grey engineering coastal protection options in Galway Bay, Ireland?"

In what follows we first introduce the study site and briefly review the history of the native oyster, *Ostrea edulis,* at the location. In Section 3, we then present the travel cost valuation method used to estimate the recreational use benefits and the approach taken to assess the costs of the alternative approaches to protecting the coastal walking trail. Section 4 presents the travel cost model results, welfare estimates, cost of protection estimates as well as presenting the results from a cost benefit analysis that compares the net present values of the nature based and grey infrastructure options. Section 5 presents a discussion of results along with a sensitivity analysis of the CBA findings and offers some conclusions.

2. The Study Site and Native Oysters

This study was carried out at a coastal walking trail, on Galway Bay on the west coast of Ireland. It is located in the outskirts of Galway City, approximately 3 km from Oranmore village. The trail extends from a single lane road that runs adjacent to the Galway Bay Sailing Club, the Galway Bay Golf Resort and to the Renville recreational forest park.[2] The mainly gravel walking trail is at sea level, along the edge of a shingle/rocky seashore. While a loop walk can be completed over a 7.2 km distance that takes in the park, the gravel trail and the tarmacked road leading up to it, the majority of users do a much shorter 4 km return trip along the gravel trail and short section road starting out from the sailing club or forest park carpark. The gravel walking trail beyond the tarmacked road is 1.07 km from its start to the end of the headland (Renville Point). The gravel trail (in red) and other locations mentioned above are shown in Fig. 1.

While Galway Bay is relatively well protected from large Atlantic swells due to the situation of the three Aran Islands at the mouth of the bay, the low lying shorelines in the inner bay are still impacted by storm surges. Renville Point, which marks the turning point of the walk, has being seriously eroded in recent years and storms in the winter months cause damage to the trail on an almost annual basis. The tidal floods and damage of the trail diminishes the quality for the recreational experience for users, especially those who are less mobile. While in recent years rock armour has been placed along some of the short tarmacked section of the road leading from the sailing club to the gravel walking trail, no major works have taken place on the gravel trail section except to fill in the gaps left after storm damage. Although beyond the scope of this analysis the continued erosion of the trail will also increase the risks of damage to the adjacent golf club and farmland.

Analysis of the flooding and erosion potential of Ireland coastline has been carried out by the Irish Office of Public Works in recent years (OPW, 2019). Maps were generated in order to assess the different scales on flood extent, flood depth and coastal erosion for the coasts of Ireland. The results suggest that the coastline in Renville Bay, from Renville Point to beyond the start of the walking trail, is highly vulnerable to coastal flooding (defined as a greater than 1 in 200 chance of coastal flooding in any given year) and without any remedial action is likely to see significant levels of erosion by 2050. Because of the golf course that lies behind the wall inshore of the path, it is not possible in the short to medium term to move the trail back from its current location so inwards adaptation is unlikely. As seen in fig. S1 in the supplementary material the local council regularly put up signs at the start of the gravel trail warning walkers of storm damage.

Renville Bay was at the centre of a region where the native oyster was abundant since prehistoric times (Wilkins, 1989; Wilkins, 2001). Native oyster shell middens in inner Galway Bay also provide evidence of the intensive use of oysters over many centuries in the area (Murray, 2007). However, similar to native oyster stocks worldwide these once highly productive reefs have been overharvested and the remaining stock in Renville Bay are close to functional extinction (Beck et al., 2011). Similar to other initiatives worldwide, work on restoring the native oyster in Galway Bay has started and is being led by the Marine Institute and the community based organisation *Cuan Beo* within the Native Oyster Network.[3] In late 2020 the first effort to rebuild an oyster

[2] Previous research that carried out a travel cost analysis of the demand for recreational pursuits in the adjacent forest park noted that, similar to the coastal trail, the forest park was not a tourist destination in its own right but was used heavily by the local urban communities as a recreational amenity (Hynes and Cahill, 2007).

[3] The Native Oyster Network is a community of academics, conservationists, oystermen and NGO's who are working to restore self-sustaining populations of native oysters across the UK and Ireland. See https://nativeoysternetwork.org/network/

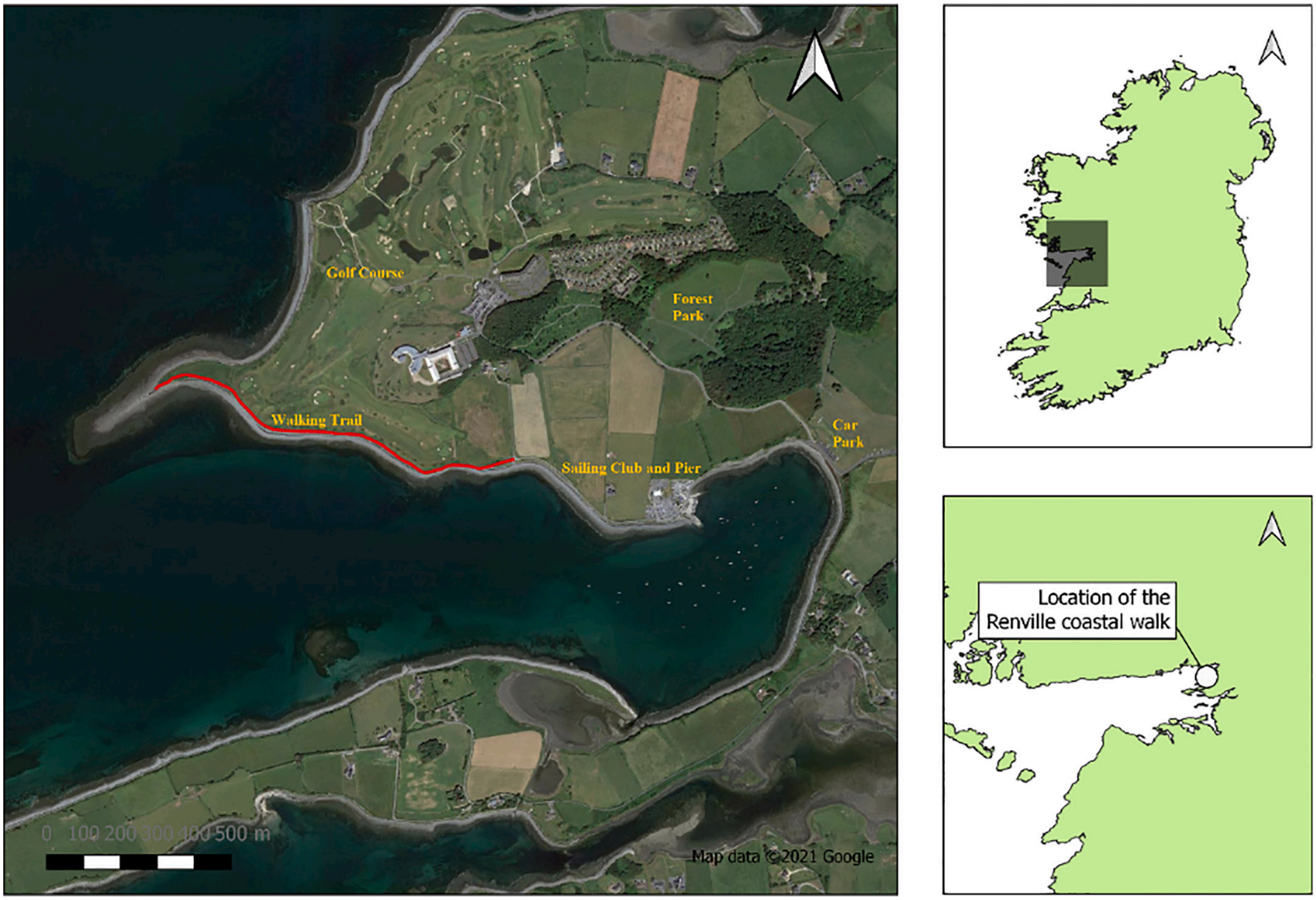

Fig. 1. Renville coastal walk and surrounds.
Gravel trail marked in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reef in the bay was undertaken by this group. They distributed 200 t of empty pacific oyster (*Magallana gigas*) shell covering an area of 50 m radius and 1 m height on to the seabed to the south of Renville Bay. The project team are currently monitoring the settlement of the substrate and plan to seed it with native oyster stock in 2021.

2.1. The Coastal Defence Options Considered for the Site

Following discussions with marine scientists involved with oyster reef restoration in Galway Bay and local civil engineers two options are considered that offer protection for the coastal walking trail in Renville from storm damage – a shoreline coastal defence barrier in the form of a revetment or sea wall (both of which were deemed suitable for the site) and a restored oyster reef bar where a raised bed of oysters is once more put in place along the length of the shoreline adjacent to the gravel path. As described by Hudson et al. (2015) seawalls are vertical, sloped or stepped walls usually constructed of concrete or masonry directly on the landforms of the coast. Their primary purpose is to reduce the impacts of tides and waves. Revetments on the other hand are an armouring layer applied to a sloping surface of an embankment or shoreline. These can be permeable or impermeable. The function of permeable revetments is to reduce the erosive power of the waves by means of wave energy dissipation in the interstices of the revetment and are usually built with rock or concrete armour units. Impermeable revetments are continuous sloping defence structures of concrete or stone blockwork, and are used to provide a fixed line of defence particularly against storm waves. While shown to be effective in protecting shoreline property, revetments in effect cover the natural ecosystem of the shore and are less adaptable to future needs given that they often require complete replacement if it becomes necessary to enlarge their height or extent (Hill, 2015).

As a natural coastal defence alternative oyster reefs can function as natural breakwaters for vulnerable coastlines as they are structures that interact with tidal and wave energy to reduce shoreline erosion. This coastal protection service is similar to that supplied by coral reefs, saltwater marshes and kelp forests (Reguero et al., 2018; Hynes et al., 2021). A number of studies have demonstrated that oyster reef restoration can provide significant shoreline protection (Meyer et al., 1997; Piazza et al., 2005; Scyphers et al., 2011). As noted by Grabowski et al. (2012) oyster reefs also have the added advantage that they automatically adjust to sea level rise as they can grow vertically faster than sea levels are expected to rise. The authors argue that this makes the use of oyster reefs as a nature based solution for dealing with coastal erosion and storm surges a more resilient option than hard engineered solutions. Natural oyster reefs also provide additional ecosystem services in the form of denitrification and nutrient sequestration as well as food and refuge for other marine species (DePiper et al., 2017). Given their cultural significance to many local communities there may also be significant existence/bequest non-use values associated with them.

3. Research Design and Model Estimation Methods

3.1. Estimating the Recreational Use Value of the Coastal Walking Trail

In order to obtain information relating to the demand for recreational walking along the Renville coastal path, an on-site survey of users was conducted in June and July 2018. The sample comprised of 207 individuals aged 17 plus. In carrying out the survey, walkers were approached on the road between the parking lot and the start of the gravel coastal path. The participants were not necessarily taking a walk on the coastal trail that particular day. In some cases they might have been entering the forest park close by instead. In all cases, however the respondents indicated that they had used the trail at least once in the previous 12 months. In total, 207 surveys were completed. The survey instrument was modelled on a similar travel cost study by Hynes and Greene (2016) and a focus group discussion involving 8 users of the site and pilot testing of the questionnaire were carried out to ensure that the questions asked were fully understandable by participants.[4]

Respondents to the survey were first asked about the purpose of their trip and their visitation rate in the previous 12 months. Information was also collected on the time and distance travelled (one-way) from home to the site in addition to the mode of transportation used (car, bike, walk, other). To verify and compare travel data, individuals were then asked to indicate an approximate home location on a digital map, which automatically geocoded the point of residence. Similar to modelling the demand for a good in an established market the price of any substitute good is an important determinant to consider in recreational demand modelling (Pearce et al., 2006). Recreationalists were also therefore asked to indicate whether the Renville coastal walk was their preferred walking site, and to indicate on the digital map their next most preferred site for undertaking their recreational pursuits. This facilitated the calculation of travel cost to the next most preferred alternative site. Finally, socio-demographic information relating to age, gender, marital status, highest education level achieved, employment status, sports, recreation and environmental organisation membership, and income was also gathered from the survey.

Travel cost is the key component in a TCM and a travel cost variable has to be constructed based on information collected in the survey. In calculating the round trip travel cost to the coastal walking trail the Automobile Association (AA) of Ireland's calculations for the marginal costs of motoring for a car of average size was used (€0.21 per km). For those who indicated they cycled or walked to the site, nominal operating cost estimates of €0.047 and €0.041 per km from Gössling et al. (2019) were used respectively. Any monetary valuation of the opportunity cost of the leisure time spent on-site or travel time to the site in the travel cost calculation is omitted. It is not believed that this will lead to any bias in the resulting estimates as the users of the site are mainly from local communities and are frequenting the site in what is their free time from work. The high observed frequency of visitation, the low average distance travelled from home to site and the shortness of the walk itself also point to that conclusion and to the fact that disutility from time spent travelling to the site should be negligible and may, as suggested by Tardieu and Tuffery (2019) and Börger et al. (2021), in these cases, be considered as part of the recreational experience.[5]

In order to model the demand for walking activity on the coastal trail it was also necessary to account for the unique data and sampling issues connected with an on-site survey approach. Firstly, the number of walking trips taken is a non-negative integer (Creel and Loomis, 1990) and the distribution of trips tends to be positively skewed towards zero. Over-dispersion is also often a feature of this type of data where the variance in trips taken is larger than the mean. In such cases the negative binomial count data models is employed (Englin and Shonkwiler, 1995; Haab and McConnell, 2002). One additional important sampling issue associated with on-site sampled data needs to be considered in this estimation. There is truncation of the data at zero trip level as walkers who make zero trips in the time period are not observed and their use value of the walking trail resource is not accounted for in the results.[6]

Accounting for these data issues and following Martınez-Espineira and Amoako-Tuffour (2007) and Hynes et al. (2015) the truncated negative binomial model is adopted in order to estimate a function for trip demand at the coastal walking trail. Assume T is the number of walking trips made during period j. The truncated negative binomial model is defined with a probability density function (PDF) given by:

$$Pr(T=t|T>0)=F_{TNB}(t)=\left[\frac{\Gamma(t+\alpha^{-1})}{\Gamma(t+1)\Gamma(\alpha^{-1})}\right](\alpha\lambda)^{t}(1+\alpha\lambda)^{-(t+1/\alpha)}[1-F_{NB}(0)]^{-1}$$
$$t=1,2,\ldots \qquad [1]$$

where λ, the expected number of trips, is modelled as a function of the explanatory variables thought to influence T, which can include travel cost to the site, travel cost to substitute site and relevant socio-demographic characteristics of the respondents. That is:

$$\lambda = exp(\beta X) \qquad [2]$$

where β is a vector of unknown regression coefficients that can be estimated by standard maximum likelihood methods (Greene, 2007), and X is the vector of variables thought to influence trip demand. Also Γ denotes the gamma function, and α is the over dispersion parameter. The larger is α, the greater the amount of overdispersion in the data. The conditional mean is given by $E(T|X,T>0)=\lambda[1-F_{NB}(0)]^{-1}$. The truncated negative binomial model provides unbiased and consistent estimates in the presence of overdisperson. Estimating a travel cost model for the walkers using the Renville coastal path, and correcting for zero-truncation, allows us to recover the underlying latent demand function for walking trips for the population using the site. In the final model specification, the number of trips taken to the coastal trail is estimated as a function of the travel cost per trip, the number of obligation free days per year, the travel cost per trip to next preferred (substitute) site, whether or not the walk was the main purpose of the visit on the day, whether or not the walk was the most preferred recreational site of the respondent and a number of socio-demographic characteristics.

Following Englin and Shonkwiler (1995), and using the results of the travel cost model the consumer surplus (CS) per person per trip to the coastal walking trail is estimated as:

$$CS_{perTrip} = \frac{1}{-\widehat{\beta}_{TC}} \qquad [3]$$

The consumer surplus figure can be thought of as the access value to the site. The aggregate access value is then calculated by multiplying this estimate by the total number of trips in the previous 12 months, such that $CS_{Total} = [CS_{per\ Trip}.\ Total\ trips]$ where CS_{Total} is the aggregate value of the total number of trips taken over the period. With very little indication of the number of persons using the site in aggregate a trail counter was mounted along the coastal trail to get an accurate count of the users over a 12 month period (CS_{Total}).

[4] The on-site survey instrument is provided as Supplementary Material to the paper.

[5] The incorporation of the value of time in the calculation of the travel cost variable in TCM studies has been a source of debate since the earliest applications of the model. While an in-depth review of this issue is beyond the scope of this paper the interested reader is directed to the following sources for an exploration of the developments in this regard: Clawson and Knetsch, (1966), Garrod and Willis (1999), Hynes et al. (2009); Fezzi et al. (2014).

[6] Endogenous stratification is another on-site sampling issue that can arise because the most frequent users of the recreational site tend to be over-represented by on-site sampling (Shaw, 1988). However, it is not deemed to be an issue in this case as participants in the survey were not necessarily using the coastal walking trail on the day of interview even though all indicated having used it at least once in the past 12 months.

3.2. Estimating the Costs of Protecting the Coastal Walking Trail Using Grey Solutions

As previously mentioned, two options are considered when estimating the costs associated with protecting the coastal walking trail in Renville from storm damage – a man-made coastal defensive revetment/seawall and natural protection provided by a restored oyster reef bar. In the first instance the costs associated with erecting and maintaining a permanent impermeable revetment or seawall are considered. A comprehensive study of structural flood defence options by Hudson et al. (2015) provides indicative costs for a range of coastal erosion and flood management activities including sea walls and revetments designed to limit tidal overtopping.[7] The reported capital cost estimates are based on previous work by the Scottish Natural Heritage (2000) and the UK Environment Agency (2007). Annual maintenance costs for the revetment or seawall option used in this study are based on estimates from Norton et al. (2018).

3.3. Estimating the Costs of Protecting the Coastal Walking Trail by Restoring the Oyster Reef Bar

The costs associated with putting in place an oyster reef bar consist of purchasing reef material, placing the material and the costs of seeds. It is assumed that the reef will be a protected site and no fishing for oysters occur. The dimensions of the reef bar are assumed to be 1070 m by 6 m by 1 m. Furthermore it is assumed a pacific oyster shell substrate is used, supported by mesh. A seeding rate of 100,000 half-grown native oysters per hectare was also assumed. Cost estimates of reef material (substrate) purchase and placement are based on Fitzsimons et al. (2019)'s overview of a number of international oyster reef restoration initiatives and their associated construction/restoration costs.

Seed costs are based on estimated from Laing et al. (2006). In particular the cost of *O. edulis* adult seed was based on those reported for the Essex reef restoration project (Essex Native Oyster Initiative[8]). The assumptions made when transferring from the international restoration initiatives to Ireland for the substrate and seed cost estimates are discussed further in the results section and presented in Table 6. All figures were adjusted from original years to €2018 values using the relevant industrial input price index (or agricultural input price in the case of seed costs), exchange rate and purchasing power parity.

3.4. The Cost–Benefit Analysis

After calculating the annual recreational benefit value associated with the coastal walking trail and the costs of the alternative approaches to its protection from storm surges, a cost–benefit analysis (CBA) over a 20 year time horizon is carried out. CBA is an economic method for comparing the desirable and undesirable impacts of proposed environmental and natural resource policies (Arrow et al., 1996), although it is widely used in a number of different contexts. It is the most extensively developed method of policy analysis grounded in welfare economics (Pearce et al., 2006). As summarized by Haab and McConnell (2002) in CBA the "idea of a potential Pareto improvement provides the rationale for public intervention to increase the efficiency of resource allocation. If the sum of benefits from a public action, to whomever they may occur, exceeds the costs of the action, it is deemed worthwhile by this criterion".

As the benefits and costs take place over multiple years, a standard discounting procedure is employed to calculate the net present value (NPV) of the benefit and costs for each scenario. Based on a Social Rate of Time Preference methodology, the standard test discount rate (r) for application in economic appraisal of current and capital expenditure proposals carried out in accordance with the requirements of the Irish governments Public Spending Code is used in the analysis (Irish Department of Public Expenditure and Reform, 2013). This is set at 5%.

$$\text{The } NPV = \sum_{t=0}^{t=T} \frac{B_t - C_t}{(1+r)^t} \qquad [4]$$

where B is the annual benefit value, C is the annual cost value, r is the discount rate and t is the year ($T = 20$).[9] The total discounted use benefits are divided by the discounted costs of the alternatives to identify which option has the highest benefit cost ratio. Finally, a sensitivity analysis is carried out to evaluate how robust the findings of the CBA are under a number of alternative assumptions. These include employing a higher discount rate, applying lower estimates of the benefits and capital costs used for the hard engineered solution, the addition of maintenance costs or the costs of some rock armour in a hybrid solution as part of the oyster reef restoration alternative and the situation where not all the recreational use value is lost following damage.

4. Results

4.1. Survey Summary Statistics

Table 1 presents summary statistics for the sample of 207 visitors to the site. The average visitor takes 65 trips in the year at an average travel cost per trip of €5.68. The high average frequency of annual trips and the low average travel cost confirm the fact that this is a coastal amenity used regularly by the local population. In fact only 20 individuals in the sample had travelled further than 20 km from home to the site on the day of being interviewed. The majority of the sample (191) drove to the location to undertake the walk. Of the remainder 11 persons walked and just 5 indicated they cycled. Forty two percent of the sample were male while 49% indicated that they were married. Forty three percent of respondents indicated that they were members of a sport, recreation or environmental organisation. Only 14% of the sample were between the ages of 17 and 34 indicating that an older profile of walkers are on this coastal trail. Average household income was approximately €49,000. Interestingly, 86% of the sample were visiting the site on the day of the interview with the specific purpose of using the walking trail and 79% indicated that it was their preferred walking location (again suggesting a high percentage of local users). Fig. S2 in the supplementary material shows the distribution of trips amongst the sample over the previous 12 month period.

4.2. The Travel Cost Modelling Results

Table 2 shows the results of the travel cost model. While the basic negative binomial model is preferred to the basic Poisson model they are both rejected in favour of the negative binomial models that adjusts for the on-site sampling issue of truncation. In the truncated negative binomial model, α, the overdispersion parameter is positive and significant, indicating that the data is overdispersed. The estimated coefficient

[7] Other options considered in the report included breakwaters and groynes (cross-shore structures) designed to reduce longshore sediment transport and reduce wave heights. Based on discussions with local engineers these were not deemed as suitable for the site under consideration here.

[8] The Essex Native Oyster Restoration Initiative is a collaboration between the oystermen, scientists, conservationists and the UK government to restore native oysters in Essex, UK. The restoration efforts under the initiative are taking place in the 284km^2 marine protected area of the Blackwater, Crouch, Roach and Colne Estuaries' MCZ (Allison et al., 2020).

[9] While repair works could be done maintaining the path each year it is assumed that eventually the point is reached where total loss occurs and that represents $t = 0$ in this situation. Based on discussions with local civil engineers a 20 year time horizon was considered appropriate for the timeframe of the analysis.

Table 1
Sample summary statistics.

Variable	Description	Mean/ Proportion	Standard deviation
Travel cost per trip	€ per trip from home to site (return)	5.68	11.61
Trips per year	Number of trips to undertake walking at coastal trail in previous 12 months	64.77	67.46
Obligation free days per year	Number of days per year respondent is free from other obligations so that they can take the time to undertake this kind of recreational activity	142.12	95.58
Gross income	Household's approximate gross income (€'000)	49.17	32.50
Most preferred walking site	Respondents favourite coastal walking trail (0/1)	0.79	0.41
Female	Female (0/1)	0.58	0.49
Married	Respondent is married (0/1)	0.49	0.50
Third level education	Respondent has a third level qualification (0/1)	0.81	0.39
Member of organisation	Respondent is a member of a sport, recreation or environmental organisation(0/1)	0.43	0.50
Travel cost per trip to substitute site	€ per trip from home to most preferred alternative site to undertake today's activities (return trip)	9.47	13.09
Aged 17–24	Respondent is aged 17–24 (0/1)	0.07	0.25
Aged 25–34	Respondent is aged 25–34 (0/1)	0.07	0.25
Aged 35–44	Respondent is aged 35–44 (0/1)	0.20	0.40
Aged 45–59	Respondent is aged 45–59 (0/1)	0.26	0.44
Aged 60+	Respondent is aged 60+ (0/1)	0.25	0.43
Main purpose of trip	Respondent came to the area on day of interview with the specific purpose of using this walking trail (0/1)	0.86	0.35

Table 2
Parameter estimates for the truncated negative binomial count model.

Parameter	Coefficient (Standard error)
Travel cost per trip	−0.089*** (0.019)
Obligation free days per year	0.002** (0.001)
Gross income (€'000)	−0.007** (0.003)
Most preferred walking site	0.088 (0.211)
Female	0.101 ((0.163)
Married	0.020 (0.189)
Third level education	−0.110 (0.228)
Member of sport, recreation or environmental organisation	0.048 (0.164)
Travel cost per trip to substitute site	0.017* (0.010)
Aged 25–34	0.473 (0.332)
Aged 35–44	0.580* (0.334)
Aged 45–59	0.747** (0.336)
Aged 60+	1.042*** (0.362)
Main purpose of trip	0.068 (0.244)
Constant	−12.454 (127.2)
Alpha	1.278
Log likelihood	−953
AIC statistic	10.11
Wald χ^2 Statistic (14 d.f.)	55.37

Standard errors in parenthesis. *** indicates significance at 1%, ** 5%, * 10%.

for travel cost is of the expected sign and significant at the 1% level. Travel cost to the substitute site is positive (although only significant at the 10% level) indicating that the higher the cost of visiting the next most preferred site the more trips will be made to the Renville coastal path.[10] Household income and being aged 45 or older are also significant and positive predictors of the number of trips taken. As expected the higher the number of obligation free days a person has the higher the frequency of trips they are likely to take to the coastal path.

4.3. Welfare Estimation

The expected annual trips and welfare estimates derived from the travel cost model are presented in Table 3. Consumers' surplus was estimated following Englin and Shonkwiler (1995) as outlined in Section 3. The consumers' surplus per trip is estimated to be €11.71. This estimate of per-trip consumer surplus is estimated with 95% confidence to be between €7.81 and €19.38. By summing the average consumer surplus per person with the average travel cost a measure of the average willingness to pay (WTP) per person for a trip to the Renville walking trail of €16.92 is estimated. The consumer surplus element of this sum represents the net recreational value on average per trip.

To calculate the aggregate use benefit value of the coastal walking trail for inclusion in the CBA the CS per trip is multiplied by the aggregate annual number of trips taken to the site. Haab and McConnell (2002) point out that the total benefits from a public action entail two kinds of information: the first is knowledge of the individual benefits, while the second is a means of expanding the benefits to the relevant population. In relation to the latter, they state that knowledge of the number of individuals who benefit is an essential ingredient in determining the aggregate benefits but such data requires a census of site users that is frequently unavailable. Outside a national park setting (and often not even then) it is therefore generally unusual to have an accurate estimate of the aggregate number of trips taken to a recreational site but in the case of the present study the figure for expected annual trips comes from a people counter placed on the trail for the 12 months starting in October 2018.

The analysis of the data from the people counter suggests a minimum number of annual trips of 57,123.[11] This coupled with the consumer surplus estimate from the TCM implies an annual net recreational benefit of €642,063. This represents the benefit value of the site to walkers on an annual basis and suggests that the loss of the site to local users could be substantial if the trail was to become unusable due to

Table 3
Expected trips and benefit estimates.

Expected trips and benefit	Value
Expected annual trips	57,123
Consumer surplus per trip (€)[a]	11.24 (7.81–19.38)
Willingness to pay per trip (€)[b]	16.92 (11.71–26.37)
Aggregate consumer surplus (€)	642,063 (446,130–1,107,044)

[a] 95% confidence intervals in parenthesis.
[b] Willingness to pay per trip is the addition of actual travel cost to the site and estimated consumer surplus per trip. Aggregate consumer surplus equals observed annual trips*CS per trip. Expected annual trips is from a people counter placed at the trail for 12 months.

[10] The inclusion of the travel cost to substitute sites in a single site demand function is important as not to do so will lead to omitted variable bias and also may lead, as pointed out Stoeckl and Mules (2006), to consumer surplus being estimated incorrectly.

[11] Fig. A1 in the appendix shows the monthly trip numbers on the walking trail based on the data collected from the people counter from 20th October 2018 to 19th October, 2019 while Table A1 analyses the drivers of the variation in the hourly trip rates from the people counter.

storm surges and erosion.

4.4. Estimated Costs of Alternative Coastal Protection Options

Table 4 provides the capital cost estimates in 2018 euro prices for a number of the grey infrastructure options compiled from the review of the literature. The values range from €1021–€4477 per metre for permeable rock revetments to €4624–€11,560 per metre for impermeable revetments and seawalls. This translates to a total initial capital cost for the estimated 1070 m required at Renville of between €1,092,763 for the permeable rock revetment to €12,369,618 for the impermeable seawalls. In terms of the CBA, the average of the midpoint of all options is taken and a total initial capital cost of €5,570,907 is assumed. An additional annual maintenance cost of €68,480 from year 1 onwards is assumed based on Norton et al. (2018).

Options for oyster reef material and placement costs are provided in Table 5 along with a range of estimates for seed costs. While the *O. edulis* seed costs are relatively low compared to the reef material costs they also vary depending on the source, the maturity of the oysters used at seeding and the seeding rate per hectare. Based on the estimates in Table 5 the final reef materials and seeding cost assumptions for the proposed oyster reef bar along the length of the shore adjacent to the walking trail are presented in Table 6, as is an estimate of the total cost to establish the reef in year 0. The higher cost estimate in Table 5 for seeding of €1800 per hectare is used in the analysis. Following Laing et al. (2006) it was further assumed that monitoring would be carried out by 2 scientific staff (assuming one senior and one post-doctoral level scientist) 5 days per year. Maintenance of the ground (cleaning the ground of potential predators, removal of litter, etc.) is necessary and it is assumed it would be done during the summer (when spawning occurs) using relatively cheap methods such as mops or lines over a period of 10 working days. This amounts to annual monitoring and maintenance labour costs of €12,640. An additional €2500 is assumed for monitoring and maintenance equipment costs per annum from year 1 onwards. Based on these assumptions the total cost of establishing the reef in year 0 is €259,796.

4.5. Comparing the Costs and Benefits with Sensitivity Analysis

The final step in the analysis was to compare the net benefit values of ensuring the coastal trail continues to be usable to the alternative protection option costs in a CBA framework. The results of each option are shown in the first two rows of Table 7. The present value (PV) of the benefit and costs are calculated over a 20 year time horizon assuming a 5% discount rate. Assuming the grey infrastructure solution costing €5,570,907 in year 0 with annual maintenance costs of €68,480 thereafter, the PV of the costs are €6,424,319. In comparison, the PV of the costs of oyster reef alternative is €448,474. The NPV of the use benefits from protecting the coastal trail is assumed to be the same no matter what protection option is chosen. Over the 20 year time horizon it is estimated to be €8,643,587. Under these assumptions protecting the walking trail produces a positive net present value (NPV) under both protection options. However the oyster reef nature based solution has the lowest PV cost and a benefit cost ratio of 19.27 compared to a ratio of just 1.34 when the grey infrastructure alternative is employed and is therefore the more attractive option from an economic perspective.

The robustness of the results presented in the CBA were examined by adjusting the discount rate used and by applying lower- and upper-bound estimates of the benefits and costs used. In the first sensitivity analysis scenario shown in Table 7 the lower bound estimate for the aggregate consumer surplus value shown in Table 3 was used instead of the average value to calculate the PV of benefits. This results in a BC ratio of just 0.93 in the case where the grey infrastructure option is used to protect the coastal trail whereas the BC ratio remains well above unity in the oyster reef alternative at 13.39. If in addition a higher 7% discount rate is used (consistent with Callihan et al. (2016)), then the respective BC ratios fall to 0.82 and 12.31 respectively (scenario 2 in Table 7). In fact even if the average of the lower bound total capital estimates for the grey infrastructure solution in Table 4 of €2,392,188 is used the grey infrastructure BC ratio of 1.65 is still lower than any of the alternative oyster reef scenarios (scenario 3 in Table 7).

It may be the case that some repair work to the trail will be required intermittently over the 20 year period or that a hybrid situation of some nature based and some grey infrastructure such as permeable rock armour will be employed. Indeed hybrid solutions that mix hard infrastructure with ecosystem-based infrastructure are common practice (Cohen-Shacham et al., 2016). Scenario 4 therefore includes additional costs of trail maintenance and protection of €100,000 per annum in the oyster reef CBA at the higher discount rate of 7% and the lower bound estimate of benefits. Even in this extreme scenario the BC ratio for the oyster reef option remains greater than unity at 3.50. This is still greater than the ratio of 1.34 for the grey infrastructure alternative under the original CBA values and discount rate of 5%. Finally, rather than the implicit assumption that the erosion caused by the storm damage results in a total loss of benefits for recreational users at the site, scenario 5 examines the situation where 50% of walkers may still use the trail even if severely damaged, i.e. the additional use value due to protection of the site is reduced by half. In this scenario (which also includes the 7% discount rate, the lower bound benefit estimates and the annual additional maintenance costs of scenario 4) the BC ratio for the oyster reef option still remains greater than unity at 1.75.

5. Discussion and Conclusions

This paper examined the recreational use values associated with a coastal walking trail under threat from increased episodes of storm surges and coastal erosion, and the cost of alternative grey and nature based infrastructure options that could protect it. The results of a travel cost model suggest that the coastal walking trail has considerable recreational use value to local communities in the area. The costs associated with protecting the amenity from erosion and storm damages were found to be much lower for the NBS of a restored oyster reef than the alternative impermeable hard barrier option built along the coastal path. In terms of a CBA it was found that both protection options resulted in a positive net benefit over a 20 year time horizon but the NBS had a benefit cost ratio multiple times larger than the grey infrastructure alternative. The conclusions of the analysis were found to remain valid under sensitivity analysis. There has been growing interest in the use of NBS for climate mitigation and adaptation and the results presented here add to the general evidence base of the benefits of coastal protection, as well as providing a cost comparison of a NBS versus a more conventional coastal defence approach.

There is an implicit assumption in the analysis that the erosion

Table 4
Cost estimates associated with hard coastal protection options (€ in 2018 prices).

Type	Source	Capital Costs€/m	Renville (1070 m) total capital cost (€)
Rock armour	UK Environment Agency	2121–9427	2,269,585–10,087,048
Impermeable revetments and seawalls	Scottish Natural Heritage	4624–11,560	4,947,847–12,369,618
Impermeable revetments and seawalls	UK Environment Agency	1099–8483	1,176,822–9,078,343
Permeable rock revetments	Scottish Natural Heritage	2312–6936	2,473,923–7,421,771
Permeable rock revetments	UK Environment Agency	1021–4477	1,092,763–4,791,347

Table 5
Oyster reef materials and seed costs.

Reef material (substrate) purchase and placement costs[a]						
Species	Project name and Location	Reef Size (Hectares)	Reef Height (m)	Reef Material	Reef Location	Cost (€ per hectare)
Ostrea edulis	Blackwater, Crouch, Roach and Colne Estuaries, Essex, UK	0.12	0.3	Shell (scallop and cockle)	Nearshore/ estuarine	183,942
O. edulis	Borkum Reefground, German Bight, North Sea	0.04	0.3–1	Stone, mixed shell, 3D-printed sandstone	Offshore	482,642
Crassostrea virginica	Harris Creek, Chesapeake Bay, US	Various, 0.4 to 4.8 per reef	0.3	Stone, 7 cm to 15 cm diameter, and conch, clam	Nearshore/ estuarine	198,984
C. virginica	Piankatank River, Chesapeake Bay, US	6	0.15	Stone, ave. 5 cm diameter	Nearshore/ estuarine	31,753
Seed costs						
Estimates sourced from	*Seeding source*	*Shell size*	*Cost per thousand*	*Seeding rate per hectare*		*Cost (€ per hectare)*
Laing et al. (2006)	Ponds/Hatcheries	20-40 mm	59–117	100,000		5850
Laing et al. (2006)	Bonamia free area, e.g. Denmark	Half grown native oyster	42–60	30,000[b]		1280–1800
Henderson and O'Neill (2003)	Ponds/Hatcheries	Unspecified	16.51	40,469–80,937		670–1340

[a] Based on Fitzsimons et al. (2019) overview of oyster reef restoration initiatives. All figure have been adjusted from original years to €2018 values using the relevant industrial input price index (or agricultural input price in the case of seed costs), exchange rate and purchasing power parity adjustments.
[b] Based on *O. edulis* seeding rate of 3 adults per metre as deployed in Essex reef restoration project (Essex Native Oyster Initiative).

Table 6
Renville oyster reef materials and seeding cost assumptions.

Feature	Value
Reef size (1070 m by 6 m)	0.642 ha
Reef height	1 m
Reef material	Pacific oyster shell
Seeding rate per hectare	100,000
Cost of reef material (substrate) purchase and placement with mesh[a]	€246,000
Cost of seed	€1155.6
Monitoring and maintenance labour costs per annum	€12,640
Total cost to establish in year 0[b]	€259,756

[a] This estimate is based on the average of the Harris Bay and Essex Native Oyster Initiative estimates in Table 5. However conversations the oyster restoration scientists in the bay suggested a reef height of 1 m so we doubled the costs per hectare estimates used allowing for some economies of scale in moving from the 0.3 m in the estimates from Table 5 to 1 m.
[b] Additional maintenance equipment costs of €2500 are assumed from year 1 onwards.

caused by the storm damage results in a total loss of benefits for recreational users at the site but there may also be opportunities to move coastal amenities inwards as the shoreline erodes in many areas facing increased storm events. The CBA also assumed no increase in walker numbers over the 20 year period but it can be reasonably expected that the numbers using the protected coastal trail may continue to increase in the coming years which would mean even higher aggregate use values. Another limitation of the results discussed in this paper is the fact that the benefit estimates represent just the direct user value to the walking population. The analysis does not account for the many other potential regulating ecosystem service benefits that could result from the restoration of the oyster reef. It could also be possible to maintain a sustainable annual harvest of oysters from the reef after a five year bedding in period. As discussed earlier the native oyster also has substantial cultural value to Galway city and county not captured here. Nor does the CBA take into account the possible negative impacts of the grey infrastructure alternative on marine ecosystems, which would further increase the costs associated with it in a complete social CBA.

While the objective of this study was to examine the use benefits and costs of protecting a coastal amenity, from a societal perspective, and in line with the views of Morris et al. (2018), if the information can be attained, the analyses would be improved if all ecosystem services provided and impacted were considered; not just the recreational use value and the coastal protection service. However, even without the inclusion of these additional non-use and other ecosystem service benefit values of the oyster reef option or the non-use values associated with the continued existence of the walking trail or indeed the avoided protection costs for the golf course that is on the landward side of the trail, the benefit cost ratio is greater than unity for the oyster reef protection option. It is also a much lower cost alternative (even under the strictest assumption in the sensitivity analysis) than the grey

Table 7
CBA results and sensitivity analysis.

Scenario	Protection option	Discount rate	Annual benefits	Annual cost yr 0[a]	PV benefits	PV costs	BC ratio
CBA	Oyster Reef	5	642,063	259,796	8,643,587	448,474	19.27
	Revetment	5	642,063	5,570,907	8,643,587	6,424,319	1.34
1	Oyster Reef	5	446,130	259,796	6,005,896	448,474	13.39
	Revetment	5	446,130	5,570,907	6,005,896	6,424,319	0.93
2	Oyster Reef	7	446,130	259,796	5,172,438	420,189	12.31
	Revetment	7	446,130	5,570,907	5,172,438	6,296,385	0.82
3	Revetment	7	446,130	2,392,188	5,172,438	3,117,666	1.65
4[b]	Oyster Reef	7	446,130	259,796	5,172,438	1,479,591	3.50
5[b]	Oyster Reef	7	223,065	259,796	2,586,219	1,479,591	1.75

[a] Annual capital cost for the revetment is zero after year 0. Maintenance costs of €68,480 for the revetment is assumed from year 1 onwards. Monitoring and maintenance costs remain the same for the oyster reef option in all years.
[b] Scenario 4 and 5 assumes coastal trail maintenance costs of €100,000 per annum in addition to the placement cost of the oyster reef in year 0. Scenario 5 also assumes that only half the recreational use value is lost.

infrastructure alternative.

Various restoration efforts and associated research have shown the potential for success of native oyster stock regeneration and valuable information on the factors affecting success has been gathered that can inform future restoration initiatives (Laing et al. 2006; Pogoda et al., 2019). Based on the results presented in this paper the restoration of native oyster reefs should also be considered as a possible avenue to reduce the now unavoidable costs associated with coastal protection and adaptation. Given the public funding that will be required to deal with these challenges policy makers and planners in coastal areas will be required to demonstrate cost effectiveness in the options chosen. As demonstrated here there is a compelling case for embedding NBS in climate adaption and flood management planning as the costs can be much lower than more conventional approaches as well as providing other ecosystem service benefits.

While the cost of the oyster reef bar option assessed in this study may appear low relative to the grey infrastructure alternatives it should be noted that Bayraktarov et al. (2016), in a review of 23 oyster reef restoration studies, reported a median cost of restoration of US$66,821 per hectare and average value per hectare of US$386,783 (in 2010 prices). This is comparable to the figures used here. The fact that the needed construction work is close to the shore and that there is easy access via a close by pier should also help to keep the costs lower than what might be seen in other marine ecosystem restoration projects. It also needs to be kept in mind that while NBS such as the oyster reef option presented here appear much more cost effective, such solutions often face a range of barriers that can impede their developments. These range from a lack of knowledge of local planners (Johns, 2019) to a lack of community empowerment due to perhaps a history of centralised environmental governance in an area (Finewood et al., 2019). A blue-green infrastructure barrier identification framework has been developed by Deely et al. (2020) that could aid planners to identify the issues that may be faced when developing a NBS project.

The fact that oyster reefs can also adapt to sea level rise with vertical growth rates that are faster than the expected rate of sea level rise also makes them a good NBS to consider for dealing with climate change-related natural hazards in low lying coastal areas. As pointed out by Wilkins (2017) the high density of oysters, which was a characteristic of the historical natural beds in Galway Bay, suggests that the successful active restoration of native oysters will be a long and demanding process. This may indeed be the case but just putting in place the necessary substrate for the oysters can start to offer protection to coastal communities from wave and storm surges even before any seeded oysters start delivering other ecosystem service benefits. Oyster reef restoration may however only be a coastal protection option in less exposed areas such as the inner Galway Bay site that is examined here where the shoreline is not in the direct path of Atlantic swells. While a number of studies have demonstrated that oyster reef restoration can provide shoreline protection Piazza et al. (2005) concluded, based on their field experiments, that they were effective in low-energy environments but their usefulness may be limited in high-energy environments. Also Narayan et al. (2016) note that no actual wave reduction field measurements within oyster reefs could be found in their review of the literature in relation to the effectiveness of nature based coastal defences. More research focused on the measurement of the effectiveness of oyster reefs as a coastal defence is warranted in order to build in uncertainty about the protective ability of the oyster reef option in the CBA.

Traditional grey infrastructure such as removable flood-barriers, rock armour, breakwaters, groynes permanent revetments and sea walls will continue to be an important option to deal with coastal flooding. However, policy makers should give a much higher degree of consideration to blue nature based infrastructure options such as restored oyster reefs, salt marshes and kelp forests. Such restoration options, either on their own or in combination with a reduced grey infrastructure requirement, not only can help to mitigate the impacts of climate change-related natural hazards but also deliver multiple additional ecosystem services that traditional grey infrastructure alone does not, such as water purification, increased biodiversity, carbon sequestration and increased scenic value (Opperman et al., 2010). Given the additional ecosystem services that can result and the increasing demand for coastal protection options due to climate change, nature-based solutions are attractive but lack the associated cost-benefit information to support policy makers. The contribution of this study is that it provides such evidence in terms of the cost effectiveness of a restored native oyster reef versus a more traditional grey solution for the protection of the recreational use values associated with a vulnerable low-lying coastal trail.

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.

Acknowledgement

This study has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 689518, project MERCES (Marine Ecosystem Restoration in Changing European Seas).

Appendix A. Appendix 1

Fig. A1 shows the monthly trip numbers on the walking trail based on the data collected from the people counter from 20th October 2018 to 19th September 2019. As can be seen from the graph the variation across the seasons is not as dramatic as one might expect although there is an obvious increase in activity over the peak months of June, July and August. The negative binomial model shown in Table A1 analyses the hourly trip rates from the people counter as a function of season, time of day, and hourly weather data for the location. As expected, the number of trips taken is lowest when the wind is blowing from a westerly position as this is the most exposed heading in the bay. They also decrease with increasing wind speed. Trips increase with temperature and are highest during the hours of 12 pm to 5 pm. While the sign on the daily rain variable, measured in millimetres, is negative as expected it does not have a statistically significant influence on the hourly trip rate.

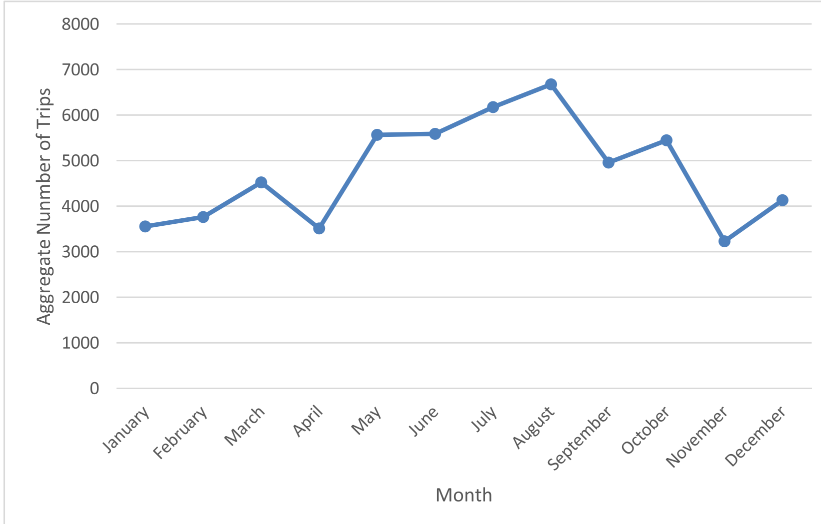

Fig. A1. Aggregate monthly trips to Renville Coastal Trail.

Table A1 and Fig. A1 are based on the data collected from an on-site people counter that recorded persons passing on an hourly basis from 20th October 2018 to 19th October 2019. Observed counts were divided by two on the assumption that the persons have to return on the same trail each trip. Local hourly weather data was obtained from https://www.met.ie/climate/available-data/historical-data

Table A1
Hourly aggregate trip count Negative Binomial model based on on-site people counter.

	Coefficient	Standard error
Daily rain (mm)	−0.005	(0.003)
Hourly temperature	0.048***	(0.004)
Wind speed	−0.021***	(0.004)
Northerly wind direction	0.219***	(0.046)
Southerly wind direction	0.235***	(0.036)
Easterly wind direction	0.147***	(0.038)
Summer month	0.392***	(0.054)
Autumn month	0.075*	(0.042)
Spring month	0.208***	(0.043)
Hours of 7 am to 8 am	3.055***	(0.078)
Hours of 9 am to 11 am	4.117***	(0.073)
Hours of 12 pm to 5 pm	4.738***	(0.070)
Hours of 6 pm to 8 pm	4.695***	(0.072)
Hours of 9 pm to 11 pm	3.362***	(0.073)
Constant	−2.832***	(0.079)
Alpha	1.059	0.024
LR chi2(14)	7109	
Pseudo R2	0.16	

Standard errors in parenthesis. *** indicates significance at 1%, ** indicates significance at 5%, * indicates significance at 10%.

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