

TOWARDS AN INDEX OF COASTAL RESILIENCE: A METRIC TO SUPPORT ADAPTATION PLANNING IN A CHANGING CLIMATE

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Understanding the resilience of coastal systems in a changing climate is key to support the transition from traditional management towards more sustainable planning. This work describes a pilot methodology developed and applied to quantify a Coastal Resilience Index (CRI) for a 2 km sand dune system at Nairn in North-East Scotland. As a proof-of-concept exercise, CRI was kept simple but incorporates inputs that look at the system's baseline conditions, historic change and future projections. Asset's locations and dune and beach morphology and dune vegetation are the variables that were used. The site was schematised into cross-shore transects at 10 m spacing as a grid for the CRI calculation. CRI performance and suitability was assessed by calculating it temporally and using different sources of underlying data (Topography, EO, combination of both) to understand sensitivity to varying inputs. Resilience results indicate that temporal changes align with the observed decadal historic change assessment. Assuming topography-sourced CRI provides the most robust results, EO-sourced CRI was shown to under/overestimate resilience by as much as one class interval. The CRI, tested at Nairn as proof of concept, shows promising results as a metric to quantify dune resilience in support of adaptation planning. The use of EO data is encouraging for a potential implementation of resilience calculations strategically, at regional or national scales, at low cost. Further developments are planned to move towards a "near-real-time" monitoring system that continuously acquires and integrates data, providing an up-to-date measure of resilience.

Keywords: coastal resilience; coastal change; adaptation planning; earth observations; coastal systems

INTRODUCTION

Coastal resilience can be defined as the capacity of the coastal system to cope with, and respond to, pressures induced by external factors (Masselink and Lazarus, 2019). These factors can be anthropogenic and/or induced by natural forces, like a storm event. With climate change increasing sea levels and altering wave conditions, understanding the resilience of coastal systems is critical. In response, we must also adapt the way we manage our coasts with traditional management becoming absorbed into more holistic approaches. Ideally a resilience framework should support the transition towards more sustainable practices.

Several studies have already developed methods to express coastal vulnerability (Bertoni et al., 2019, McLaughlin and Cooper, 2011) or coastal resilience (Townend et al., 2021) into a single metric at various scales, local to national. The metric normally comprises of several high level environmental, economic, and social factors. However extreme event impacts and geometrical factors of beach/dune systems were incorporated into a resilience indicator by Dong et al. (2018) and Torres-Freyermuth et al. (2021).

The work presented here focuses on the development of a Coastal Resilience Index (*CRI*) as a metric to measure resilience of a coastal sand dune system and explores its potential to support monitoring and delivery of future adaptation measures through dynamic pathways. Site monitoring to understand coastal changes through time will be crucial for a constant evaluation of pathway suitability. Being able to condense elements responsible for resilience into a single metric seems to be a valuable, while a simple/manageable way to tackle the complexity of setting dynamic pathways.

The nature of this work is exploratory and is aimed to proof the concept with two main objectives:

1. Establishing if the *CRI* is a suitable indicator of resilience.

The *CRI* has been conceived as a measurable metric that can be applied in space and time to support a continuous evaluation of implemented adaptation measures, plans or strategies. Implementation of new strategies, changes to the system and the climate could result in changes in resilience and therefore the *CRI*. Here, the *CRI* is being tested to resolve the suitability as a valid indicator of resilience for a natural dune system.

2. Establishing data requirement and suitability to derive the *CRI*.

How variable the *CRI* is in relation to the inputs used? Can the *CRI* be derived from publicly available data? Does the use of publicly available data influence outcomes and potential use?

CASE STUDY, SURVEYS AND DATA REVIEW

The case study for this application is Nairn, a coastal town in Scotland (Figure 1). The study area comprises of both West Beach and East Beach (Figure 1) which are separated by the Nairn Harbour.

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Both West and East beaches present a natural sand dune system which protects the landward low-lying community. The dunes are the main protection measure for coastal flood hazards and need to be preserved or adapted to maintain protection in the future.

Most of West Beach is confined between the harbor (eastern end) and a groyne (western end). Overall West Beach features a narrower beach and dune system in comparison to East Beach which presents a wide and healthy beach and a wide and densely vegetated dune system. In West Beach the dune volume increases eastward and the beach widens. In East Beach the dune volume generally increases eastward but narrows at the eastern end due to wetland constraints and limited sediment supply from the spit located on the northeast (Figure 1).



Figure 1. Nairn, Scotland, and the study area of West Beach and East Beach. Frame of the drone footage overlooking at West Beach from the eastern end.

Topography: baseline and historic change

Beach and dune morphology changes were assessed through analysis of available topographic datasets. A drone survey was conducted to map topography of the dune and beach system for West Beach and East Beach. A second topographic dataset is available for Nairn from LiDAR from the Scottish Remote Sensing Data portal, and used to investigate changes in beach elevation, shoreline contours and cross-shore profiles. To support this, the site was schematised into cross-shore transects at 10 m spacing (Figure 2 a and b). A summary of the decadal changes for both West Beach and East Beach are summarised below:

- **West Beach.** The western half of the beach experienced erosion, with levels lowering by up to 1 m, while the eastern side saw accretion, with levels rising by up to 2 m (Figure 2a). The central area showed minimal change. The MHWS (Mean High Water Spring) contour receded by approximately 15 m in the west and advanced by about 14 m in the east, between surveys (Figure 2a). Cross-shore profiles revealed that in the west, the beach elevation dropped by approximately 1 m, but the dune toe remained stable, indicating an erosive beach with a stable dune system (Figure 2c). In contrast, the east side experienced beach elevation gains of approximately 1 m and a seaward migration of the dune toe by 10 m, highlighting accretion in both the beach and dune system.
- **East Beach.** Most of the beach experienced accretion, with levels increasing by up to 5 m, while the far eastern section underwent erosion, including dune recession and up to 4 m of beach lowering (Figure 2b). The MHWS contour advanced by up to 68 m across much of the beach but receded by 30 m in the far east. In the west and central sections of East Beach, elevations increased by 1–3 m, with minimal change to dune toe positions, indicating a stable dune system and accretive beach (Figure 2d). Conversely, the far east side saw beach lowering by about 1 m and a 15 m inshore migration of the dune toe, marking significant erosion of both the beach and dune system.

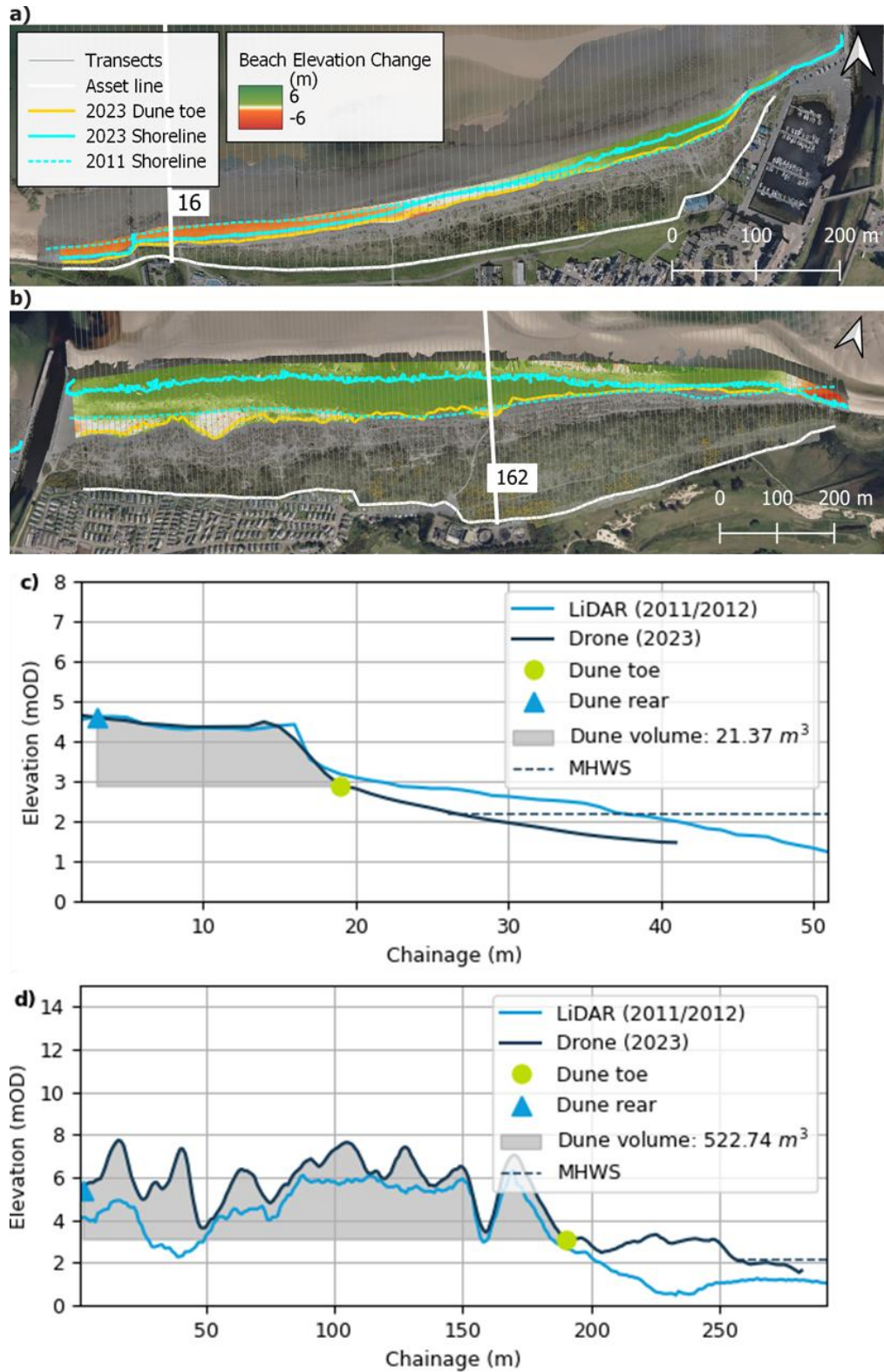


Figure 2. Drone orthomosaic, cross-shore transects, present and past system features and decadal beach elevation change for West Beach (a) and East Beach (b). Dune and beach cross-shore profiles examples highlighting systems features for West Beach (c) and East Beach (d).

Earth Observations (EO)

Shoreline extraction

Publicly available satellite imagery was used to complement the historic change assessment and test suitability of free data for the *CRI*. Earth Observations (EO) from satellite imagery is available from as early as 1984 to present day and can be extracted from Landsat and Sentinel-2 images. Historic shoreline position was detected using CoastSat (Vos et al., 2019), a toolkit developed to allow for low-cost and long-term shoreline data collection from publicly available satellite imagery. Due to satellite sensors availability and characteristics, the following distinction could be made from the extractions at Nairn:

- Data pre-2017. Lower frequency and low-spatial resolution of 30 m (Landsat imagery).
- Data post-2017. Higher frequency and higher spatial resolution of 10 m (Sentinel-2 imagery).

Using data prior to 2017 made identifying trends in cross-shore distance difficult and uncertain. In contrast, data from 2017 reduced uncertainty in shoreline positions. Thus, the analysis on shoreline position for this assessment only considers data from 2017 to 2023. A total of 55 and 65 cleaned and tidally corrected shorelines from 2017 to 2023 were extracted for West Beach and East Beach respectively. Annual average change in shoreline position (m/y) was calculated determining differences in annual average shoreline position from year to year (Figure 3).

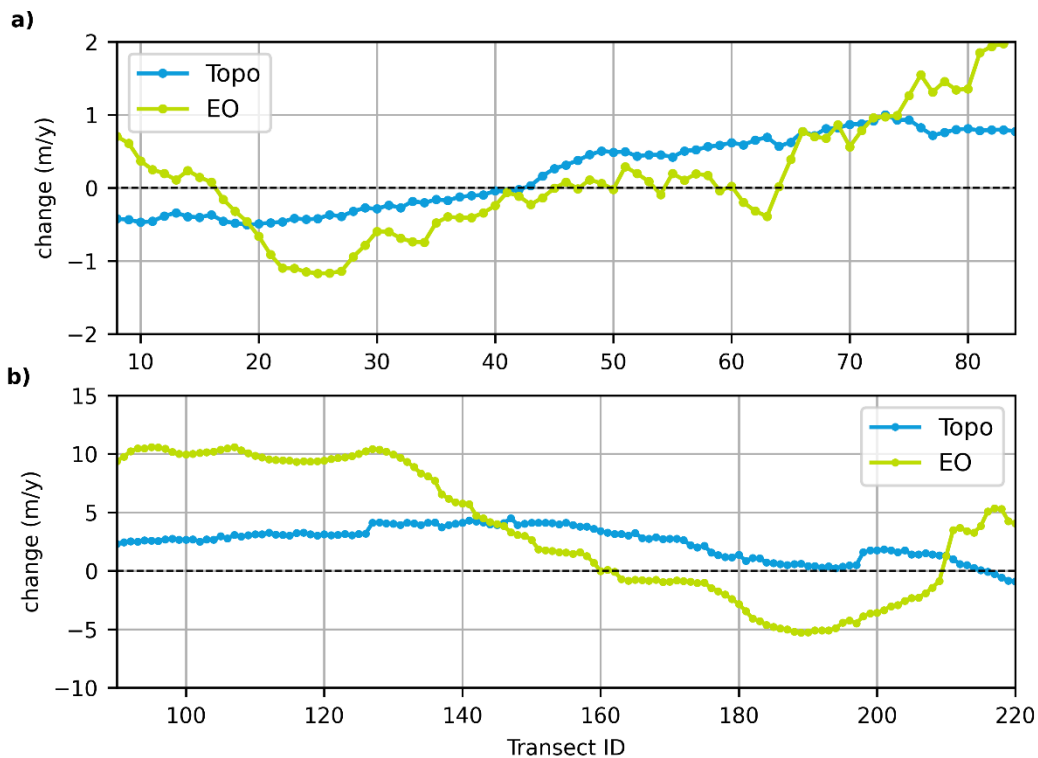


Figure 3. Shoreline annual rate of change derived from EO imagery and topography data for West Beach (a) and East Beach (b).

Key findings from the EO analysis are summarised below for both sites:

- **West Beach.** The rate of change from topography data is erosive (confined within -0.5 m/y) for the western side (transects 1-40) and accretive (peaking at 1 m/y) for the eastern side (transects with ID > 40). Generally, although the magnitudes between topography and EO differ, the trend from negative to positive change agrees for the middle section (IDs 20-60).
- **East Beach.** EO successfully captures the accretive behaviour occurring on the western side of East Beach. However, magnitudes of rate of change in shoreline position vary considerably from the topography. The eastern side of East Beach shows varying behaviour captured from EO, from accretion to erosion and again accretion moving towards the east. This is not aligned with the

topography data (although the eastern section, IDs 210-220 is known to be highly variable and dynamic).

Vegetation extraction

As the dunes are vegetated, vegetation species cover and extents can be used as an indicator of dune stability and therefore, potential resilience to forms of erosion. As well as extracting shoreline positions, EO imagery can be used to understand vegetation cover (density) change through time. As part of this study, a method for mapping the extent of vegetation cover using multi-spectral EO imagery from Sentinel-2 was developed (Figure 4).

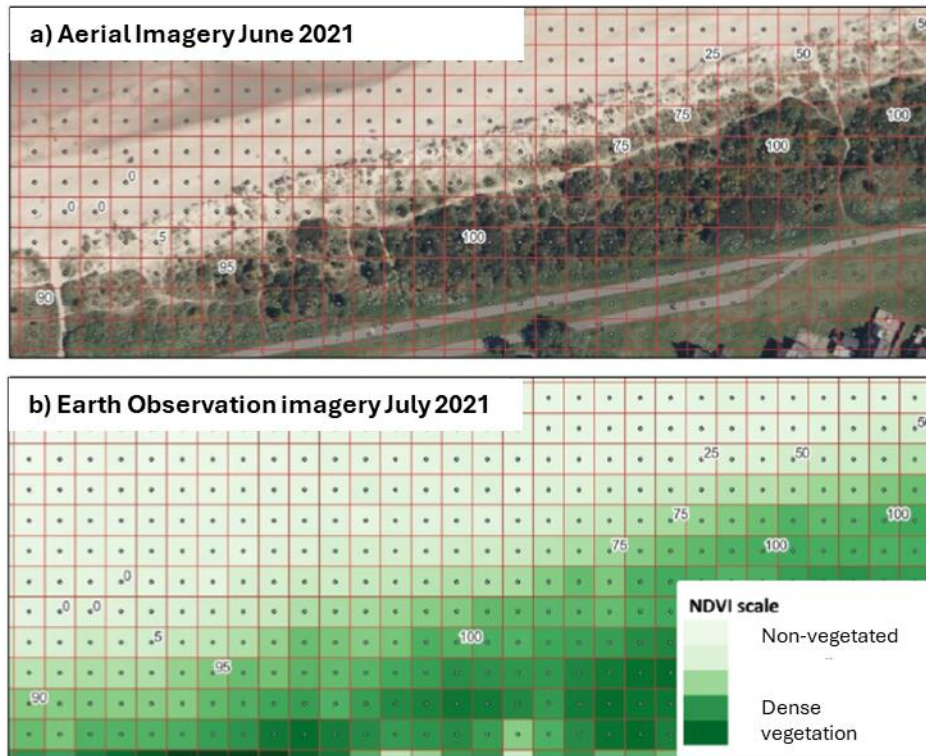


Figure 4. Correlation between ground vegetation cover estimates interpreted from aerial imagery (a) and Earth Observation (EO) derived NDVI (b) shaded light green to dark green from low to high NDVI respectively. Red lines indicate EO pixel grid, and numbered centre points show user-estimated percentage cover (%).

Mean annual vegetation cover change percentage was calculated across each transect by determining differences in annual average vegetation cover from year to year. Key findings from the analysis for vegetation cover change are summarised below for both sites:

- West Beach.** Annual average vegetation cover changes fluctuate around 0%, with variations ranging from vegetation loss (transects 6–48) to stability (transects 48–82) and back to vegetation loss (transects 82–89) moving west to east. The largest vegetation increase (+0.4%) occurred west of the groyne at Nairn Beach, while the largest decrease (-2.9%) was observed east of the groyne. Vegetation cover variability is greatest (ca. 40%) between 2018–2021, particularly in the west (transects 3–30), while the least variability (ca. 9%) is in the east (transects 78–89). Shoreline change also shows the highest variability in the west and the least variability in the east.
- East Beach.** Annual average vegetation cover change fluctuates near 0%, with stable vegetation coverage observed in the west (transects 90–129) and east (transects 168–220), while vegetation loss occurs centrally (transects 129–168). The largest vegetation increase (+0.9%) occurred at the far east, while the largest decrease (-2.0%) was in the central area. Vegetation cover variability peaked at approximately 25% between 2018–2019, with the greatest shoreline variability occurring centrally (transects 130–175). The least variability in vegetation cover (ca. 4%) and shoreline change is observed in the west (transects 90–126) and east (transects 180–207).

Ecological survey

A National Vegetation Classification (NVC) survey was undertaken in May 2023 to identify vegetation communities within the dune system. The survey consisted of a combination of a walkover across the frontage of the study area, handheld GPS to survey specific quadrats, and the use of field maps to define boundaries of consistent population of vegetation communities (Figure 5). A total of 16 vegetation communities were recorded during the survey. Three of these communities are present only in one specific location or have only a proportionally small level of coverage across the site and are therefore not considered a key habitat to site function. Therefore, the final total number of key habitats is 13, plus bare sand and artificial structures/ surfaces (Table 1 and Figure 5).

Table 1. NVC codes and descriptions of key vegetation/habitat types (see Figure 5 for extents).		
NVC Code	NVC (Sub)Community	Description and common names
MC8a	<i>Festuca rubra</i> - <i>Armeria maritima</i> maritime grassland, Typical sub-community	A salt-tolerant coastal grassland community dominated by a thick mat of Red Fescue grass . Mosses are sparse. Typically grows in sandy soils.
MC8d	<i>Festuca rubra</i> - <i>Armeria maritima</i> maritime grassland, <i>Holcus lanatus</i> sub-community	As above, with the addition of inland grasses, most notably Yorkshire-fog , and a higher frequency of plants including thistles and plantains .
OV23c	<i>Lolium perenne</i> - <i>Dactylis glomerata</i> community, <i>Plantago major</i> - <i>Trifolium repens</i> sub-community	Managed grassland of Perennial Rye-grass and Cock's-foot , typical of verges and playing fields. This sub-community supports common enriched grassland species including clovers and plantains .
OV24	<i>Urtica dioica</i> - <i>Galium aparine</i> community	Tall stand of vegetation dominated by Common Nettle and sprawling Cleavers . Indicative of high nutrient levels and disturbed habitats.
OV25b	<i>Urtica dioica</i> - <i>Cirsium arvense</i> community, <i>Rumex obtusifolius</i> - <i>Artemisia vulgaris</i> sub-community	Less dense stand of Common Nettle often with thistles present. In this instance, the stand was dominated by Mugwort . Indicative of high nutrient levels and disturbed habitats.
OV27	<i>Epilobium angustifolium</i> community	Tall stand of Rosebay Willowherb , almost to the exclusion of any other species. Highly typical of heavily disturbed habitats.
SD6c	<i>Ammophila arenaria</i> mobile dune, <i>Leymus arenarius</i> sub-community	Typical of younger foredunes on beachfronts, this habitat is dominated by Marram Grass . This sub-community indicates a notable amount of Lyme-grass present amongst the Marram Grass.
SD6d	<i>Ammophila arenaria</i> mobile dune, Typical sub-community	Typical of younger foredunes on beachfronts, this habitat is dominated by Marram Grass .
SD7a	<i>Ammophila arenaria</i> - <i>Festuca rubra</i> semi-fixed dune, Typical sub-community	A transition habitat between Marram Grass foredunes and inland grass species dominated communities. This habitat is formed of a mix of Marram Grass and Red Fescue and indicates a transition to more stable dune system.
SD8b	<i>Festuca rubra</i> - <i>Galium verum</i> fixed dune grassland, <i>Luzula campestris</i> sub-community	Dune grassland that has transitioned from Marram Grass foredunes to more stable inland grass species, most notably Red Fescue . This sub-community frequently supports Field Wood-rush and Sand Sedge .
SD8d	<i>Festuca rubra</i> - <i>Galium verum</i> fixed dune grassland, <i>Bellis perennis</i> - <i>Ranunculus acris</i> sub-community	Dune grassland that has transitioned from Marram Grass foredunes to more stable inland grass species, most notably Red Fescue . This sub-community frequently supports additional species including Daisy and Buttercup .
SD10a	<i>Carex arenaria</i> dune, <i>Festuca rubra</i> sub-community	Grey dune grassland formed of abundant Sand Sedge with some Red Fescue present. Salt-tolerant plants like Silverweed and Sea Mayweed can also be common. These grasslands develop on stable dunes with sandy substrate.
W23a	<i>Ulex europaeus</i> - <i>Rubus fruticosus</i> scrub, <i>Anthoxanthum odoratum</i> sub-community	Mature scrub community, typically made up of Gorse and Bramble but dominated by Broom along the dunes of Nairn. This is a recognized variant of this sub-community. These habitats indicate that the dune system has been stable for a relatively long period.
Bare sand	N/A	Open sand substrate with no vegetation cover
Structures	N/A	Any artificial structures

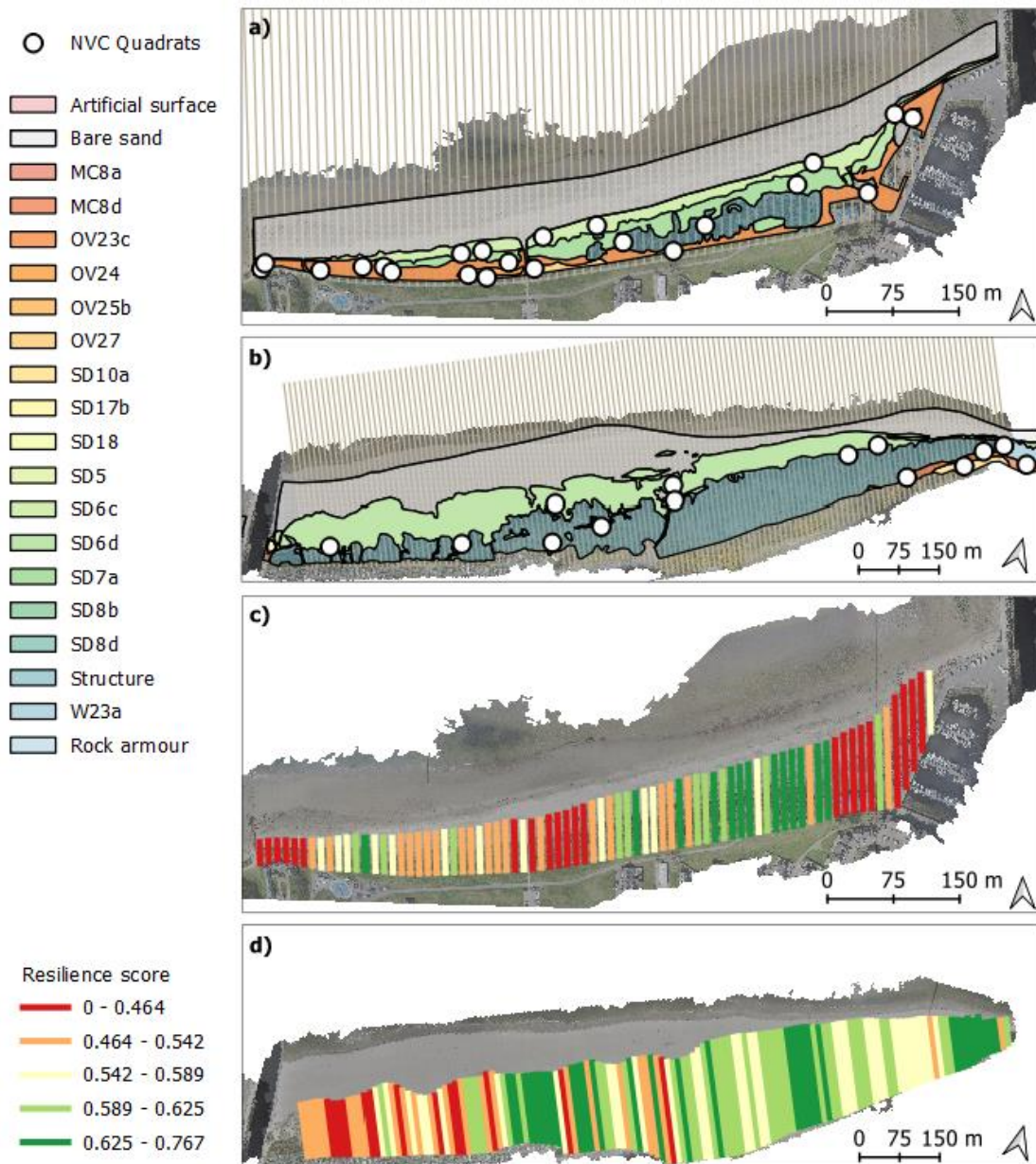


Figure 5. Location and extent of the identified vegetation communities (NVC codes and description in Table 1) for West Beach (a) and East Beach (b). Cross-shore transects color coded based on the present-day vegetation resilience for West Beach (c) and East Beach (d).

Resilience scores were assigned to individual species present on the Nairn beaches based on ecological niche and function (Laporte-Fauret et al., 2020). The resilience scores have been applied per transect to indicate longshore changes in the resilience of dune vegetation (Figure 5 c and d). The scores are presented as a total value between 0.0 and 1.0. Low scores (red/orange lines) correspond to a lower level of resilience whilst high scores (green) indicate higher resilience (Figure 5 c and d).

The transects were drawn from seaward toe of the dune to the back of the dunes (no beach), so there are only few extensive areas of bare sand. Therefore, extremes of high and low scores are not frequent outcomes of this calculation. The lowest dune vegetation resilience score for a transect was 0.052 and the highest was 0.767. The lowest score was considerably lower relative to the next lowest score (0.239). This is because the lowest scoring transect is over an area where people had trodden a path through the dune vegetation, creating a narrow strip of bare sand. These maps show that vegetation resilience correlates strongly with an established scrub community, seen as a later successional stage of dune

vegetation communities and generally associated with a higher level of dune stability (Sigren et al., 2014). Although Marram Grass is recognised as contributing to dune stability, extensive areas of younger dune with Marram Grass are still very susceptible to erosion by storm events and coverage through wind blow. These maps also clearly pick out areas more heavily impacted by human activity, as frequently trodden areas through the dunes create areas of bare sand deeper in the dune systems, and these reduce the resilience score of the transects overlaying these de-vegetated areas.

METHODOLOGY

Quantification And Classification of *CRI*

The Coastal Resilience Index (*CRI*) is indented as a metric that incorporates information from multiple sources and informs the resilience of the dune and beach system to be able to withstand and recover from coastal hazards. The *CRI* is proposed to be updated when new data is available or to test the progress and success of potential adaptation measures. At this stage *CRI* is developed in a form specifically for the dune systems at Nairn. Sites with a different type of coastlines will have to be defined in a different way. Although the principles should remain.

For the sandy dune-beach system in Nairn, six inputs were identified for the *CRI* calculation including baseline conditions of dune-beach morphology and vegetation, resilience to future sea level rise, potential storm events and potential vegetation change. For clarity and ease of interpretation the *CRI* was designed to range from 0 to 100%, where 0% is worse resilience and 100% is highest resilience. Each input was categorised into five classes, assigning values ranging from 1 (minimum resilience) to 5 (maximum resilience). As a result, *CRI* was calculated as:

$$CRI = 100 \frac{(D_{S-A} + CC_{storm} + CC_{SLR} + Veg_0 + Veg_{0-cover} + Veg_{h-change}) - C_1}{C_2} \quad (1)$$

where D_{S-A} is the distance between present day shoreline and asset line, CC_{storm} is the storm induced coastal change, CC_{SLR} is the Sea Level Rise (SLR) induced coastal change, Veg_0 is the present day vegetation species resilience, $Veg_{0-cover}$ is the present day dune vegetation cover, $Veg_{h-change}$ is the vegetation dune system historic vegetation cover change, C_1 and C_2 are constants that enable *CRI* to be expressed between 0 and 100%. They are dependent on the number of inputs and the range of values to be assigned to each input. In this case $C_1 = 6$ and $C_2 = 24$.

Values of the *CRI* were calculated for each cross-sectional transect for spatial comparisons (the system was schematised into 10 m spacing cross-shore transect, Figure 2, labelled 8-84 for West Beach and 90-220 for East Beach).

CRI testing approach

The *CRI* was calculated for Nairn using different data sources and for different epochs to investigate its suitability and sensitivity to varying inputs. Based on the available data and analysis conducted in Nairn, *CRI* was calculated for the following:

- *CRI* 2023 (present-day) – Topo
Represents the dune resilience at present day. *CRI* was calculated using topographic data (Topo) as a source of any morphological feature for both present and historical input.
- *CRI* 2011 (historical) – Topo
Represents the dune resilience in 2011. *CRI* was calculated using data available up to 2011, chosen due to the Scottish Government Lidar availability. Topography data was used as a source of any morphological feature.
- *CRI* 2023 – EO
2023 *CRI* was calculated using Earth Observation data from publicly available satellite (EO) as a source of any morphological feature for both present and historical input.
- *CRI* 2023 – All
2023 *CRI* was calculated using a combination of Topo and EO as a source of any morphological feature for both present and historical input.

Calculation of the four *CRI* enables comparisons in terms of:

- Temporal
Comparisons of *CRI* calculated at different epochs is used to validate whether *CRI* has potential as a functional and effective tool for monitoring future dune resilience at Nairn.
- Morphological data sources

COASTAL ENGINEERING 2024

Comparison of *CRI* from Topo, EO and All sources helps understand the data requirement, limitations, and any future application of the *CRI*.

***CRI* inputs**

As each *CRI* input was categorised between values 1 (least resilience) and 5 (most resilience), a specific categorisation was selected for each input to capture the range of results observed in Nairn but also potential out of range data to allocate future change. The categories were defined to include extreme conditions but to be reflective of incremental change. For this reason, they have been weighted where needed. Thus, if an input is closer to the worse end of the range (i.e. the dune volume loss due to a storm is close or equal to the dune capacity) there are one or two categories to express it. On the contrary, the most resilience end of the category spectrum may include a larger range of inputs. This way different critical conditions can be captured and differentiated.

Assets

The D_{S-A} input represents the distances between an asset position and the shoreline. Asset position for Nairn this is defined as edge of the coastal path which closely aligns to the rear toe of the dune system (Figure 2 a and b). The shoreline position was identified with the MHWS contour (2.2 mOD) for topographic data and as tidally corrected sea-water intersection from satellite imagery.

Resilience associated with this input spans from Low to Highest for West Beach, with it generally increasing towards the east. East Beach scores mostly Highest. Usage of EO data as a sole source results in either the same resilience class or, at maximum, provides one class of difference. This indicates that although publicly available EO data may be less suited for feature detection depending on the results are used (mainly related to the 10 m resolution of the imagery), they seem more reliable when processed and used to inform on resilience that in this case is expressed via bands. Therefore, the uncertainty in the data result in plus or minus a category.

Storm induced Coastal Change

The CC_{storm} input represents the percentage of dune volume loss that the system may experience due to an individual extreme storm event, relative to the existing dune volume. Here, the loss was calculated for the 1 in 200-year return period storm event, to reflect what is commonly set as a condition around flood risk management planning using an analytical solution of runup-dune volume balance equation (Larson et al., 2004).

Inputs needed for the CC_{storm} calculation include the dune toe elevation and dune volume. Resilience associated with this input is confined between Low and Highest for both epochs. However, only west side of West Beach shows Low and Medium resilience. The rest of the system scores either Highest or High. Resilience decreased in 2023 for west side of West Beach while the east side shows an increase of resilience. Overall, no big changes are observed for East Beach.

Sea level rise induced Coastal Change

The CC_{SLR} input represents the potential long-term coastal change. This is a function of historic behaviour and response to future sea level rise. It is expressed via projecting the shoreline into a future epoch and reference it to the asset line for context. Here, the projection was made to 2050 using a probabilistic approach, accounting for variability in input data using a modified version of the Bruun rule (Vousdoukas et al., 2020) framed into a probabilistic approach to mitigate the uncertainties and variability of the inputs. Specifically, a lower, mean, and upper limit was retained. Inputs needed for the CC_{SLR} calculation include asset position, shoreline location position, historic shoreline rate of change.

All sources available were used to determine the rate of change. These are topography (Topo), Earth Observations from publicly available dataset (EO) and a mix of the two (All). Resilience associated with this input is confined between Lowest and Highest depending on the limit (upper, mean, lower), source of data and epoch. Based on Topo-based results, while West Beach is a mix of the Lowest-Highest range of resilience, the majority of East Beach is scored as Highest. The exception at East Beach is at the very east, where resilience drops. In contrast, the Lowest, Low and Medium resilience on West Beach from Topo data is not captured by the upper and lower limits of EO data. This is due to the variability affecting EO-based shorelines and historic rate of change which results in a different output, that in some cases can generate an opposing measure of resilience. The mean limit is therefore a safer choice as it resembles

more closely the outputs from the Topo data, considered more accurate and used as a comparison to validate EO sourced data.

Vegetation baseline resilience

The *Veg_{0-cover}* input represents the present-day vegetation cover across the dune system. Vegetation cover for the last five years was estimated through EO data. Inputs are Vegetation imagery/maps. Resilience ranges between Low and High resilience.

Vegetation historic

The *Veg_{h-change}* input represents the historic rate of change in vegetation cover across the dune system. The annual rate of vegetation change can be calculated by subtracting the percentage cover of the current year from previous year percentage cover.

RESULTS

CRI 2023 - Baseline

The categorised *CRI* inputs for 2023 (using the mean *CC_{SLR}* scenario from Topo data sources) and *CRI* baseline are shown in Figure 6a and 6b respectively. In 2023, West Beach has lower resilience than East Beach, with resilience increasing from west to east. The area west of the groyne has the lowest resilience, transitioning to low resilience on the west side, medium resilience in the central section, and high resilience toward the east. However, no area on West Beach achieves the highest resilience rating.

East Beach is more resilient overall, predominantly scoring as highly resilient. There are no areas with the lowest or low resilience. Medium resilience is limited to the far eastern section (transect 220), while high resilience spans most of the beach. The highest resilience is found in a small central section (transects 182–186). From this, the *CRI* is shown to provide a good reflection of the conditions observed from the baseline analysis and the understanding of the current conditions of both dune and beach systems. Lower scores of resilience are associated to parts of the dune system that are narrower in width and have a more landward shoreline. East Beach, having a wider beach and a wider dune system, shows high scores of resilience across the frontage.

Temporal

CRI results for West Beach and East Beach at Nairn show some changes between 2011 and 2023 (Figure 6b). At West Beach, *CRI* has decreased in the western sections, with resilience dropping from Low to Lowest between transects 8–11 (west of the groyne), from Medium to Low between transects 11–22, and from High to Medium between transects 22–48. Conversely, *CRI* has improved toward the eastern sections, increasing from Medium to High resilience between transects 51–77. At East Beach, *CRI* has decreased in the eastern and central sections, with resilience falling from Highest to High between transects 166–200. In contrast, *CRI* has slightly increased in the western sections, although this improvement has not resulted in a change in the resilience category.

Change in resilience from 2011 to 2023 aligns with the decadal historic change assessment conducted. Resilience has increased where accretion was observed and has decreased where erosion was noted (West Beach). No changes resulted for the East Beach in terms of resilience scores.

Topographic sources

Generally, inputs sourced from EO data result in a higher *CRI* result compared to Topo (Figure 6c). Inputs sourced from Topo data result in minimal variability in *CRI* results. *CRI* results are variable across the whole frontage at West Beach. The greatest variability in *CRI* results corresponds the high variability in *CC_{SLR}* input at West Beach. Inputs sourced from EO data result in the greatest variability (ca. 20%) in *CRI* results, which results in a lower or upper *CRI* class at a maximum. *CRI* results are variable only towards the east of East Beach. The greatest variability in *CRI* results corresponds the high variability in *CC_{SLR}* input at the east of East Beach. Inputs sources from EO data result in the greatest variability (ca. 20%) in *CRI* results.

Differences in resilience between Topo and EO results are primarily due to the baseline shoreline location and how close this is to the asset line (categories are weighted towards the shore for distances). The large variability of resilience observed from EO data when comparing lower, mean, and upper limits is related to large variations in shoreline position and thus the historic rate of change. This is not observed for the Topo data.

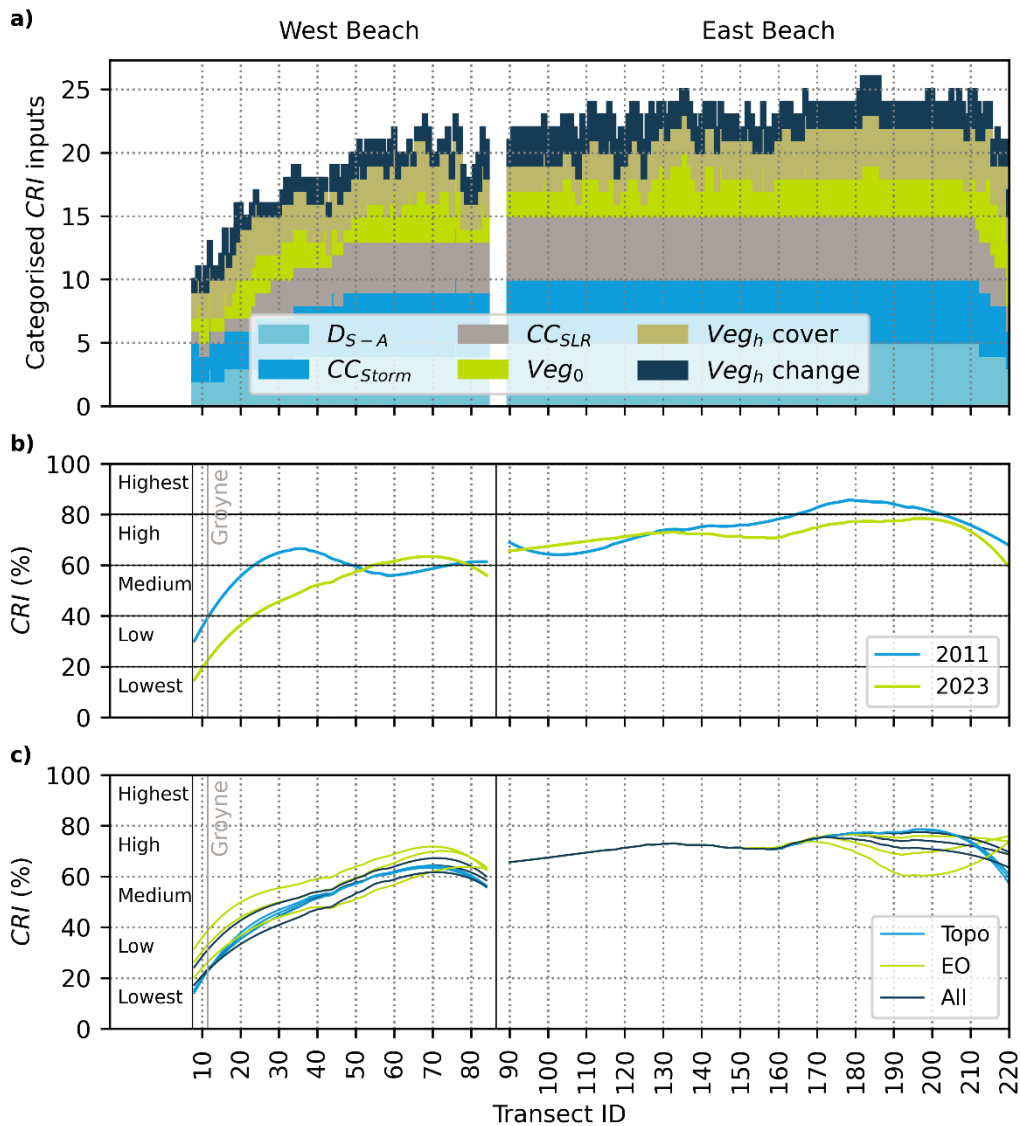


Figure 6. Coastal resilience index inputs example and results. a) Categorised 2023 CRI inputs using Topo sourced data. b) Temporal comparison between 2011 and 2023 CRI derived using the Topo sourced data. c) 2023 CRI derived using Topo, EO and combined (All) morphological sources.

CONCLUSIONS AND DISCUSSION

The CRI, tested at Nairn as proof of concept, shows promising results as a metric to quantify dune resilience in support of adaptation planning. The findings show that the CRI exhibits a decrease or increase in resilience where expected based on the observed changes. There is therefore potential to use CRI as an indicator to monitor resilience of the dune systems into the future.

Although the EO data analysis highlighted large uncertainties in the features (coastline position), this is not reflected in the EO based CRI results. The CRI from EO data do not provide results that contrast with what is expected (calculated from more accurate topographic survey). Thus, the use of EO data is encouraging for a potential implementation of resilience calculations strategically, at regional or national scales, at low cost.

Ideally a tiered approach for monitoring would be adopted with different levels of detail to suit resource and financial constraints. Testing whether EO data, either alone or as a supplement, can be used to measure dune resilience is important as it could prove to be a valuable and freely available source. EO imagery has gained notable attention over recent years in coastal monitoring, mainly for

shoreline detection and more recently also for vegetation edge detection. They provide a global free source of data which is valuable given high frequency, easy access and availability. *EO* imagery can be fundamental for remote location or large-scale applications, at least for a strategic-level assessment.

Further developments are planned to move towards a “near-real-time” monitoring system that continuously acquires and integrates data, providing an up-to-date measure of resilience. Alongside, additional work to broaden the *CRI* towards a “system-of-systems” indicator of resilience will be explored, to be inclusive of different coastal typologies, habitats, built structures and risk receptors.

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