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Dynamic Coast

Adaptation and Resilience Options for Central Tiree

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Adaptation and Resilience Options for Central Tiree

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The cover image shows: (Top) Storm waves reflecting and undermining artificial defences at Golspie, Highland. Copyright: A. MacDonald (2020). (Bottom left) coastal erosion of the beach crest adjacent to the World Heritage Site at Skara Brae, Bay of Skaill in Orkney. Copyright: A Rennie / NatureScot (2019). (Bottom right) an oblique aerial image of the Splash play park at Montrose looking north. In the 1980s the play park was set-back within the dune, due to the subsequent coastal erosion, now it is in a more exposed position relying on artificial coastal defences. Copyright: F. McCaw (2021).

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Purpose and Status of this Report

This report aims to provide Resilience and Adaptation Options to organisations with responsibility for coastal erosion and flood risk management, including Argyll & Bute Council (ABC), Scottish Environmental Protection Agency (SEPA), NatureScot and local partners.

Structure of Report

The report has been structured to be practitioner focused. It leads with an executive summary and proposed Resilience and Adaptation Options, followed by contextual information and methods within a technical summary, which includes key results. The report is designed to be viewed alongside the National Overview and online resources at www.DynamicCoast.com.

Acknowledgements

Argyll & Bute Council

Executive Summary

1. The coastal beach and sand dune ridges of Central Tiree provide natural erosion and flood protection to the low-lying interior land behind the coastal dunes.
2. Despite past landward retreat of Mean High Water Springs (MHWS) in the largest of Tiree's beaches, there has been a recent reduction in the rate of retreat between 2006 and 2018. The lower shorefaces have seen the greatest loss of sediment with the upper shorefaces less so, indeed the frontal dune ridges have increased in sediment volume over the last 12 years to offset earlier loss.
3. As a result, the vegetation edges of the dunes have accreted seaward by a small amount but remain highly dynamic with occasional storm overwash and wind-blow of beach sediment inland.
4. Nevertheless, the dune ridges behind all the Central Tiree beaches remain narrow, with potential flood corridors at low points and where inland streams transit onto the beaches from low interior ground. Any future erosion of the dune ridge poses a risk of flooding and wave overtopping that will enhance existing road infrastructure damage.
5. Modelling of coastal change driven by future sea level rise varies along and between beaches but, by 2050, up to 30m of recession is anticipated at Balephetrish Bay, up to 30m at Hynish Bay and up to 72m at Gott Bay with faster recession to 2100 and this will impact on the roads that run along or just behind the dune crest.
6. In most cases rising ground levels inland limit the risk of flooding except in the area south of Balphetrish Bay and north of the east part of Hynish Bay where the present day High Probability 1:10yr flood event (3.05mOD) produces a flood corridor connecting the low-lying ground between both bays with only a narrow dune cordon in the north and south: adding the extra sea level expected by 2050 produces a High Probability 1:10yr flood event (3.36mOD) further narrowing the dune cordon and enhancing erosion of the seaward face with the potential for breaching.
7. There is a need to develop a Dynamic Adaptive Policy Pathway for Central Tiree to enable existing assets, such as roads, to be relocated if or when their present location become exposed to erosion/flood risks. Space on land needs to be identified and safeguarded now to keep open future options, avoid future risks, and reduce the need for some "erosion resist" options.

Introduction

This report sets out Resilience and Adaptation Options for central Tiree (Argyll & Bute). Its scope covers the coastal environment of central-east Tiree, encompassing Hynish Bay in the central south (Balemartine to Baugh), Balephetrish Bay in the central north, and Gott Bay in the south-east (ferry port to southern Ruaig). The aim is to support key partners in their planning for anticipated increase in the threat of coastal erosion and flooding. The Executive Summary and Technical Annex below are not intended to be precise predictions of a certain future, rather they are scenarios based on a realistic and precautionary interpretation of available evidence. As such the details within should not be interpreted as management decisions in themselves, but supplementary evidence on which government agencies, organisations and landowners may choose to deliver against statutory requirements.

The National Coastal Context

The 2017 Dynamic Coast project published a review of historic, recent and modern maps across Scotland's entire erodible coast (DynamicCoast.com). It showed that the period since the 1970s has seen a 22% fall in the extent of Scotland's shores accreting seawards, a 39% increase in the extent of shores eroding landwards, and a doubling of the average erosion rate to 1 m/yr. This coastal response is consistent with climate change and is expected to quicken as sea levels continue to rise.

The latest research (Dynamic Coast Phase 2) incorporates new tidal surveys and shows that erosion is currently affecting more shores than was the case in 2017 and anticipates that by 2100 accretion will be rare and erosion will dominate much of the soft coast. These projections are based on the high emissions sea level rise scenario and anticipate over 1/3 of Scotland's soft coast will be eroding at greater than 1m/yr by the end of the century. The increased threat of coastal erosion also increases the risk of coastal flooding, so that planning ahead for coastal change, both inland and at the shoreline, is both pragmatic and necessary.

Local coastal context and anticipated coastal changes in Central Tiree

The sand beaches of Tiree's largest bays (Hynish, Balephetrish and Gott) have generally seen landward retreat of Mean High Water Springs (MHWS) between 1975 and 2006, but with a reduction of retreat rates between 2006 and 2018. The largest amount of recession generally occurs across the centre of each bay, with the mean 1975–2006 recession rate being 0.81 m/yr and 0.58 m/yr from 2006–2018.

Recent topographic change analysis shows sediment losses to have dominated the lower shoreface of each bay with ~261,000 m^3 of sediment being lost over the last 12 years, with smaller losses across the upper foreshore of each bay totalling close to 100,000 m^3. However, more recently over the last 12 years, the front dune ridge of each bay system has shown accretion totalling ~113,000 m^3 that appears to be a combination of gain from wind-blown sediment transport and vegetation edge progression seaward. The natural supply of shell sand to the beaches from the highly productive seas around Tiree (part of their designation as a Marine Protected Area link, as well as wave-cast kelp, is an important factor in coastal resilience, albeit poorly quantified.

Vegetation edges have fluctuated between erosion and accretion over the last century, with an overall trend of accretion in the last decade and a mean seaward movement rate of >0.1 m/yr. Occasional wind-blow or overwash of sand inland (e.g. onto roads) during storms shows the potential for dune systems to expand landward.

Whilst most of the dune cordon provides a good level of flood protection to the low-lying interior, the cordons are narrow, with potential flood corridors where inland streams transit the dunes and onto the beaches. An Fhaodhail, at Hynish, is the largest of these and exits onto Tràigh Bhàgh via an underground an un-flapped conduit and channel. Only partially protected by the dune crest and defences along the road behind the dune, any further erosion of the dune ridge poses a risk of flooding and wave overtopping that will enhance existing road infrastructure damage.

Future Resilience and Adaptation Planning

As climate change quickens erosion and increases flood risk, our attention needs to shift from short-term engineering choices at the coast edge, to dynamic adaptational land-management inland, to enhance social and economic resilience.

The emerging consensus worldwide is that adapting to climate change sooner will greatly reduce societal risks and costs in the long run. Recent research on climate change adaptation at the coast shows that landward retreat of assets is likely to be required to manage long-term risks from sea level rise, regardless of any coastal risk management options taken now. Where the need for coastal adaptation is increasingly urgent (globally and locally), more transformative solutions are needed. Whilst the generic aspects of these concepts are explored within the National Overview, the following text explores management options in Central Tiree within an international context of best practice. To aid users of this report in adopting this approach to adaptation, Dynamic Coast has identified actions that can be taken **now**, that will provide both physical and policy windows to make space for adaptation have a long-term impact (See National Overview report). For example, in Scotland the emerging Clyde Marine Planning Policy provides an example of best practice at the coast to support transformative forms of adaptation where possible. Practical implementation mechanisms are also required along with strategic plans and policies, so that adaptation measures such as realigning key infrastructure such as roads and utilities are ready to be rolled out and implemented when erosion happens. This shifts erosion management from reactive to proactive and optimises the long-term societal resilience to coastal climate change with the least social and economic costs.

Dynamic Coast provides the evidence base to assess current and future coastal erosion risks for local government to make risk-informed decisions and policy instruments. The generic coastal risk management and adaptation options can be accessed in the National Overview Report (www.DynamicCoast.com/reports), but their application in the context of central Tiree is listed in Table 1 below. These lie along a spectrum from **doing nothing or non-active intervention**; **accommodate erosion** by adapting development plans and relocating existing assets; **erosion resist** either using traditional engineering structures or nature-based solutions, such as beach feeding; and by **advancing the coast** seawards, perhaps using artificial offshore structures or large-scale beach feeding (e.g. mega nourishment schemes) (see National Overview Report for context).

Table 1 applies these to Tiree along with suggested short and long term management options that aim to increase resilience and address any anticipated risk. These management and adaptation options require a robust appraisal to allow organisations to help identify acceptable, efficient and effective measures that can be taken forward and actioned. Adaptation considerations are explored within the technical appendix below, however, it remains the responsibility of coastal landowners and Local Authorities to address issues of coastal erosion and flooding. Table 1 outlines the past erosion rates observed in Central Tiree and identifies both areas at greatest risk and management and adaptation options. All risk management and adaptation responses require robust appraisal to allow organisations to better manage coastal erosion risk and improve societal and ecosystem resilience.

Roads are the asset with the greatest risk in Central Tiree. Any further erosion of the defences or dune ridge poses a risk of flooding and wave overtopping that will enhance existing road infrastructure damage.

Coastal erosion, flooding and erosion-related flooding are considered as the key risks impacting Central Tiree now and in the future. Landowners and Local Authorities (LA) have responsibility for, and powers to address, coastal erosion and flooding. LA also have shared powers under the Flood Risk Management (Scotland) Act 2009 and the Climate Change (Scotland) Act 2010, including a statutory duty to report on climate change adaptation progress. Guidance on planning for coastal change can be found here (SNH, 2019). Consistent with a Shoreline Management Plan approach, three bays of Central Tiree are each classed as a management unit area (Figure 2, Table 1) to identify coastal erosion risk and management approaches to improve resilience of natural and societal assets in the short-term, and adaptation options to improve long-term resilience of Tiree to the same risks. Each management option in Tiree will have differing impacts on sediment dynamics, beach function and the natural capital that beach-dune systems provide. Importantly, these responses to managing coastal erosion risks involve both the management of activities on land as well as at the coastal edge. Tiree has small settlements connected by essential, and at risk, road infrastructure and utilities, as well as rural areas with scattered houses. The island has been subject to past erosion (0.81 m/yr), where recent 2006-2018 erosion has reduced (0.58 m/yr) and in some areas, there has been recent accretion, notably the dune front ridges along with modest vegetation edge accretion <0.1 m/year. This means that these natural beach-dune systems currently have reasonably good natural capital functioning and this is providing some partial risk alleviation benefits to society. However, dune cordons are narrow and there is a risk of erosion-induced flooding if these get beached or overtopped, such as via storms, which would further damage and limit functioning of key transport infrastructure across the Island.

This requires strategic development planning decisions to be taken *now*, to provide physical and policy space to accommodate future erosion by adaptation to minimise societal impact and cost.

It is important to note that many of the adaptation options presented in Table 1 and associated text require **strategic planning decisions to be taken *now*, to provide physical and policy space to accommodate future erosion by adaptation** to be possible. For example, if planning permission is granted now for assets or infrastructure on land that may be at erosion risk in the future, the opportunity for future landward adaptation to occur is constrained, becomes more expensive, or both. Land-based strategic plans that account for future risks are needed when planning today (e.g. Local Development Plans), to create and safeguard 'windows of opportunity' to accommodate erosion by adaptation with minimal societal impact and cost; concepts acknowledged within the NPF4 (Consultation documents) and National Land Use Strategy (Consultation documents).

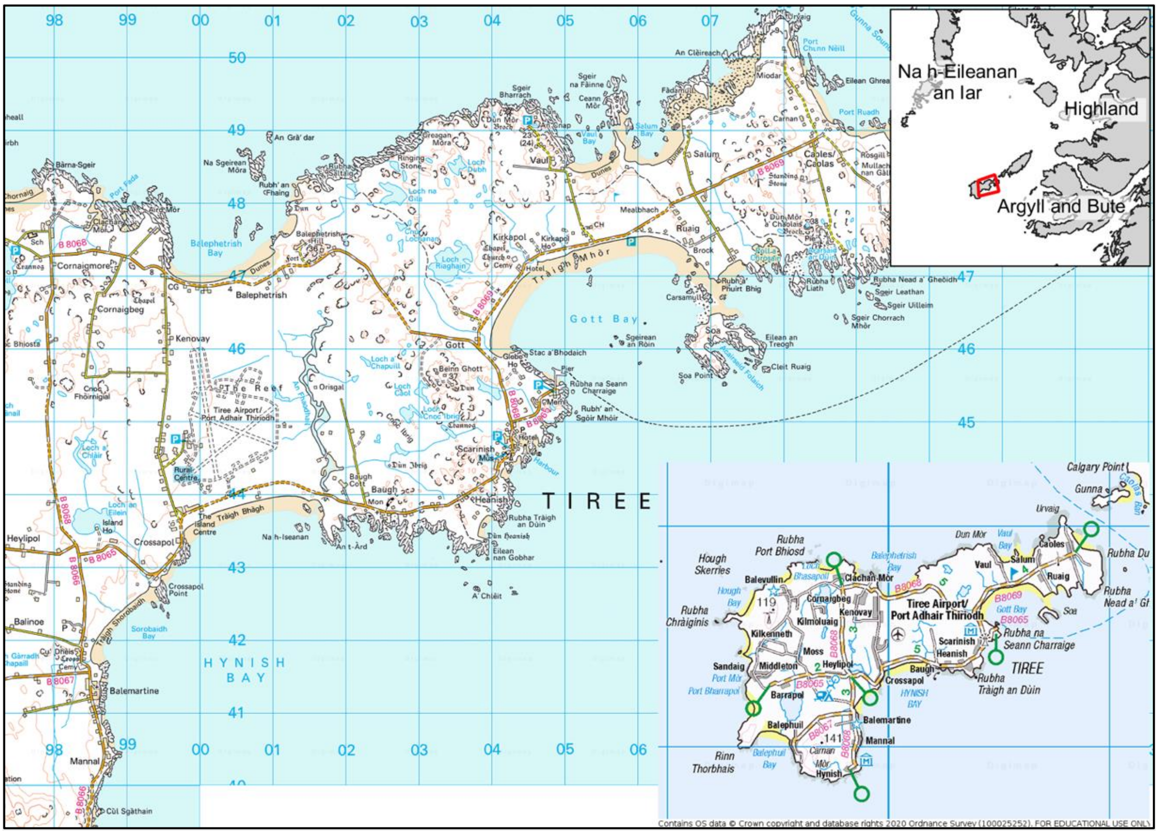

Figure 1 OS Location map of Tiree. Grid squares are Easting and Northing of size 1 km x 1 km. Crown copyright and database rights OS 2020 100017908.

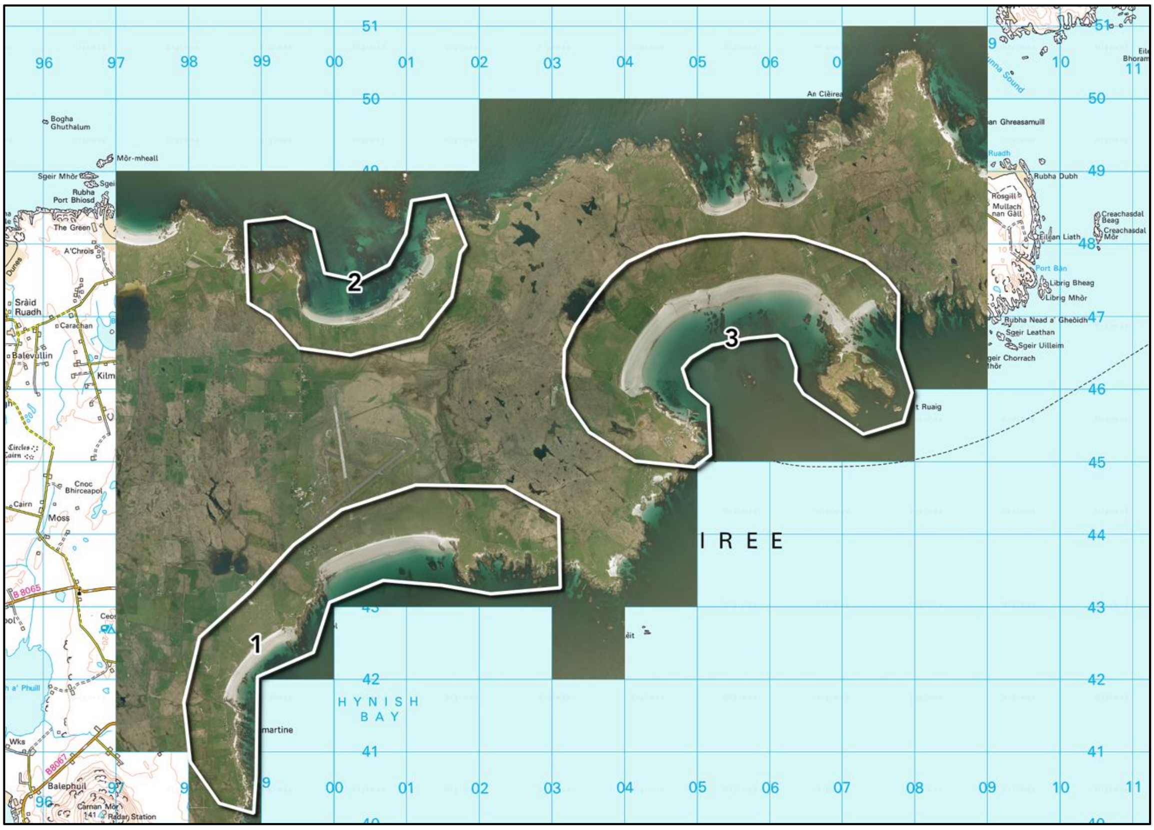

Figure 2 Management unit areas for Resilience and Adaptation Options. Labelling relates to options in Table 1.

Resilience and Adaptation Options at central Tiree

Table 1 outlines the management options along the coast which are recommended to be considered alongside dynamic adaptational land-use planning aspects inland.

Table 11 Risk management, Resilience and Adaptation Options for Tiree, grouped by management unit area, past and anticipated changes alongside 'do nothing' implications. Short and Longer-term options are outlined.

Management Unit Area	Shore Character and Assets	Coastal changes	'Do nothing' implications	Future – 'Short term' risk management options	Future – 'Long term' adaptation options to improve resilience
Area 1. Hynish Bay (Baugh to Balemartine) 	Sand bays framed by rock headland, backed by narrow dune ridge. B8065 road, Crossapol housing and farmland, Tiree Airport runways, The Island Centre, An Fhaodhail and Allt a' Gheadain drainage channels	Low Water 1898–2018: 35 to 70 m loss High Water 1898–1975: 5 to 40 m gain 1975–2018: 20 to 65 m loss Volume 2006–2018: 85,200 m³ Vegetation Edge 2009–2019: 1 to 10 m gain	Foreshore lowering & modest retreat (2100 MHWS -30 m) Loss/reworking of existing dunes where present, exposure of machair/fields where absent. Assets at risk: 3 x100 m of B8065 may be at risk. Erosion at burn may exacerbate inland flooding.	**Non-Active Intervention:** 1. **Monitor changes and allow erosion to occur (where no assets at risk):** This results in changes to natural sections of amenity beach: monitor change/no intervention. Cost: zero; Risk: moderate. **Accommodate Erosion:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated/relocated, if or when their present location become exposed to erosion/flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be now safeguarded to maintain future options. **Erosion Resist:** 1. **Install defences (0–20 yrs):** Expand direct hard defences constructed at above MHWS. Cost: high; Risk: high. 2. **Feed beach (0–10 yrs):** Short-term local feed to beach and dune profile to improve natural resilience of the beach. Cost: moderate; Risk: moderate. 3. **Reprofile beach (0–5 yrs):** Short-term local reprofiling of upper beach profile to improve natural resilience of beach at key points. Cost: low; Risk: moderate.	**In addition to continued deployment of short term options:** **Non-Active Intervention:** 1. **Monitor change/no intervention:** Squeeze of natural sections of amenity beach: monitor change/no intervention and effects of erosion and/or erosion-induced flooding on society. **Accommodate Erosion:** 1. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated/relocated, if or when their present location become exposed to erosion/flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded now to maintain future options. 2. **Reposition vulnerable assets (2050 onwards):** Some realignment of strategic assets (e.g. roads, water, power cables, septic) would avoid future risks and reduce the need for some "erosion resist" options. 3. **Reposition vulnerable assets (2070 onwards):** Non-strategic assets (farmland, car parks) could be relocated to lower or risk free sites. **Erosion Resist:** 1. **Combined enhanced defences and beach feed (2050):** Direct defences constructed and set back, with fronting beach nourished with sand and gravel to both maintain amenity and reduce wave impact on existing defence structures remain in place. 2. **Enhance defences (2050):** enhance/expand defences to resist increasing erosion and erosion-related flood risks. **Advance:** 3. **Mega-nourishment (2050)** of the entire bay. Cost: high; Risk: high.
Area 2. Balephetrish Bay 	Narrow sand bay framed by rock headland, backed by shingle and narrow dunes. B8068 road, Balephetrish and Kenovay farmland and housing, wind turbines	Low Water 1898–2018: stable High Water 1898–1975: 5 to 45 m gain 1975–2018: 5 to 35 m loss Volume 2006–2018: 89,300 m³ Vegetation Edge 2009–2019: 3 m loss to 8 m gain	Foreshore lowering & moderate retreat (2050 MHWS -30 2100 MHWS -60 m) Dune ridge expected to be lost & fields inland Assets at risk: 1 house by 2050, 2 by 2070 & 4 by 2080. 900 m of B8068 may be at risk	**Non-Active Intervention:** 1. **Monitor changes and allow erosion to occur (where no assets at risk at eastern third of bay):** This results in changes to natural sections of amenity beach: monitor change/no intervention. Cost: zero; Risk: moderate. **Accommodate Erosion:** 2. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated/relocated, if or when their present location become exposed to erosion/flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be now safeguarded to maintain future options. 3. **Managed Realignment (0–20 yrs):** Phased re-location of at risk assets to sustainable locations. Cost: moderate; Risk: moderate. **Erosion Resist:** 4. **Install defences (0–20 yrs):** Install/expand direct hard defences constructed at above MHWS. May need to be considered for road & buildings. Cost: high; Risk: high. 5. **Feed beach (0–10 yrs):** Short-term local feed to beach and dune profile to improve natural resilience of the beach. Cost: moderate; Risk: moderate. 6. **Reprofile beach (0–5 yrs (where road & buildings are in close proximity, western half of bay):** Short-term local reprofiling to upper beach profile to improve natural resilience of beach at key points. Cost: low; Risk: moderate.	**In addition to continued deployment of short term options:** **Non-Active Intervention:** 1. **Squeeze** of natural sections of amenity beach: monitor change/no intervention and effects of erosion and/or erosion-induced flooding on society. **Accommodate Erosion:** 2. Develop **Dynamic Adaptive Policy Pathway**, to enable existing assets to be adaptated/relocated, if or when their present location become exposed to erosion/flooding risks. Choice of timing is dependant on locally defined trigger points, space on land needs to be safeguarded now to maintain future options. 3. **Reposition roadways and relocate assets (2050):** Some realignment of strategic assets (e.g. roads, water, power cables, septic) would avoid future risks and reduce the need for some "erosion resist" options. 4. **Managed Realignment (2040 onwards):** Phased re-location of at risk assets to sustainable, inland locations. Cost: moderate; Risk: moderate. 5. **Erosion Resist:** 6. **Feed beach (2040):** 7. **Combined enhanced defences and beach feed (2050):** Direct defences constructed and set back, with fronting beach nourished with sand and gravel to both maintain amenity and reduce wave impact on existing defence structures remain in place. 8. **Enhance defences (2050):** expand defences to resist increasing erosion and erosion-related flood risks. **Advance:** 9. **Mega-nourishment (2050)** of the entire bay. Cost: high; Risk: high. 10. **Nearshore breakwater (2050):** to reduce storm wave impacts to beach & dune. Cost: high; Risk: moderate.
Management Unit Area	**Shore Character and Assets**	**Coastal changes**	**'Do nothing' implications**	**Future – 'Short term' risk management options**	**Future – 'Long term' adaptation options to improve resilience**

Area 3. Gott Bay (Ruaig to ferry port) 	Broad sand bay backed by low dunes and machair. B8069 road, Kirkapol an Ruaig farmland and housing, Tiree Lodge Hotel, Sruthan Chircepol and nan Clachan Dubha	<u>Low Water</u> 1898–2018: 0 to 85 m loss <u>High Water</u> 1898–1975: stable 1975–2018: 5 to 45 m loss <u>Volume</u> 2006–2018: 72,600 m^3 <u>Vegetation Edge</u> 2009–2019: stable	Moderate retreat (2050 MHWS –30 m 2100 MHWS –70 m) Dune ridge expected to be lost / reworked. Assets at risk: Over-wash already occurring on B8069, further loss expected: of 180 m on B8068 & 800 m on B8069 by 2030 1 house at risk, flood risk along streams.	**<u>Non-Active Intervention:</u>** 1. **Monitor changes and allow erosion to occur (where no assets at risk, eastern third of bay):** Monitor changes and allow erosion to occur. This results in changes to natural sections of amenity beach: monitor change/no intervention. Cost: zero; Risk: moderate. **<u>Accommodate Erosion:</u>** 1. **Managed Realignment (for 800 m section of B8069) (0–10 yrs):** Phased re-location of at-risk assets (road) to sustainable inland location. Cost: moderate; Risk: moderate. **<u>Erosion Resist:</u>** 1. **Reprofile beach (where road & buildings are in close proximity, western half of bay) (0–5 yrs):** Short-term local reprofiling to upper beach profile to improve natural resilience of beach at key points. Cost: low; Risk: moderate. 2. **Feed beach (0–10 yrs):** Short-term local feed to beach and dune profile to improve natural resilience of the beach. Cost: moderate; Risk: moderate. 3. **Install defences** (0–20 yrs): Expand direct hard defences constructed at above MHWS. May need to be considered for road & buildings. Cost: high; Risk: high.	**In addition to continued deployment of short term options:** **<u>Non-Active Intervention:</u>** 1. **Monitor change/no intervention:** Squeeze of natural sections of amenity beach: monitor change/no intervention and effects of erosion and/or erosion-induced flooding on society. **<u>Accommodate Erosion:</u>** 2. **Reposition roadways and relocate assets (2050):** Some realignment of strategic assets (e.g. roads, water, power cables, septic) would avoid future risks and reduce the need for some “erosion resist” options. 3. **Feed beach (2050):** local repair to beach and dune profile to improve natural resilience of the beach. Cost: moderate; Risk: moderate. 4. **Managed Realignment (2030 onwards):** Phased re-location of at-risk assets (road) to sustainable inland location. Cost: med; Risk: moderate {preferred option for 800 m section of B8069} **<u>Erosion Resist:</u>** 5. **Combined enhanced defences and beach feed (2050):** 6. **Enhance defences (2050):** expand defences to resist increasing erosion and erosion-related flood risks. **Advance**: 7. **Mega-nourishment (2050)** of the entire bay. Cost: high; Risk: high. 8. **Nearshore breakwater (2050):** to reduce storm wave impacts to beach & dune. Cost: high; Risk: moderate.

The greatest societal resilience and lowest costs for Central Tiree will occur when coastal risk management decisions are made alongside adapting land-based policies now to accommodate future erosion.

This section briefly summarises the key points from Table 1 above to provide a synopsis of key points by management option and area. Erosion is expected to expand and quicken over the coming decades as coastal climate change pressures increase in all three Management Unit Areas (hereafter **Areas**). If **Non-Active Intervention** (NAI) is the preferred policy option at Central Tiree, then beach and/or dune cordon erosion or lowering will continue to occur, in both the short and long-term. In Central Tiree, only **Areas 2 and 3** have options to **Advance** the current coastal position using **erosion resist** options (i.e. offshore traditional engineering structures) such as nearshore breakwaters. Use of a large-scale **nature-based erosion resist** option, such as a mega nourishment programme, may enable the current beach-dune position to be advanced seaward and/or maintained in **Areas 2 and 3**, and provide an expensive, engineered nature-based solution to erosion those bays. All other recommended **erosion resist measures** (nature-based and traditional engineering) would be applied to specific areas of the bay as detailed in Table 1. Importantly, in all areas where any NAI, advance or any type of **erosion resist** measures are implemented in the short and longer-term, it is recommended that land-based policies are adapted now to **accommodate erosion** by restricting future new development of permanent infrastructure, housing or industry in areas forecast to be eroded or affected by erosion-induced flooding by 2100. This makes space for beach-dune systems to respond naturally and dynamically to coastal climate change and avoids societal 'lock-ins' by minimising the amount of permanent development in areas at risk. It also allows land-based policies to be agreed that can 'make accommodation space' for future landward relocation of key infrastructure such as roads and utilities (e.g. water or energy supply networks). To do this now safeguards the land required to improve future resilience of key infrastructure assets that connect communities in Central Tiree and allows government and utility providers to be ready to implement adaptation plans when future erosion damages key infrastructure. In inland areas at risk of erosion by 2100, short-term economic benefits can potentially occur through innovative planning measures such as permitted temporary development, for tourism assets that are demountable and/or can be rolled inland.

The risk and management options are broadly similar across **Areas 1, 2 and 3**. In all areas, land-based adaptation mechanisms are recommended to accommodate erosion by facilitating landward retreat of natural beach-dune systems and assets on land, alongside short to longer-term erosion resist measures. The urgency for developing adaptation plans and implementation measures to accommodate erosion and realign key infrastructure (e.g. road) networks varies, with **Area 3** the most urgent (i.e. an 800m section of the B8069 by 2030), followed by **Area 2** (i.e. 900m of the B8068 by 2040) and **Area 1** (realign 11m sections of the B8065 by 2050). Fortunately, the rural nature of the island means there is space on land to accommodate realignment of key assets such as critical road infrastructure especially in **Area 2**. In **Areas 1 and 3,** the local airport lies inland of at risk areas. This will require greater multi-level and multi-sectoral discussions about how best to develop adaptation plans for critical linear infrastructure whilst maintaining the airport infrastructure. Proactive plans, effective community engagement and finance mechanisms are required to enable landward realignment of all types of assets at risk before erosion and erosion-induced flooding require costly repairs and/or isolate communities from critical supply chains (i.e. food, water, utilities). This infrastructure provides critical lifelines for the rural population of Tiree. Few houses are at risk of erosion and this results in the Tiree community emerging as only slightly vulnerable within the SVCI analysis. However, the risks to key lifeline infrastructure on the island threaten to further increase the social vulnerability of the island's population, as a whole, to erosion and erosion-related flood impacts.

Technical Summary

Methods

Identification of Flood Protection Features

High resolution Digital Elevation Models (DEMs) were automatically analysed to identify the extent of the coastal barriers protecting low-lying areas of flood risk. Regular shore-normal profiles were extracted at 10 m intervals along the DEM and analysed to identify the width of barrier and volumes of sediment above key flood elevations. These allowed potential breach points to be identified alongside SEPA's anticipated coastal flood extents. A second set of profiles were then extended along the low points of potential flood corridors to enable detailed topography to be compared with anticipated flood levels.

Anticipated Shoreline Recession due to Relative Sea Level Rise: Modified Brunn Rule

Relative sea level rise is expected to exacerbate rates of erosion of coastal barriers, with knock-on effects for any extant flood risks identified. Past rates of coastal erosion in the face of known rates of relative sea level change were used to modify and train an equilibrium model (the Bruun Rule) for shoreline change prediction (Dean and Houston, 2016). Shoreline change was then modelled to 2100 under low to high Representative Concentration Pathway (RCP) scenarios within UKCP18, encompassing predicted changes in relative sea level.

Modelling Past and Future Erosion: CoSMoS-COAST

We adapted the Coastal One-line Assimilated Simulation Tool (CoSMoS-COAST, Vitousek et al., 2017) to simulate coastal evolution under the climate change scenarios presented by UK Climate Projections 2018 (UKCP18). The model uses a process-based approach to simulate shoreline change via wave-driven alongshore and cross-shore sediment transport processes, as well as long-term shoreline migration driven by relative sea level rise (RSLR). The model is forced using local records of relative sea level change and wave hindcast data, as well as Ensemble Kalman Filtering which assimilates the modelled shoreline to historic positions of Mean High Water Springs over the 20th century. The forecast model was validated with recent shoreline position observations derived from high-resolution topographic surveys, satellite imagery and aerial photography. Shoreline change was then modelled to 2100 under low to high Representative Concentration Pathway (RCP) scenarios within UKCP18, encompassing factors such as anticipated changes in sea level rise and wave action

Vegetation Edge Analysis

The vegetation edge is a clearly identifiable feature within remotely sensed imagery, high resolution DEMs and via ground survey. Its position can be extracted manually or semi-automatically allowing time-lapse comparisons from data from different time-periods. Multiple sets of aerial imagery over the last few decades have been compared with comparable resolution ground survey to produce time-series vegetation edge retreat positions.

Updating the Extent of the Intertidal: Coast X-Ray

Dynamic Coast developed a tool (Coast X-Ray) to analyse the back catalogue of Sentinel 2 satellite imagery, using a Normalised Difference Water Index, to demarcate areas which are always water (sea), always non-water (land) and areas which are intermittently water and land (the intertidal zone). This water occurrence index is converted into a percentage figure, but the number of images used in the analysis and the median NDWI value are also available. Results show that Coast X-Ray can be used to inform potential changes to the extent and geometry of the foreshore and the low- and high-water marks.

Mapping Coastal Erosion Disadvantage

An assessment was additionally carried out to quantify the Coastal Erosion Disadvantage (ie social vulnerability of Scotland's communities to coastal erosion), using Dynamic Coast erosion data from the recent past (1970s) through to 2050. Mapping of social vulnerability in relation to coastal erosion was carried out using Scotland's Census data from 2011 and the latest data from the Scottish Index of Multiple Deprivation (2016 & 2020). Building upon previous considerations of social vulnerability related to coastal erosion and flooding, the Social Vulnerability Classification Index is a derivative of that developed by Fitton (2015). It includes existing academic and policy literature concerning coastal erosion and flooding vulnerability and identifies key indicators of social vulnerability to coastal erosion and flooding. It seeks also to extend SEPA's (2011) early approach to identifying "Potentially Vulnerable Areas" and Sayers et al (2018) flood risk vulnerability assessment, which does not consider coastal erosion.

Results

The following section provides the research results on coastal change (erosion/accretion), flood risk and coastal erosion enhanced flooding for Central Tiree. Final sections consider options, caveats and how adaptation planning might be implemented.

Coastal Change

Summary

1. The sand beach sections of Tiree's largest bays (Hynish, Balephetrish and Gott) have generally seen MHWS retreat between 1975 and 2006, but these retreat rates reduced between 2006 and 2018. The largest amount of recession is generally seen across the centre of each bay, with the mean 1975–2006 recession rate being 0.81 m/yr and 0.58 m/yr from 2006–2018.
2. Recent topographic change analysis shows sediment losses have dominated the lower shoreface of each bay with ~261,000 m^3 of sediment being lost over the last 12 years, and smaller losses across the upper foreshore of each bay. However, more recently over the last 12 years, the vegetation edges and first dune ridge of each bay system has shown steady accretion totalling ~113,000 m^3; this gain appears to be primarily from wind-blown sediment transport.
3. Vegetation edges have fluctuated between erosion and accretion over the last century, with an overall trend of accretion in the last decade and a mean seaward change rate of ~0.6 m/yr.
4. Whilst most of the dune cordon provides a good level of flood protection to the low-lying interior, it is essentially narrow with some potential flood corridors occurring where inland streams exit through the dunes and onto the beach. The largest of these, the An Fhaodhail, exits onto Tràigh Bhàgh on Hynish Bay via an underground un-flapped culvert and open channel. Only partially protected by the dune crest and defences along the road behind the dune, this poses a present risk of flooding, wave overtopping and erosion damage to the road infrastructure that will increase with future sea level rise and attendant erosion of the dune ridge.

The first phase of Dynamic Coast summarised the coastal changes to the three central bays covered in this report (see pages 26–34 of Cell 5 report) between 1893, 1975, and 2006. From 1975–2006, all three bays were subject to erosion. Gott Bay experienced up to 25 m of MHWS recession in the centre and a lesser 10 m in the eastern and western corners, while Balephetrish Bay saw 26 m of recession in the east and west corners and a lesser 9 m across the centre in the same period. The beaches at Hynish Bay, Traigh Shorobaidh and Traigh Bhagh, saw30 m and 173 m of MHWS recession respectively over the same three-decade period.

The second phase of research, outlined below, benefits from Ordnance Survey's aerial survey undertaken in September 2018, and updated by multiple vegetation edge surveys. Whilst these are discussed in turn below, various interactive tools are available within www.DynamicCoast.com for the user/reader to interrogate the results.

Existing Topography of Central Tiree

The topography of Central Tiree is strikingly low and flat and represents what is essentially a series of low-lying rocky islets connected by wide beaches of shell sand backed by either machair grassland or boggy peatland (Figure 3). Higher ground occurs at Coalas (25 mOD) in the east, Bein Ghott (37 mOD) in the centre and Ben Hynish (141 mOD) and Beinn Hoigh (119 mOD) in the west with lower ground between. Lying between Bein Ghott in the central east and the higher ground running N-S along the B8068 in the west, The Reef is a low-lying central isthmus bounded in the north by the sand and gravel beach of Balephetrish and in the south by Hynish Bay. The beach at Balephetrish reaches 120 m wide at low tide, backed by a sharp single dune ridge that reaches 5–7 mOD at either end of the bay, but only 4 mOD in the centre. The B8068 runs along the top of the beach dune ridge at 4 mOD in the west of the bay but the land of The Reef is 3 mOD in the centre with some lower sections and a 1.4 km wide area in the north at about 4 mOD. In the south at Hynish Bay, Tràigh Bhàgh beach is 250 m wide, backed by a 7 mOD high and 40m wide dunes in the centre of the bay. In the east, at the exit of the An Fhaodhail stream, the dune ridge is only 4 mOD before falling inland to less than 2 mOD and the marshy interior of The Reef. At Gott Bay in the east, the sandy beach is 280–320 m wide and backed by a flat dune cordon that reaches 30 m wide but is only 3–4 mOD for much of its length, before merging gradually inland to 4–5 mOD. Some areas of the dunes remain at 3 mOD for 100 m inland in the centre of the bay. The B8069 runs parallel and along the 3 mOD crest of the dune ridge in the west and centre where it is less than 8 m from the coastal vegetation edge.

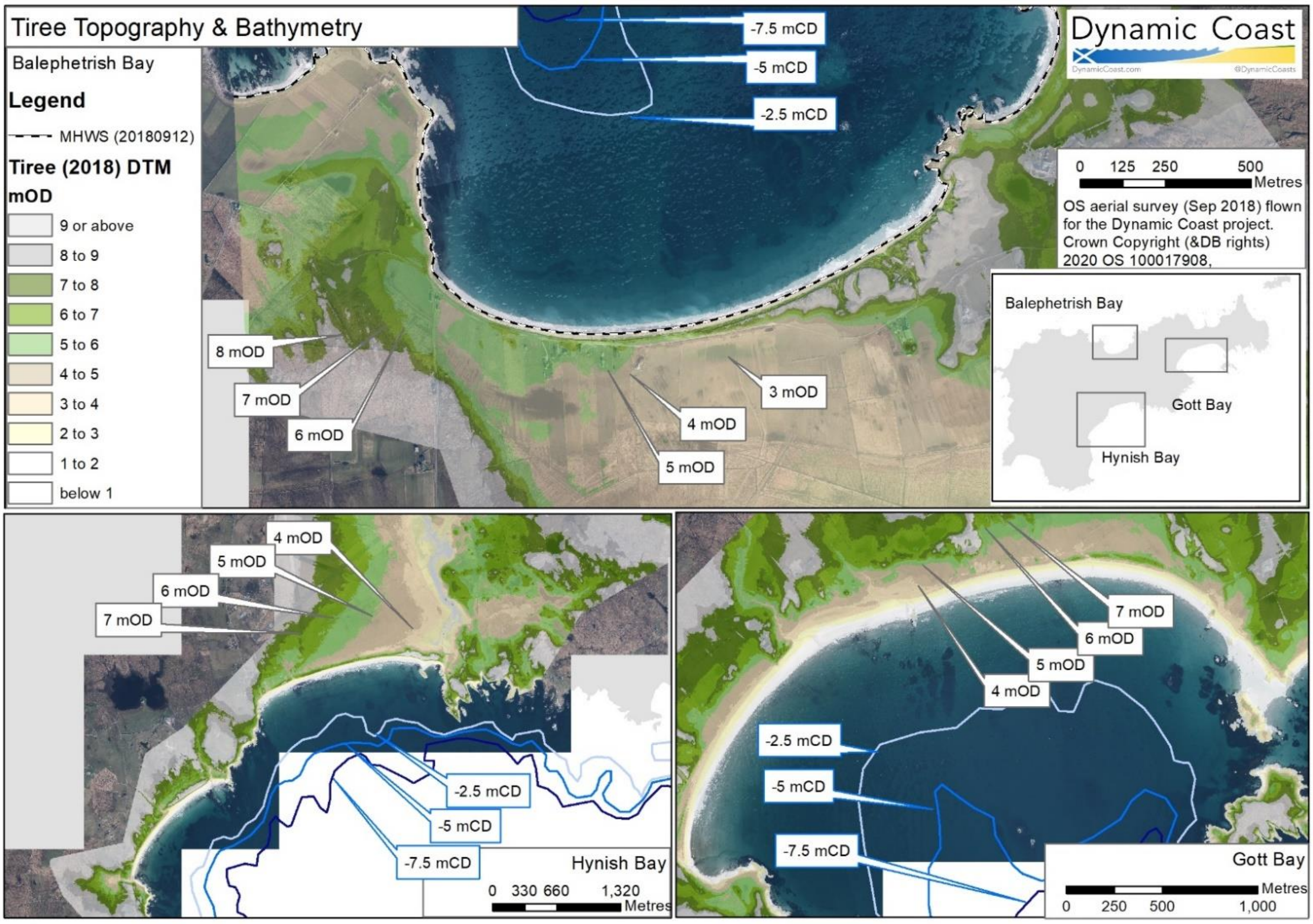

Figure 3 Topography, Bathymetry (mCD) and key flood levels (mOD) across central Tiree (from 2018 OS aerial imagery derived DSM and MarineThemes bathymetry). Note the different scale in each image.

The nearshore bathymetry for all three beaches is shallow and characterised by sandy beds and low onshore gradients. None are deeper than 7.5 m CD depth at distance offshore, and with the 2.5 m CD isobath about 1 km offshore at Gott and Balephetrish and 0.75 km at Hynish, these low gradients are associated with mainly dissipative wave conditions that serve to retain sediment locally. Contained within rocky headlands, the beaches of Central Tiree are relatively sheltered and sediment-rich and are likely to readily reconfigure the sandy bed to attenuate wave conditions more than would otherwise be expected on more exposed open coast beaches.

Natural Coastal Flood Protection Features in Central Tiree

Automated terrain analysis was carried out on Central Tiree's soft coast, to systematically identify natural flood protection features (i.e. dunes and cliffs) shown in Figure 4. These features include the extent of ridge features (identified from topographic high points), potential flood corridors (identified from topographic low points), the presence of cliff features and the extent and volume of continuously elevated ground (i.e. barriers) at location-specific flood levels. For Central Tiree, the protection function of the dune cordons can best be summarised by the dune width at 4 mOD, this being the elevation of likely future flood levels combined with wave heights and explored in the flooding section of this report. The dune cordon characteristics in Figure 4 can be compared with the elevation changes in Figure 10 to highlight sections of stabilisation and growth along the centre of Balephetrish Bay, as well as potential flood corridors if the narrow width of dune was further compromised by erosion, such as across parts of Gott Bay and Hynish Bay. The irregularity of barrier location across Gott Bay also reflects the overall low elevation of the foreshore and lack of defined ridges protecting the backdune.

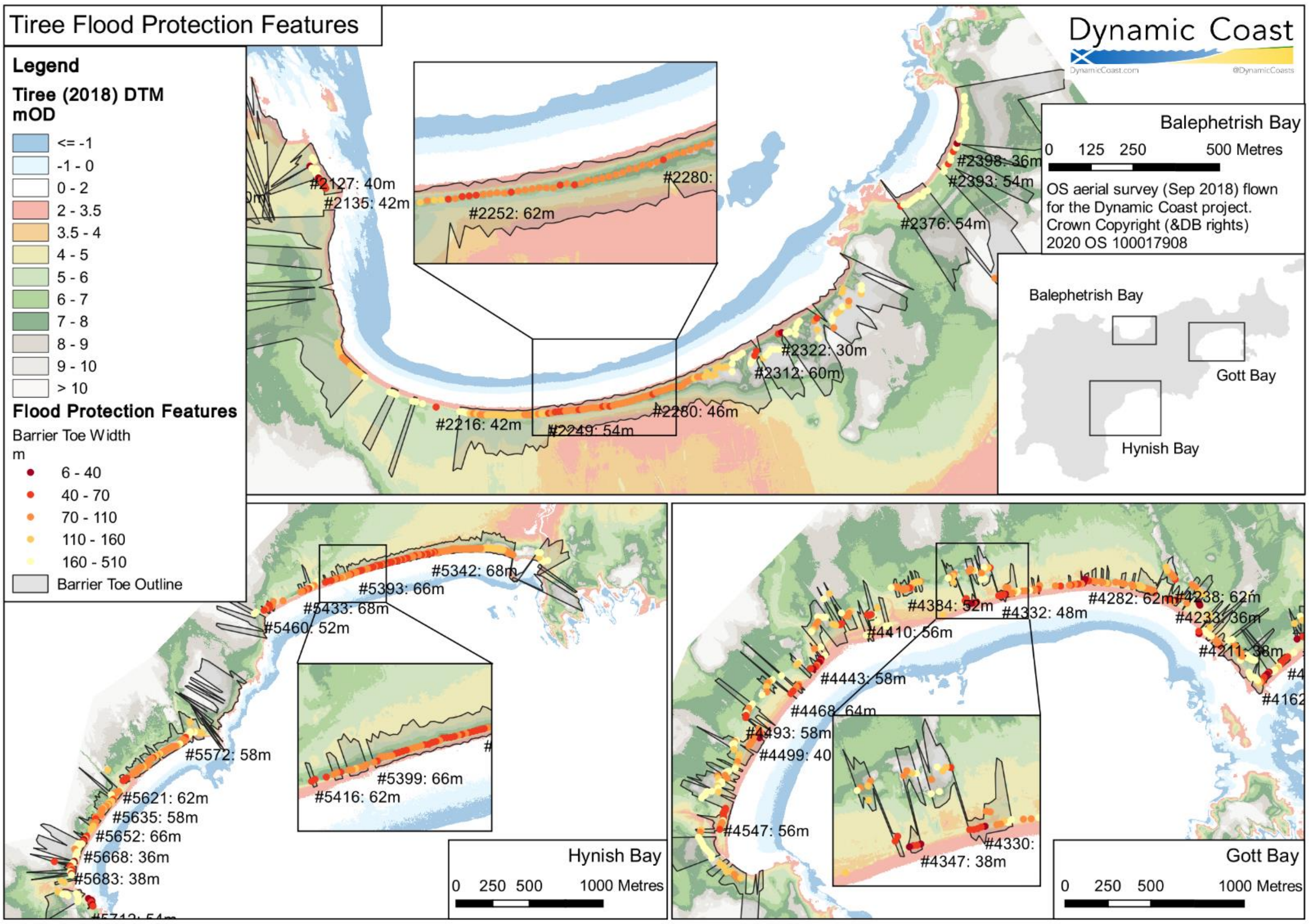

Figure 4 Flood protection features in Central Tiree, showing the extent of the barrier toe (grey box) and a selection of transects within narrow sections of the dunes. Barrier width at 4 mOD is annotated alongside transect number

Changes to High and Low Water in Central Tiree

Figure 5 shows the planimetric change in MLWS between 1893 and 2018 as derived from the sentinel satellite analysis of Coast X-Ray. In general, the period 1893 to 1975 saw landward movement of MLWS with up to 60 m of landward shift at Hynish, 17 m at Balephetrish and up to 70 m at Gott in the east, but 28 m of seaward shift in the west. The period 1975 to 2018 saw a slowing of change with no change in MLWS position at Hynish and Gott in the east of the bay but 50 m of erosion at the western side of Gott. From this, it seems the twin sections of Gott Bay act as a self-contained unit with sediment transfers occurring between sections. Balephetrish on the other hand continued to erode with 22 m recession to 2018.

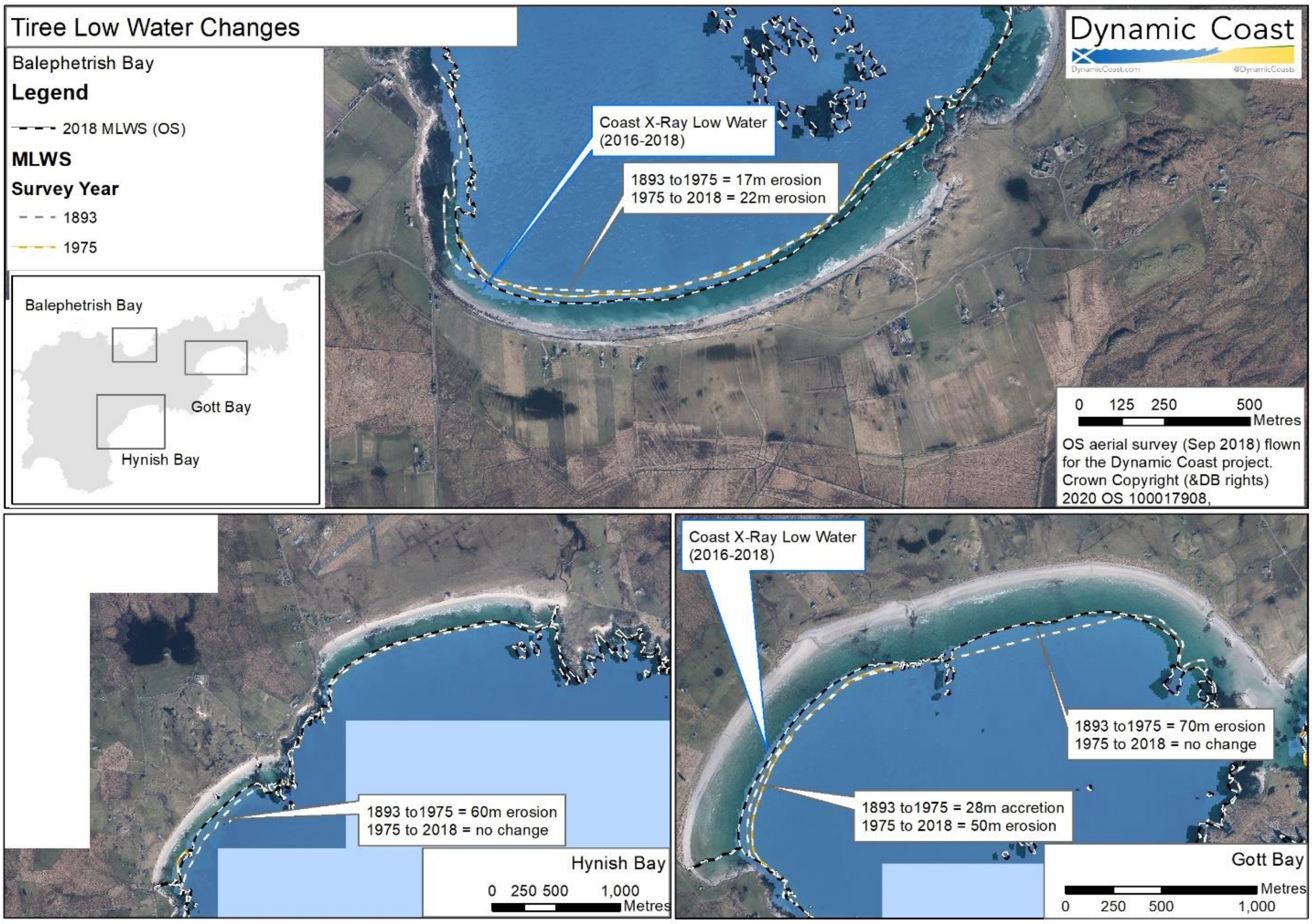

Figure 5 Changes to each lower beach – comparison of various MLWS surveys and Low water (80% water occurrence) from Coast X-ray

Figure 6 shows the changes to the upper beaches of Central Tiree as depicted by the positions of MHWS. In general, 1895–1975 was characterised by accretion and seaward shift of MHWS on all beaches, whereas the period since 1975 has seen erosion and landward shift on most beaches. The exception is on the western beach of Gott where modest accretion has occurred, again suggesting that Gott acts as a self-contained unit where losses at one end are manifest as gains at the other end and vice-verse at other times. In general, Figures 5 and 6 demonstrate the period 1893/5-1975 to show MLWS erosion and MHWS accretion and thus a steepening foreshore, whereas the period 1975-2018 shows erosion (or no change at Hynish) in MLWS and erosion in MHWS and a continuation of foreshore steepening. Note that the exception again is western Gott Bay where MLWS erosion over recent decades is partnered by MHWS accretion, albeit with a net result of steepening.

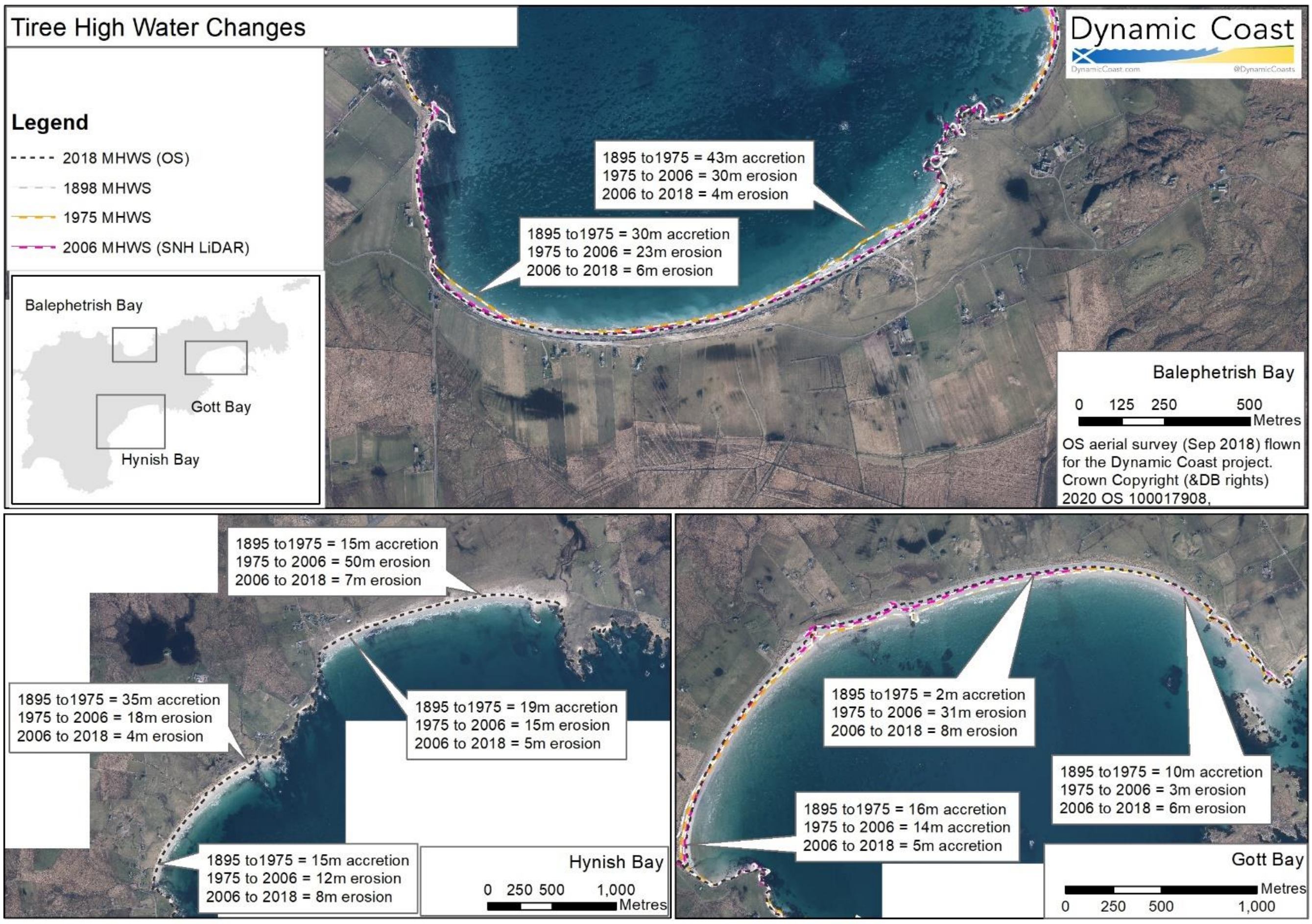

Figure 6 Changes to each upper beach – comparison of MHWS surveys dated 1895, 1975 (OS map series), 2006 (SNH aerial lidar survey) and 2018 (OS aerial imagery DSM)

Intertidal Changes in Central Tiree

Figure 7 demonstrates the net effect of changes in the positions of MLWS and MHWS as expressed in the vertical changes across the beaches as derived from DSMs. These show recent losses (2006–2018) experienced on the lower beaches. The western bay at Hynish has suffered vertical losses across most of the beach as has the western part of Balephetrish. On the other hand, most of the upper beach and dune areas have gained in height between the two dates. Together with changes in vegetation edge and heights in Figure 8 and 9, these changes in heights of beach areas form the basis for overall volumetric changes to the beach systems including beach and dune (Figure 10).

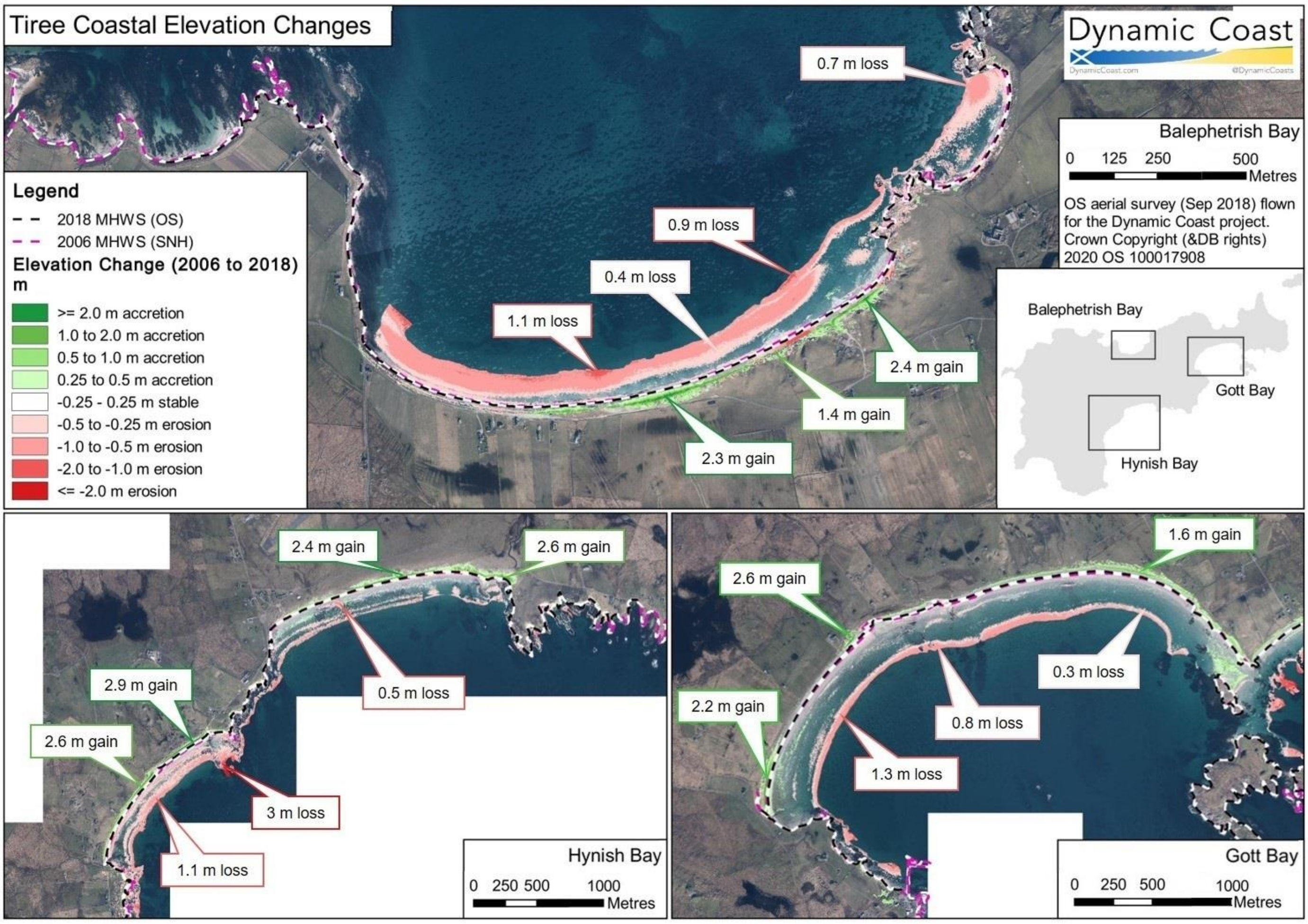

Figure 7 Changes to the foreshore - comparison of the difference in beach elevation from 2006 (SNH aerial lidar survey) to 2018 (OS DSM from aerial imagery)

Dune Vegetation Edge Changes in Central Tiree

Figures 8 and 9 demonstrate the change in vegetation edges for different survey methods and with a range of survey years from 1898-2019. There is an overall trend of recovery from the 2009 vegetation edge onwards, with the majority of edges showing greater than 0.1 m/yr accretion rate seaward. The distribution of accreting vegetation edges is supported by the trends of elevation change, as most dune ridges show an increase in elevation where accreting vegetation edges occur, suggesting dune ridges in these sections are growing seaward toward pre-2009 locations. Equally, the trends of vegetation edge stability and erosion in pockets across east and west Balephetrish and central Gott are matched by much weaker accretion of elevation and a loss of elevation across the foreshore/dune face.

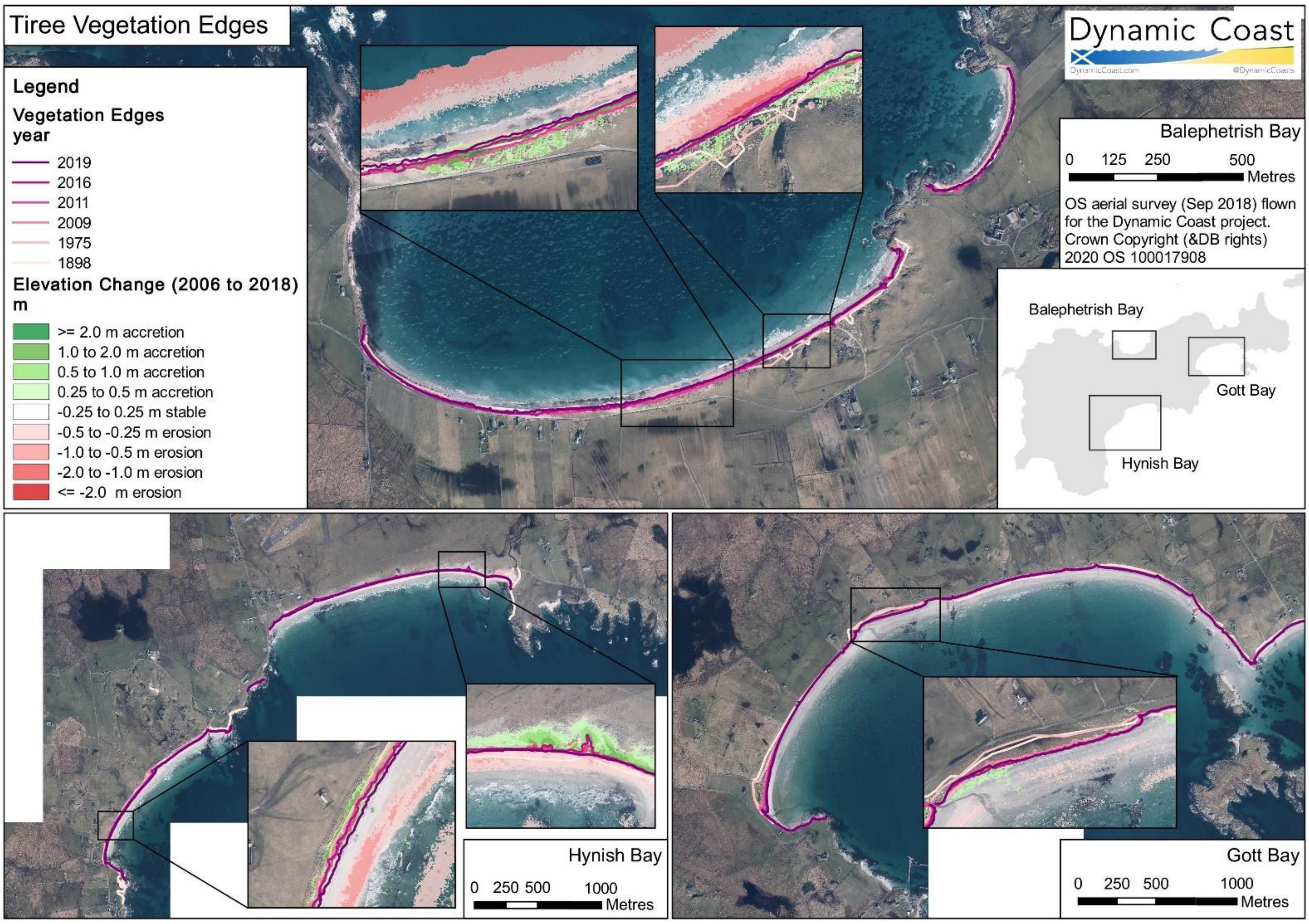

Figure 8 Detailed vegetation edge changes across central Tiree bays comparing map- digitised (1898, 1975), aerial image-digitised (2009, 2011, 2016) and ground-surveyed (2019) edges. Elevation change from 2006 to 2018 is also shown inset for context

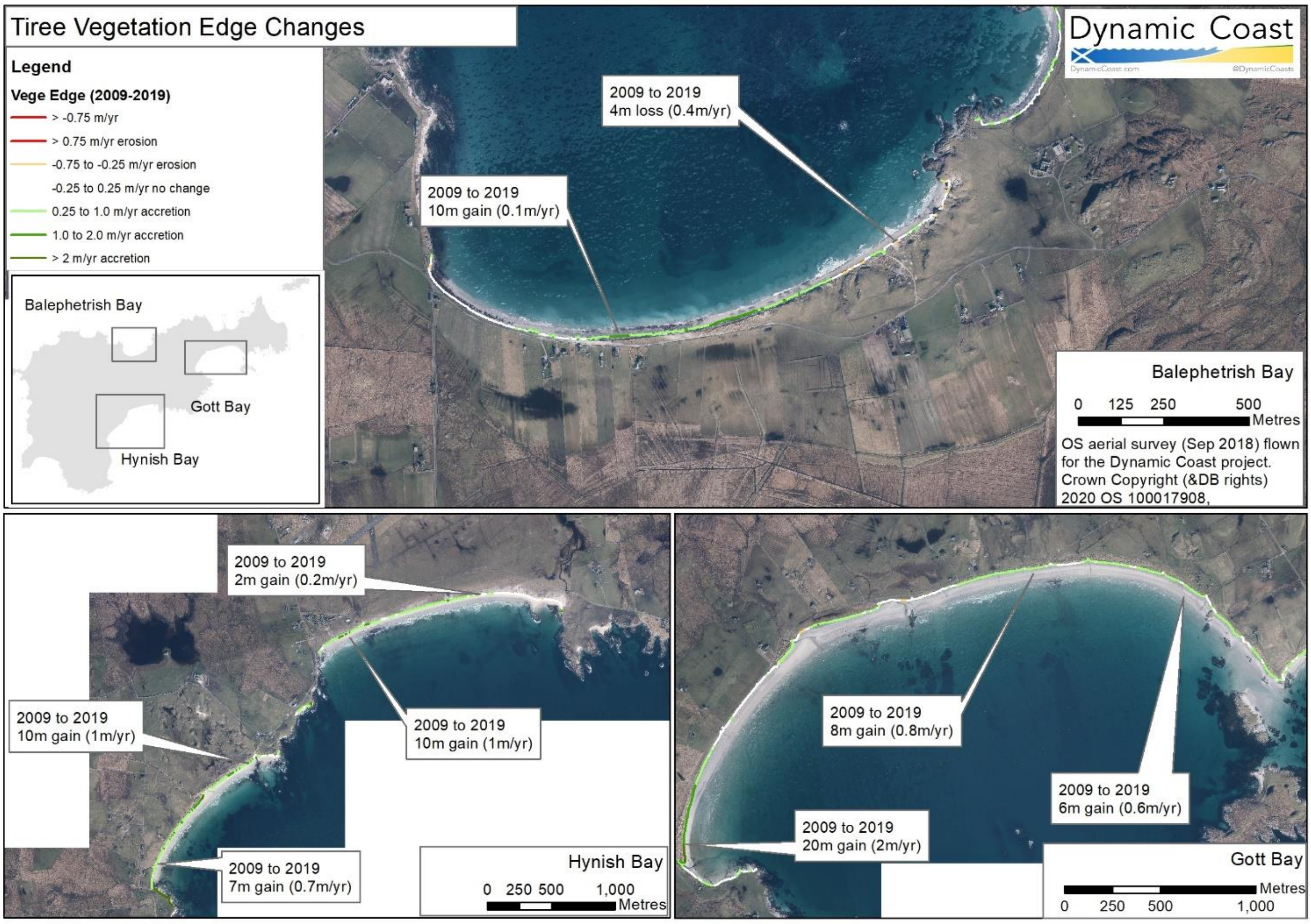

Figure 9 Recent vegetation edge change across central Tiree bays from 2009 (aerial image digitisation) to 2019 (ground survey)

Volumetric Changes across Central Tiree

The elevation changes depicted in Figure 7 allow annual volumetric change rates to be calculated for the period 2006 and 2018 on the beaches of Central Tiree (Figure 10 Comparison of rates of volume change across each geomorphic section outlined in white, from 2006 (SNH Lidar) to 2018 (OS aerial DSM)Figure 10 and Table 2). These clearly show the dunes gaining in volume, with some progressing seaward, except where the beach volume loss has resulted in narrowing of the dune ridge, as at Balephetrish West and Hynish West. Balanced against the gain of the dunes in all beaches, the lower foreshore of all beaches show a loss in volume over this recent time period and a steepening trend. However, since most of the losses and gains are of a similar magnitude, it may be that sediments are not wholly lost from the bay systems themselves, with the notable exception of Atlantic-facing Balephetrish where losses vastly outweigh gains.

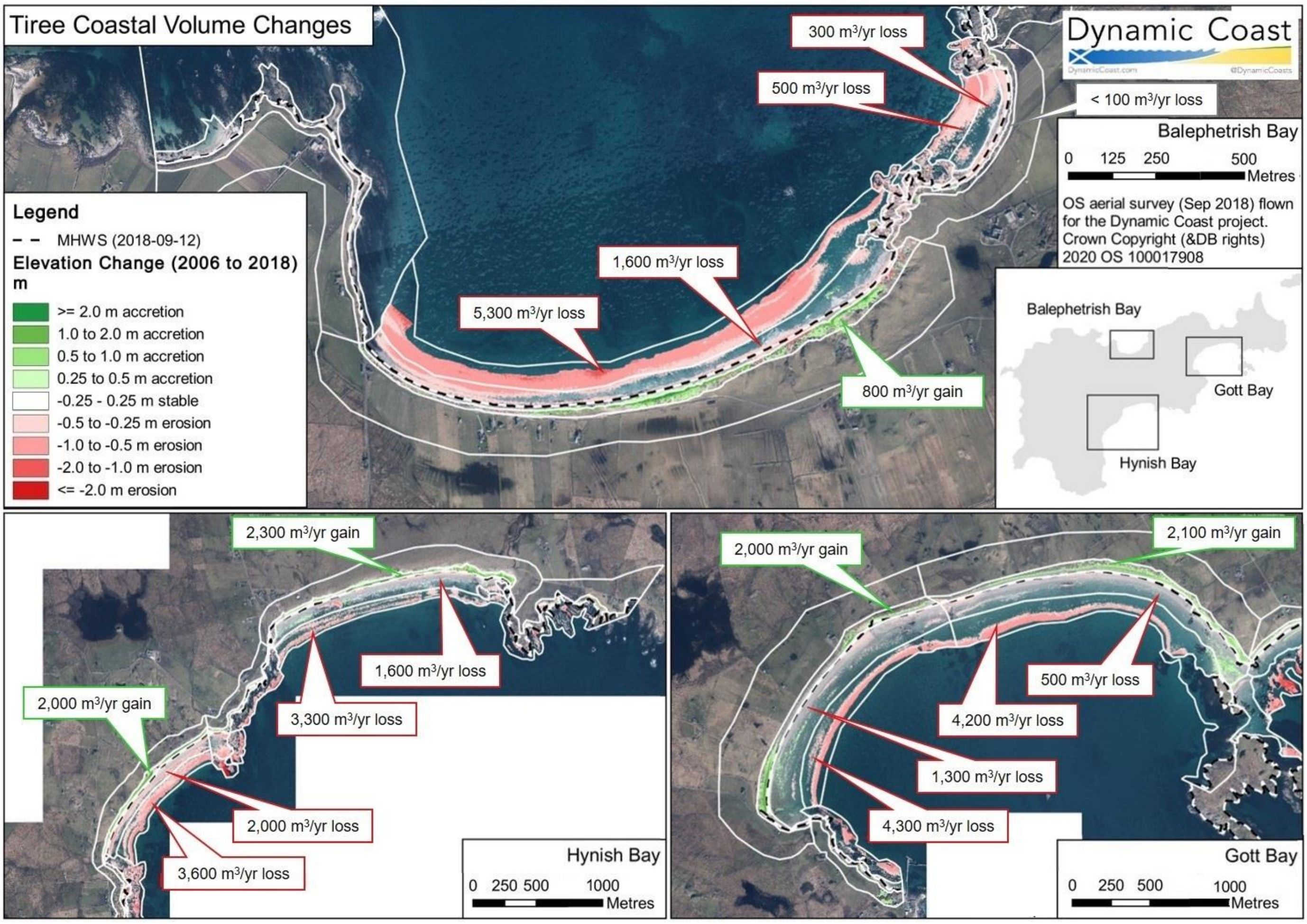

Figure 10 Comparison of rates of volume change across each geomorphic section outlined in white, from 2006 (SNH Lidar) to 2018 (OS aerial DSM)

Table 2 Summarised volume changes from 2006 (SNH Lidar) to 2018 (OS aerial DSM) across the three management units

Management Unit	Lower beach change (m^3)	Lower beach change rate (m^3/yr)	Upper beach change (m^3)	Upper beach change rate (m^3/yr)	Dune ridge change (m^3)	Dune ridge change rate (m^3/yr)
1 (Hynish)	-83,500	-7,000	-53,300	-4,400	51,600	4,300
2 (Balephetrish)	-69,600	-5,800	-27,600	-2,300	7,900	700
3 (Gott)	-108,500	-9,000	-17,800	-1,500	53,700	4,500

Total	-261,600	-21,800	-98,700	-8,200	113,200	9,500

Future Shoreline Projections

Future projections are based on the Modified Bruun Rule (see methods above) which are projected forward based on UKCP18 Representative Concentration Pathway 8.5 (UKCP18 RCP8.5) using the 95th% estimate, given the precautionary principle. The coastal change incorporates shore face gradient and is calibrated with recent coastal change data (which reflects/assumes continued sediment supply from the immediate surroundings). These anticipated shorelines are not intended to be reliable detailed predictions, but a precautionary future scenario to inform the possible scale of change.

Figure 11 shows the anticipated decadal future positions of MHWS up to the year 2100, estimated using the modified Bruun Rule calculation for a future relative sea level rise of 0.95 m by 2100 (UKCP18 RCP8.5 95th%). The amount of landward retreat in each bay generally increases with each decadal prediction, ranging from 3 m to 72 m inland by 2050 across each bay and 35 m to 156 m inland by 2100. The greatest predicted retreat occurs in Gott Bay in the east with an average retreat of 115 m from the current MHWS position by 2100, although instability exists at the two channel outlets in the centre of the bay and retreat is concentrated to the eastern half of the bay. Hard rock headlands and artificially defended shores are excluded from these predictions.

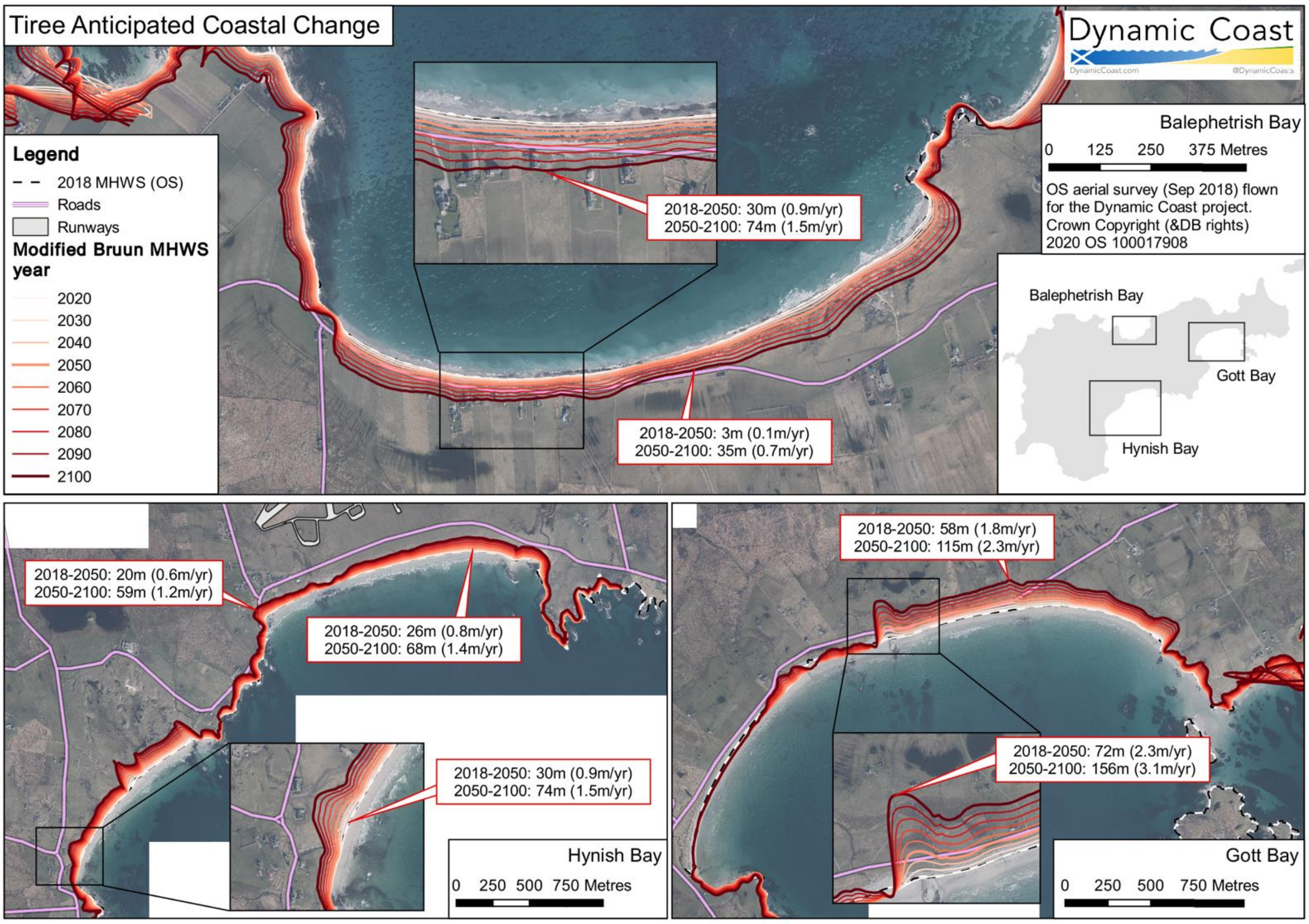

Figure 11 Anticipated shoreline change using Modified Bruun Rule.

The retreat of MHWS on each bay is normally accompanied by the undercutting of vegetation at the coastal edge, especially where any dune / machair vegetation is damaged. This vegetation edge essentially marks the common perception of erosion of the land and its assets, due to landward retreat of MHWS. However, there is a mean lateral offset of 12 m between MHWS and the vegetation edge for Balephetrish and Hynish, and a 25 m offset for Gott. This is used to project the modified Bruun MHWS predictions inland to provide insight on the timing when the un-vegetated and dynamic beach is anticipated to arrive at the position of any landward asset, such as the B8065, B8068 and B8069 coastal roads. Overall, this adjustment anticipates recession to arrive at a given point inland sooner than that predicted by the modified Brunn Rule on its own. A detailed view of decadal vegetation edge prediction using this method can be seen in Figure 12. The progress of beach and dune landward movement and vegetation offset is curtailed by the presence of rock and cliff toward the extremities of each bay.

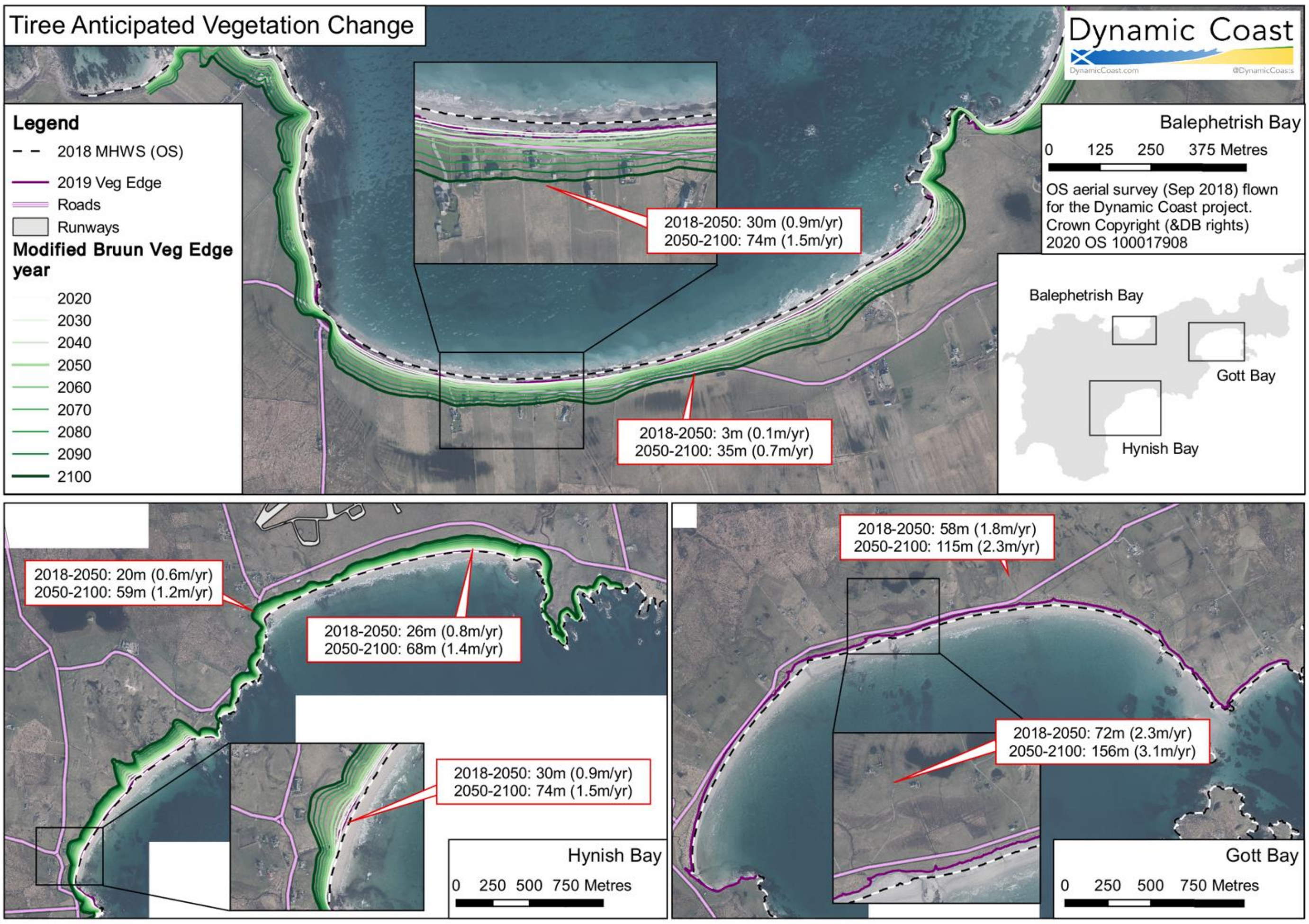

Figure 12 Anticipated shoreline change using Modified Bruun Rule for vegetation edge.

Figure 13 depicts the anticipated erosion and coastal evolution of Tiree using a different model: the Coastal One-line Assimilated Simulation Tool of CoSMoS-COAST (Vitousek et al., 2017). CoSMoS-COAST is forced by the RCP8.5 95th% sea level change scenarios within UK Climate Projections 2018 (UKCP18) and models long-term shoreline migration due to sea level rise, but also includes wave-driven along- and cross-shore sediment transport whose accumulation has the potential to offset at least some erosion. Like the Modified Bruun Rule, the model makes use of MHWS observations from the first phase of Dynamic Coast in calibrating the past predictions of shoreline position, to more accurately predicting future changes with SLR through to 2100. Under the highest future SLR pathway, all three bays show MHWS retreat by 2100, with the greatest amount of steady retreat seen in Balephetrish Bay (33 m from 2018–2050 and a further 36 m from 2050–2100). The two southern bays show more complexity in MHWS migration. The western end of Hynish Bay shows steady future MHWS retreat, while the eastern end shows accretion of 26 m seaward up to 2050 before retreating back to the 2018 position in 2100 where the exponential increase in SLR takes effect. The western end of Gott Bay shows considerable future retreat (34 m from 2018–2050 and a further 38 m from 2050–2100), whereas the centre and east that are partly sheltered by offshore rockheads show little to no erosion by 2050, but are anticipated to lose 37m by 2100. However, the irregular time gaps of shoreline observations in Tiree (1890s to 1970s and 1970s to Modern) serve to limit the ability of CoSMoS-COAST to tune its modelled erosion rates and can only partly capture the actual rates over the last decade that are needed to project into the future. In Tiree, the model offers a higher level of complexity and in places produces enhanced erosion (e.g. at Balephetrish and Gott), in other places less than Bruun (Figure 14), however, both models are in agreement on the overall anticipated direction of travel of coastal change.

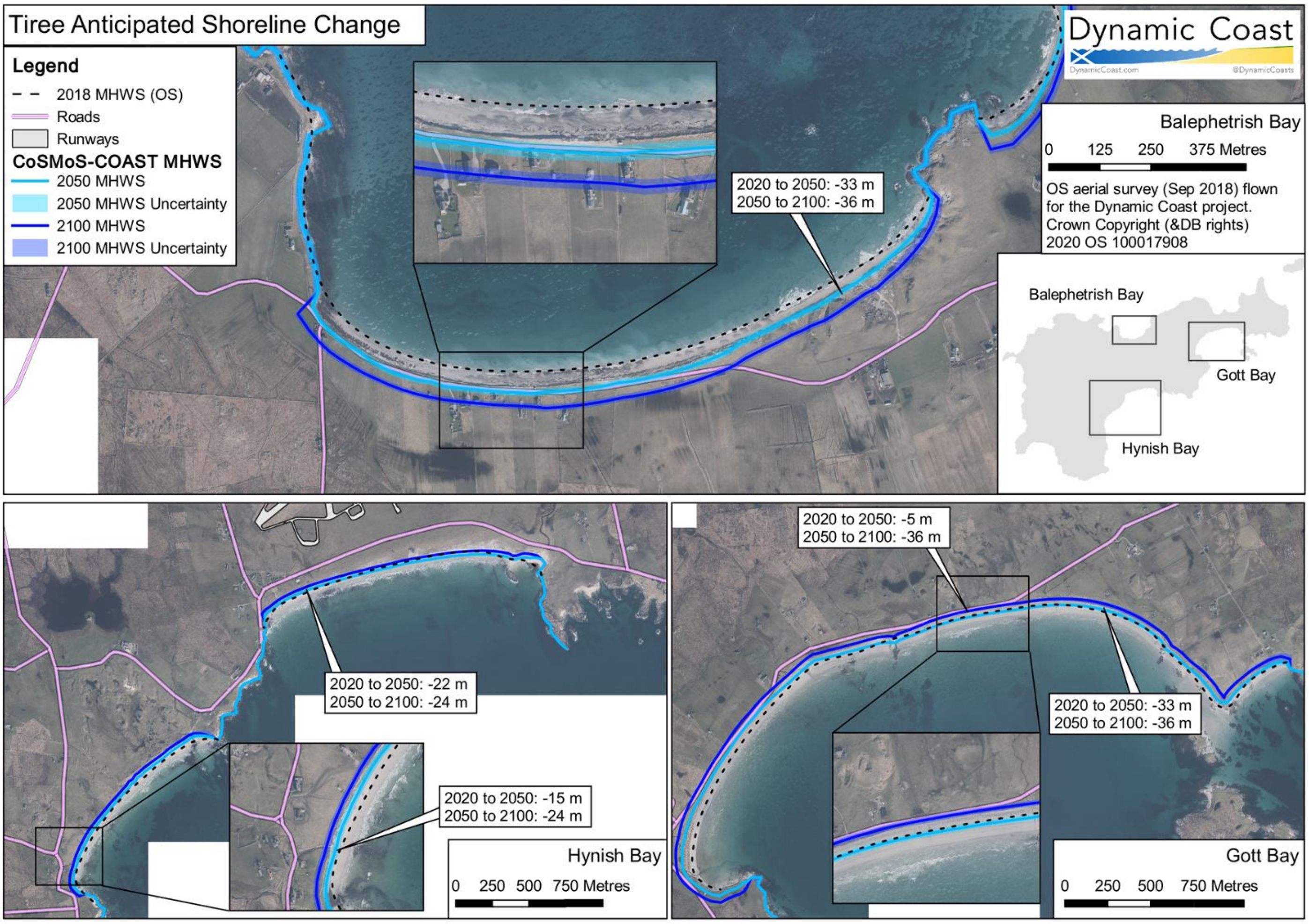

Figure 13 Anticipated shoreline change using CoSMoS-COAST modelling

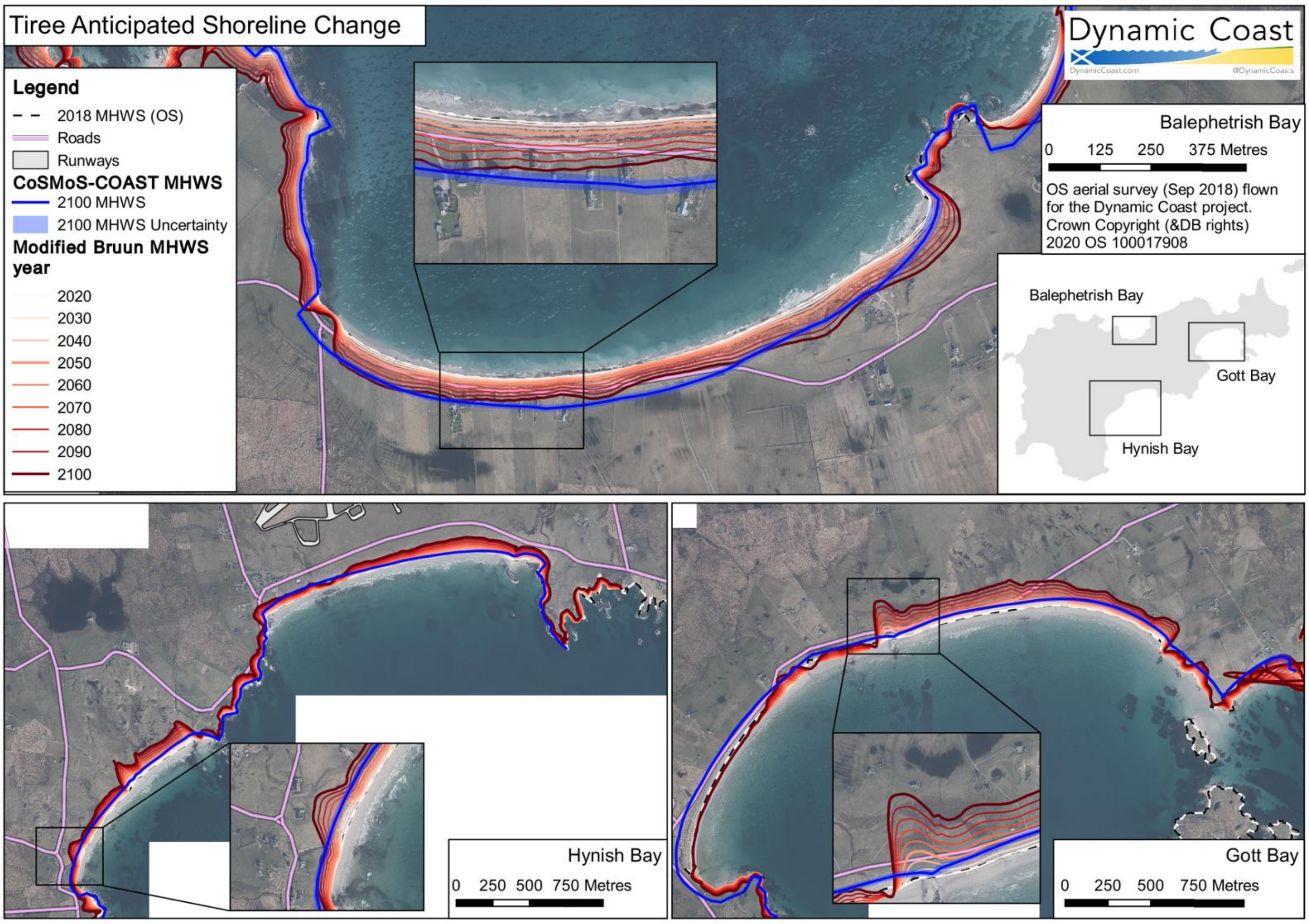

Figure 14 Comparison between anticipated shoreline change using CoSMoS-COAST modelling and Modified Bruun Rule

Social Vulnerability Classification Index

For detailed methods and reporting on the approach taken below, the reader is directed to the Technical Annex Work Stream 6 –Mapping Coastal Erosion Disadvantage (www.dynamiccoast.com/reports). The average Social Vulnerability Classification Index (SVCI) for Tiree produces weighted indicators of socio-economic vulnerability that rate most of Tiree as slightly vulnerable within the SVCI analysis (the third highest category of vulnerability within the SVCI) (Figure 15). The low density of housing on Tiree, combined with the fact that few properties are close to the coast means that the potential risk to private housing as a result of exposure to coastal-erosion-related flooding events is limited.

As is the case with many island communities, there is a need, in the context of considering the extent of vulnerability on the island of Tiree to consider the magnitude of impact of a potential coastal-erosion event on the key and/or limited resources and infrastructure on the island. This involves consideration of, for example, the resilience of key transport nodes to provide essential supplies. Such an event could severely compromise the resilience that these communities appear to exhibit. The risks posed to rural road network and transport infrastructure place this already relatively isolated island community under the threat of increased isolation, without effective adaptation strategies being put in place. Furthermore, the risk posed by coastal erosion related flooding events to life-line routes may place the island's community at risk through hampering the ability of emergency response teams to reach those communities during a coastal erosion related flooding event.

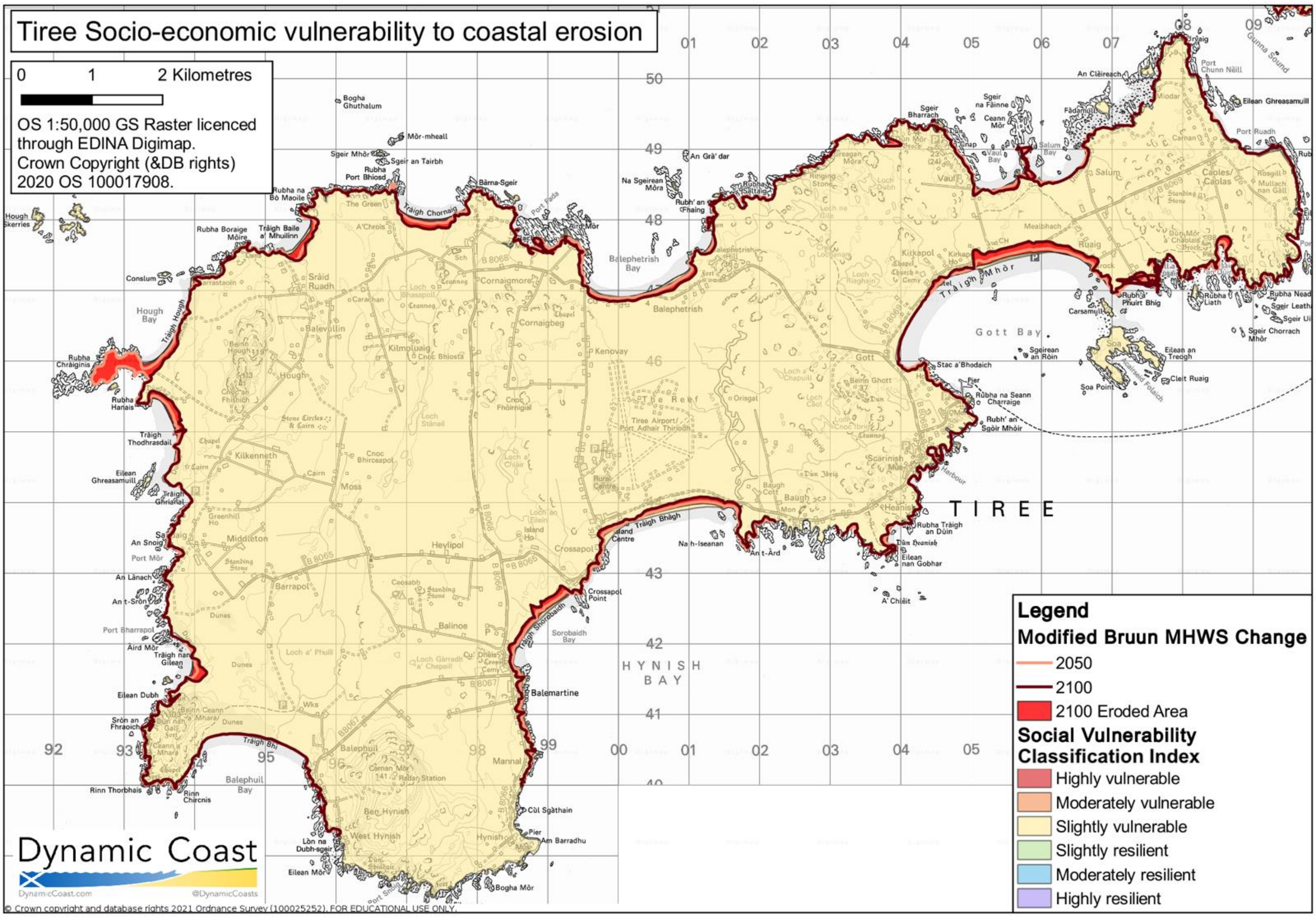

Figure 15 SVCI classifications per data zone with anticipated coastal change using the Modified Bruun Rule

Coastal Flooding

Coastal Flood Boundary

The Coastal Flood Boundary (CFB) dataset published by DEFRA in 2018 (link) shows the anticipated still water surface level of surge events at various frequencies. Still water level calculations such as these superimpose any surge level during storms to be in addition to the highest astronomic tide level. As such they exclude other hydrodynamic effects, such as wave run-up etc., that would need to be considered to gain an estimate of worst-case storm impact.

Present day Mean High Water Springs reaches 2.17 mOD and excluding weather effects the highest astronomic tide is expected to reach 2.72 mOD (Table 3). SEPA anticipate the High Probability flood level to have a still water level of 3.11 mOD with a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 3.68 mOD, with a 0.1% annual exceedance frequency.

Table 3 Tidal and flood levels for Tiree (figures from Hynish)

Description	Level (mOD)
MHWS	2.17
HAT	2.72
Base year	2.07

Description	Level (mOD)
1 yr (100% AEP)	2.62
10 yr (10% AEP) SEPA's High prob. event	3.11
100 yr (1% AEP)	3.34
200 yr (0.5% AEP) SEPA's Med. prob. event	3.45
1,000 yr (0.1% AEP) SEPA's Low prob. event	3.68

SEPA's Flood Risk Maps

The current version of SEPA's published flood risk maps take the anticipated still water surface levels from the CFB analysis (above) and intersect these with detailed topographic mapping to identify areas which would be inundated under high (10 yr return period), medium (200 yr return period) and low (1,000 yr return period) probabilities. These extents do not include the wave run up and other hydrodynamic effects, considered below.

Figure 16 shows the present-day high probability and low probability coastal flood extents sourced from present CFB water elevations, in greater detail than SEPA's Flood Risk Map for Tiree's coastal flooding as it benefits from a recent OS digital surface model (2018) and is more likely to accurately represent actual current land levels. Figure 16 demonstrates the linear nature of the flood risk as it follows the low-lying land behind the dune ridges. However, it also highlights the current high probability flood risk along the centre of Gott Bay and north-eastern edge of Hynish Bay at the mouth of the An Fhaodhail stream.

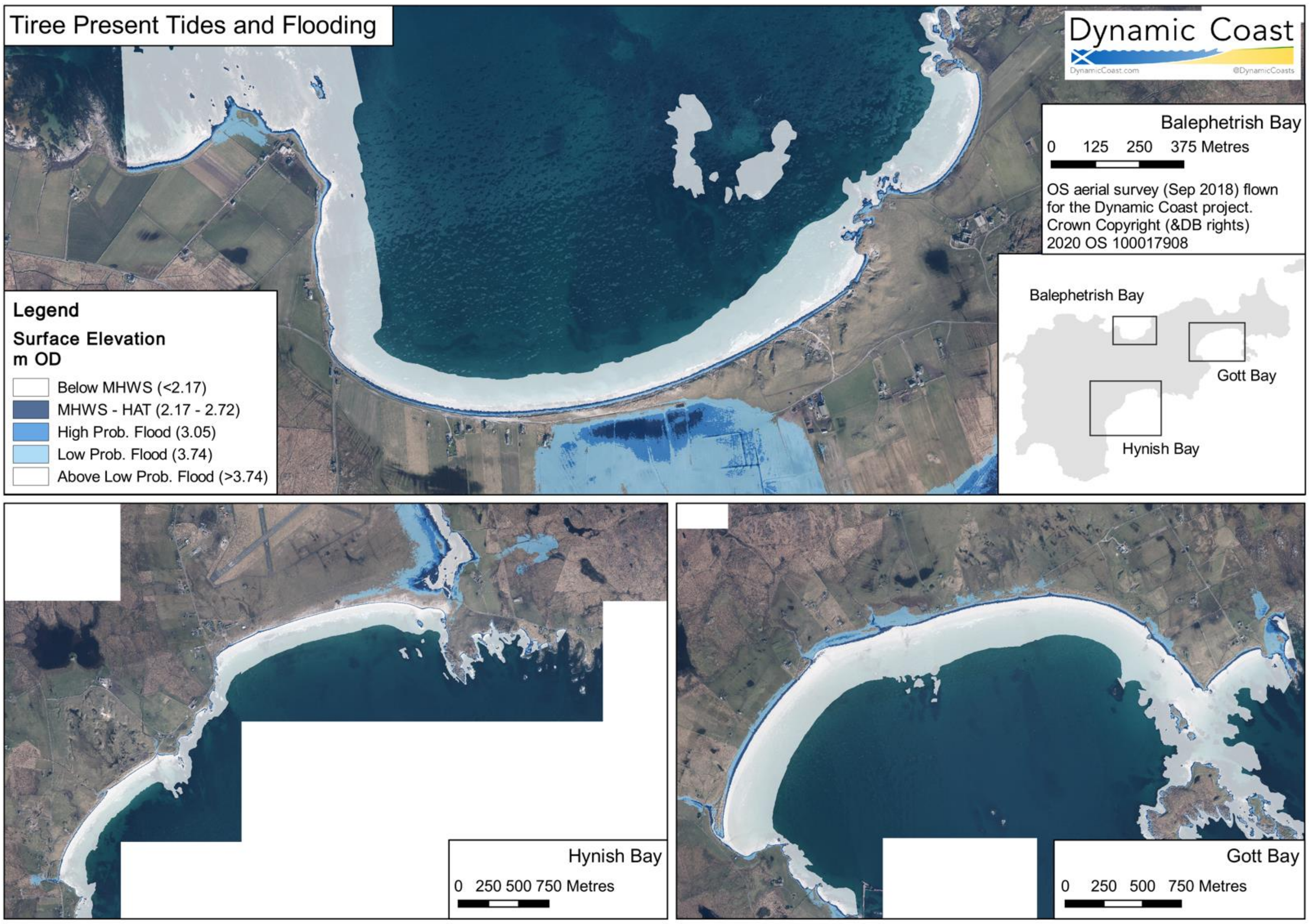

Figure 16 Summary of present-day tides and High Probability (1:10 yr, 3.05 mOD representative at Gott Bay) to Low Probability (1:1,000 yr, 3.74 mOD) flood levels around Tiree

Relative Sea Level Rise

The UK Climate Projections data (2018) has been used to anticipate increases in mean sea level around Tiree. Whilst there are considerable domestic and international efforts to cut greenhouse gas emissions, the recent global trends remain aligned with the High Emissions Scenario also known as Representative Concentration Pathway 8.5. For context, a 2°C future corresponds to the RCP4.5 50th percentile by 2085; 4°C corresponds to RCP8.5 50th percentile by 2085 and the 5.5°C future corresponds to the 95th percentile by 2085. Using the UKCP18 projections, the anticipated increases in mean sea level around Tiree are summarised in Table 4. By 2050 mean sea level is likely to increase between 0.13 m and 0.31 m above the average levels seen between 1980 and 2000. Rates of sea level rise by 2050 are expected to be between 4 mm/yr and 9 mm/yr and as likely as not above 6 mm/yr. For context, the long-term pre-industrial relative sea level trend on Tiree was -0.6 mm/yr, i.e. slightly falling (Bradley et al 2019). Given the precautionary principle the 95th percentile figures of the RCP8.5 are used throughout this report.

Table 4 Existing and future tidal extents based on UKCP18 RCP8.5 for Tiree. Shaded row highlights the worked example in the text above

Year	MSL increase (m above 1981–2000 levels)		
	5th%	50th%	95th%
2010	0.02	0.03	0.04
2020	0.04	0.06	0.09
2030	0.06	0.1	0.15
2040	0.09	0.15	0.22
2050	0.13	0.21	0.31
2060	0.17	0.28	0.42
2070	0.21	0.35	0.54
2080	0.26	0.43	0.67
2090	0.3	0.51	0.81
2100	0.35	0.59	0.95
2300	0.78	1.80	3.61

Period	Rate of increase (mm/yr)		
	5th%	50th%	95th%
2000–2010	2.0	3.0	4.0
2010–2020	2.0	3.0	5.0
2020–2030	2.0	4.0	6.0
2030–2040	3.0	5.0	7.0
2040–2050	4.0	6.0	9.0
2050–2060	4.0	7.0	11.0
2060–2070	4.0	7.0	12.0
2070–2080	5.0	8.0	13.0
2080–2090	4.0	8.0	14.0
2090–2100	5.0	8.0	14.0
2100–2300	2.2	6.1	13.3

The existing tidal inundation extents and increases anticipated by 2100 are shown in Figure 17, where the extent of land at the elevation of HAT by 2070 covers the same areas presently at risk to High Probability flooding (1:10 yr), and the land at HAT by 2100 covers the same areas presently at risk to Low Probability flooding (1:1,000 yr). Such an image is helpful in informing the growing risk of so called 'fair weather flooding' where flooding may increasingly occur in the absence of storms as the tide reaches higher and further inland due to increased mean sea level.

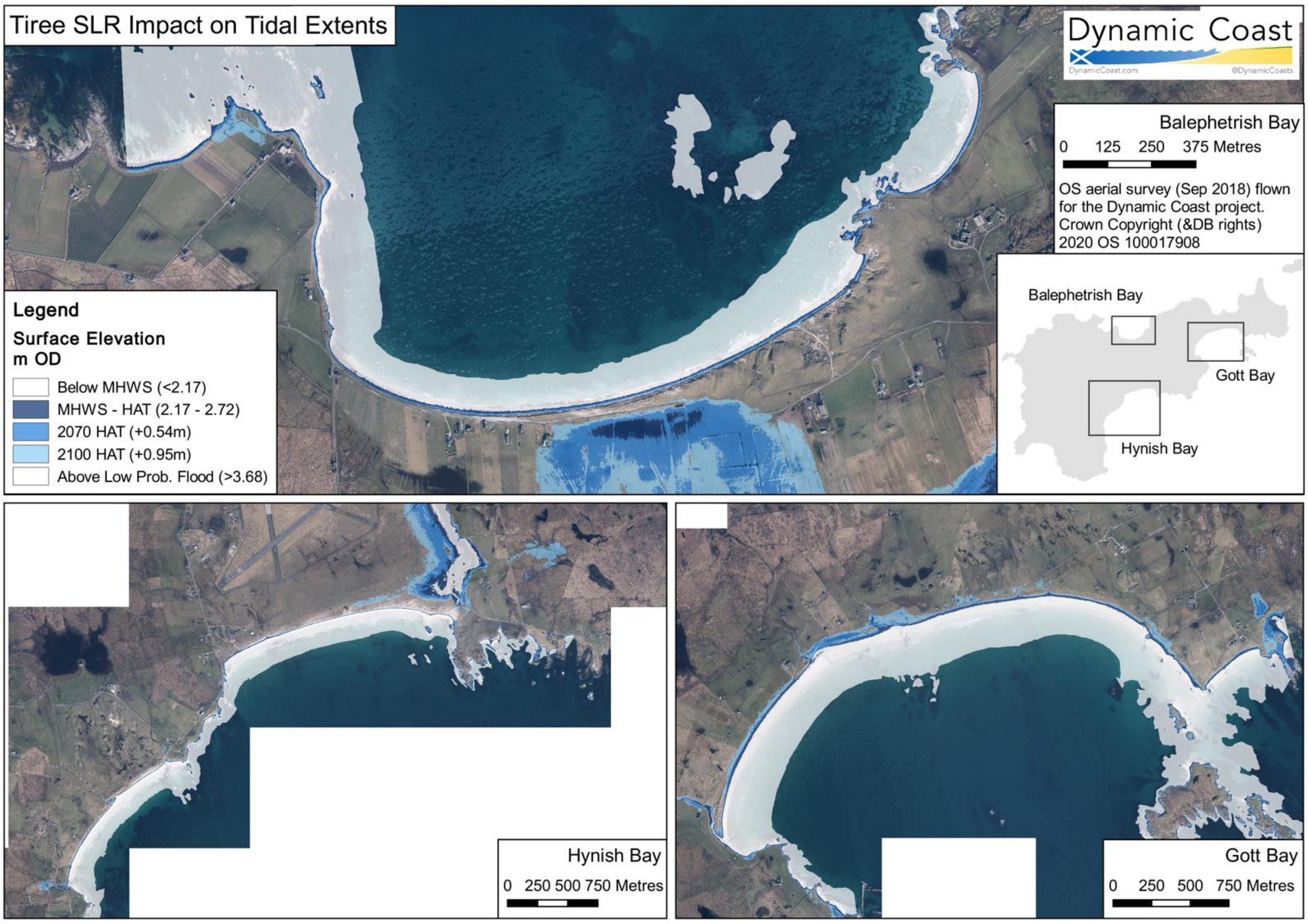

Figure 17 Present day extent of the Highest Astronomic Tide and the future sea level rise anticipated under UKCP18 RCP8.5 95% by 2070 & 2100.

Figure 18 shows the key present day and anticipated Low Probability flood elevations across Tiree by 2100, which reflect the increased impact of storm events, when 0.95 m of SLR is added to flood extents. A greater extent of low-lying land is shown as being at risk across all three bays with a greater number of entry points for corridors of flooding behind adjacent higher dune ridges, especially in Gott and Hynish Bays.

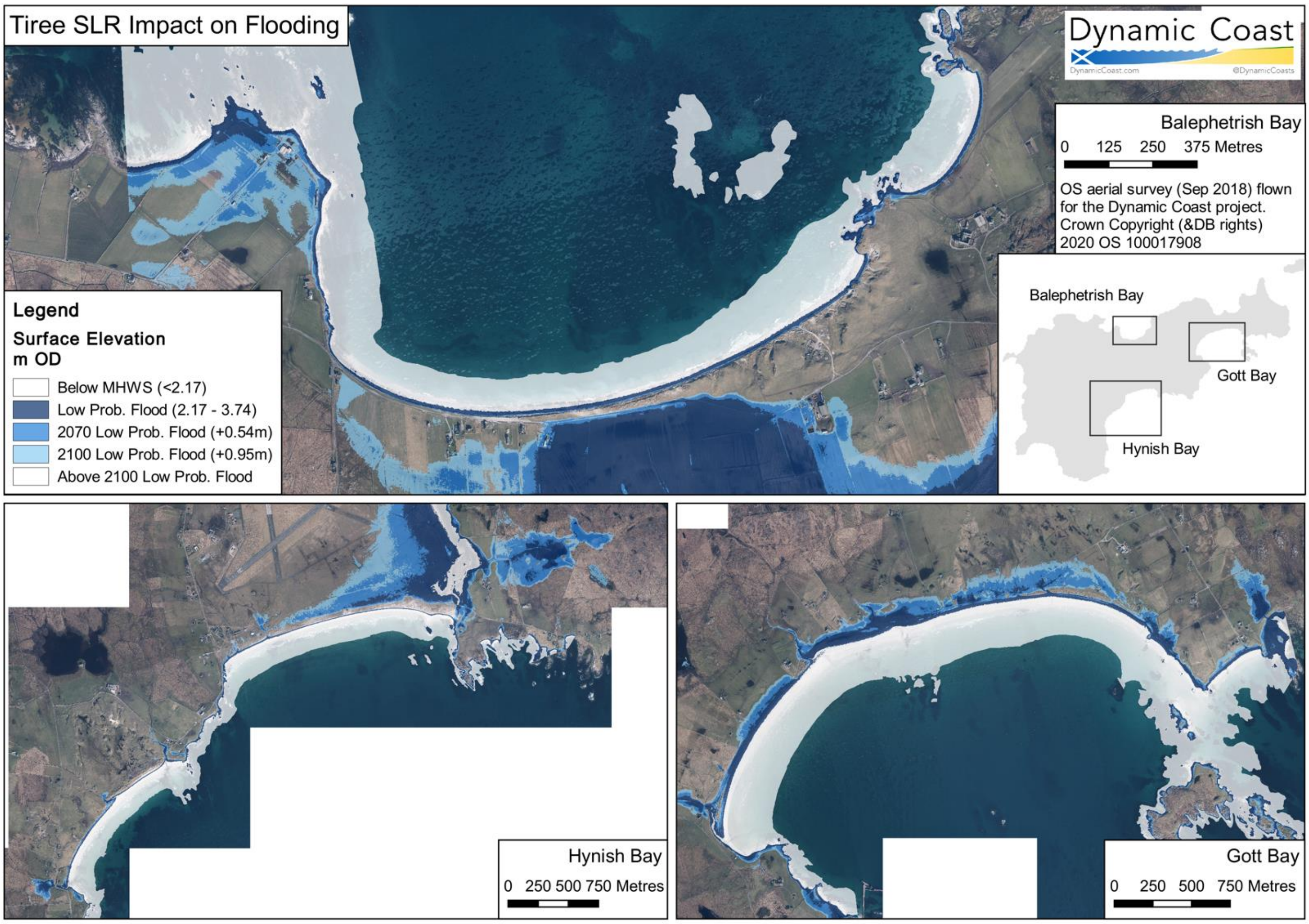

Figure 18 Present day and future flood events anticipated under UKCP18 RCP8.5 95th% sea level rise by 2070 & 2100.

Figure 19 plots out the key present day and anticipated flood elevations for Tiree. Mean High Water Springs reaches 2.17 mOD and if weather effects are excluded the highest astronomic tide is expected to reach 2.72 mOD. SEPA anticipate the High Probability flood level to have a still water level of 3.05 mOD, this has a 10% annual exceedance frequency. SEPA anticipate the Low Probability flood level to have a still water level of 3.74 mOD, this has a 0.1% annual exceedance frequency as shown on Figure 19.

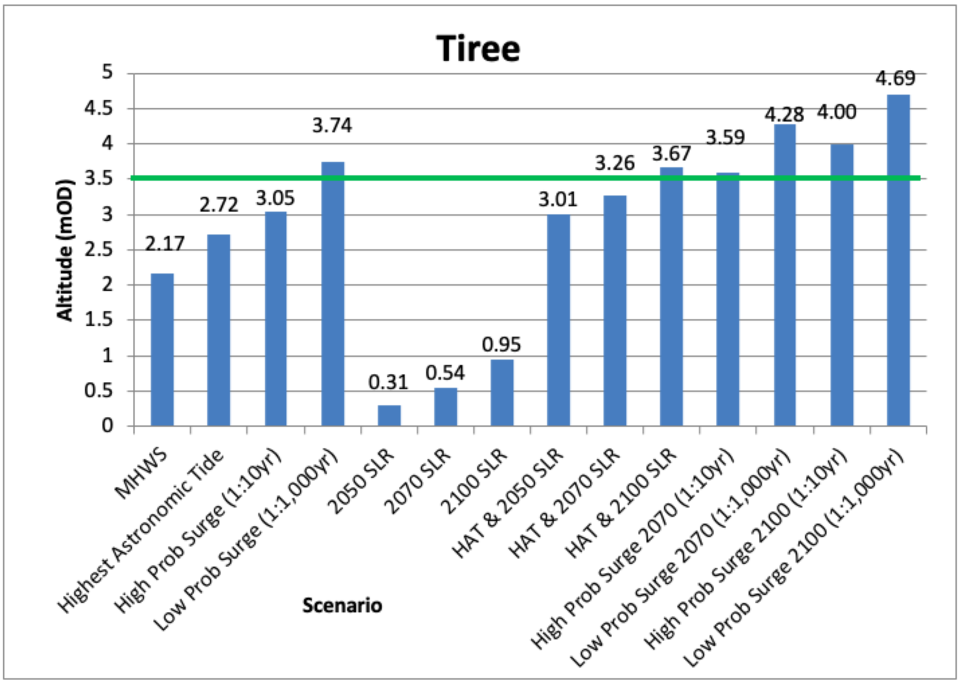

Figure 19 Summary of present and future key tide and flood levels at Tiree. There are substantial interior areas are below 3.5mOD (annotated with green line) although the dune crest and embankments are higher.

Flood Protection Features

Figure 4 depicts the protection offered by the dunes and embankments of Tiree's low-lying interior. However, the elevation cross-sections in Figure 20 highlight the issues faced by coasts where a low-lying interior is fronted by a single dune cordon of finite dimension whose function as a natural barrier is protective (or sacrificial). A typical dune height across Hynish Bay is 10.2 mOD (occasionally rising to 17 mOD), with an average barrier width of 110 m (reducing to 34 m in places). The average height and width of barriers at Balephetrish Bay are 9.5 mOD and 125 m respectively. The lowest and narrowest barriers occur at Gott Bay, with an average crest elevation of 8.9 mOD, falling to 5.9 mOD, and width of 125 m, falling to 16 m. However, all three exemplar transects highlight that much of Central Tiree has rising land behind the coast, albeit with some low-lying land currently unprotected or protected by narrow exposed barriers. Gott Bay has the least protective barriers at 4 mOD and above, but the backdune is elevated and rising inland so flooding is not a high risk. However, several key road links exist along and behind each barrier system, so the integrity of these barriers into the future may be of concern. For example, Figure 16 demonstrates the flood risk to low-lying ground behind and between the dune ridges and the current high probability flood risk, particularly at the north-eastern edge of Hynish Bay at the mouth of the An Fhaodhail stream and in the east of Balephetrish Bay. Figures 11, 12 and 13 indicate that despite parts or all of these dune barriers anticipated to be affected by future erosion, rising ground behind will limit erosional incursion inland. The exception is in the east of Hynish Bay where high tides already access the An Fhaodhail culvert beneath the dune cordon and into the interior. Future progressive dune edge erosion may exacerbate this and enhance the potential for breaching and enhanced erosion-induced flood risk to the low-lying land between Balphetrish and Hynish Bays.

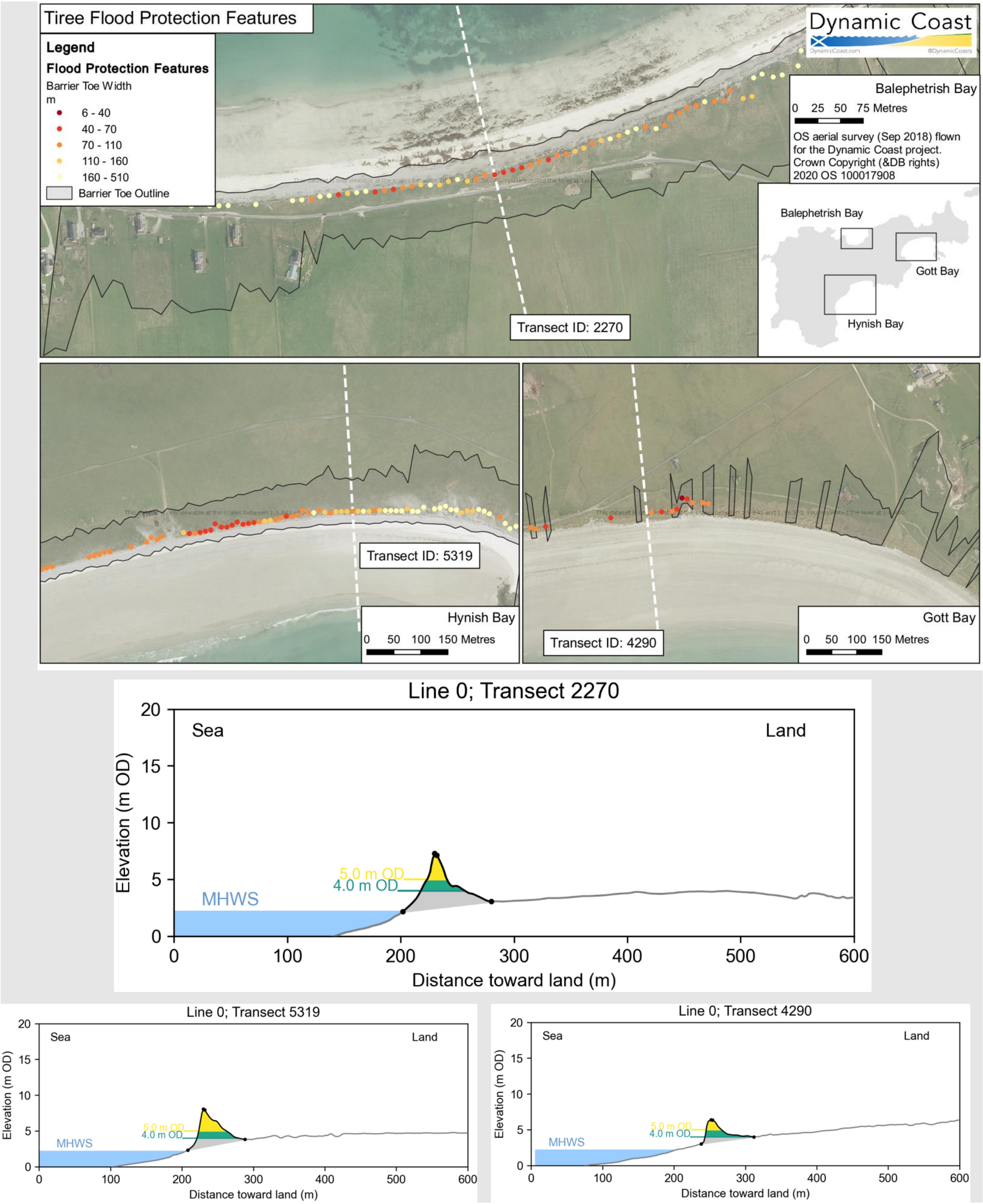

Figure 20 Exemplar transects through dune cordons at the three Management Unit sites, each providing a flood protection function.

END

Appendix

Table of volume changes

Table 5 Volume changes per management unit and sub-section, defined by geomorphic type

MGMT unit	Section	Geomorphic description	Section area (m2)	2006–2018 volume change (m3)	2006–2018 volume change rate (m3/yr)	2006–2018 change coverage (m2)
1	1	Rocky intertidal	146,500	-44,200	-3,700	119,200
	2	Sand corridor and veg edge	49,200	-5,500	-500	47,900
	3	Sandy intertidal	127,300	-43,500	-3,700	104,500
	4	Sandy foreshore	109,100	-24,900	-2,100	109,100
	5	Rocky headland	47,700	-22,500	-1,900	36,300
	6	Protected sandy intertidal	31,000	-9,400	-800	31,000
	7	Rocky intertidal	77,300	-15,700	-1,400	73,300
	8	Sand corridor and veg edge	24,100	900	100	24,100
	9	Sandy intertidal	180,200	-40,200	-3,400	153,200
	10	Sandy foreshore	238,700	-19,200	-1,600	238,700
	11	Veg edge	72,600	28,000	2,400	72,600
	12	Rocky headland	237,300	-13,900	-1,200	183,200
	59	Veg edge	38,600	23,700	2,000	38,600
	60	Backdune	65,400	-9,500	-800	61,100
	61	Backdune	155,200	-28,100	-2,400	154,900
	62	Backdune	75,500	-15,400	-1,300	74,500
	63	Backdune	378,200	600	100	377,500
	64	Backdune	204,400	5,100	500	194,900
2	40	Rocky headland	367,600	-153,700	-12,900	270,200
	41	Sand corridor	40,700	-10,800	-900	40,500
	42	Veg edge	23,900	-2,800	-300	23,800
	43	Veg edge	45,100	9,600	800	45,200
	44	Sandy intertidal	142,100	-63,400	-5,300	107,100
	45	Sandy foreshore	105,300	-19,600	-1,700	105,300
	46	Rocky intertidal	22,700	-5,600	-500	21,400
	47	Veg edge	14,000	-1,700	-200	14,000
	48	Rocky headland	11,400	-2,200	-200	10,700
	49	Sand corridor	2,800	-600	-100	2,200
	50	Sandy intertidal	17,400	-6,300	-600	15,700
	51	Sandy foreshore	17,100	-3,900	-400	17,100
	52	Sandy backshore	13,300	-4,200	-400	13,300
	53	Sandy foreshore	7,800	-2,500	-300	7,200
	54	Sand corridor	1,700	-600	-100	1,700
	55	Rocky headland	8,400	-2,000	-200	7,200
	56	Sand corridor	1,100	-200	-100	1,100
	57	Southern rock cliffs	5,400	-1,000	-100	5,300
	58	Northern rock cliffs	20,200	-4,700	-400	15,100
	73	Backdune	30,200	-5,500	-500	29,800

	74	Backdune	61,500	-12,200	-1,100	61,500
	75	Backdune	248,300	-46,700	-3,900	246,800
	76	Backdune	93,300	-27,100	-2,300	91,100
3	13	Rocky intertidal	77,200	-15,700	-1,400	63,500
	14	Sand corridor and veg edge	36,000	-2,500	-300	35,300
	15	Western sandy foreshore	323,900	-15,400	-1,300	323,900
	16	Western veg edge	125,900	24,900	2,100	125,900
	17	Western sandy intertidal	209,700	-52,300	-4,400	164,500
	18	Eastern veg edge	117,600	25,400	2,200	117,600
	19	Eastern sandy foreshore	297,100	-5,900	-500	297,100
	20	Eastern sandy intertidal	280,600	-50,400	-4,200	249,800
	21	Eastern rocky intertidal	192,100	9,300	800	150,900
	22	Rocky intertidal	135,500	-41,200	-3,500	111,300
	23	Sand corridor	67,500	-5,900	-500	66,600
	24	Veg edge	15,100	3,600	300	15,100
	25	Sandy foreshore	55,200	3,400	300	55,100
	65	Backdune	63,300	2,100	200	60,100
	66	Backdune	639,100	16,000	1,400	636,900
	67	Backdune	502,000	9,700	900	500,400
	68	Backdune	80,400	3,200	300	71,200