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South Atlantic Natural Capital Project: Soil erosion model for Tristan da Cunha

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Review table

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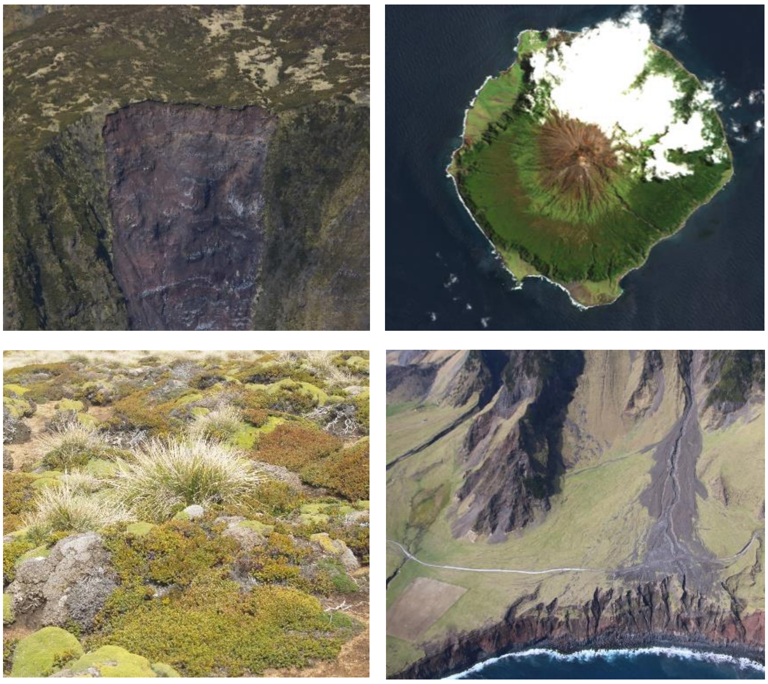
Soil Erosion Model for Tristan da Cunha

Final Report



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Executive Summary

The Tristan da Cunha archipelago is one of the most remote in the world, being separated from the nearest mainland by nearly 2,800 km of open ocean. Tristan is the only inhabited island in the archipelago, and is home to around 250 permanent inhabitants who rely on subsistence agriculture, commercial fishing, and food imports from the UK and South Africa.

Over the last few years, Tristan has suffered some major events of soil erosion, known as slumps. These slumps have destroyed a valuable area of the pasture land upon which the inhabitants rely for their subsistence agriculture. The Settlement Plain, which represents just 5.2% of the island area (Scott, 2017), is where all food crops are grown on the island (Glass *et.al*. 2005). One possible cause of these slumps is that vegetation at the top of the adjacent cliffs is becoming saturated and the water is seeping in between the soil and the unconsolidated layers of volcanic material, pooling until it reaches a sheer zone, causing the soil to slump.

This project used SCIMAP soil erosion risk model to identify a number of areas with potentially higher soil erosion risk. These were generally located around the gulches and on the steep cliffs, with particular risk where these interface with The Base. A time-series analysis of remotely sensed Earth observation data (satellite imagery) showed that the erosion risk is changing over time.

These erosion risk zones and models need to be verified on-island with a full geological survey to confirm the main risk zones particularly on the settlement plain and where the water source for the settlement is located. Mitigation measures need to be established by an on-island survey and remote sensing techniques need to be re-run on an annual or biannual basis to further establish and verify risk areas.

Introduction

Background

The Tristan da Cunha archipelago, are volcanic in origin and consist of the ‘northern’ cluster of Tristan, Nightingale and Inaccessible, and Gough Island 410 km to the southeast of Tristan. They are some of the most remote in the world, being separated from the nearest mainland by nearly 2,800 km of open ocean, and form part of the British Overseas Territory of Saint Helena, Ascension and Tristan da Cunha. Tristan is the only inhabited island and covers an area of approximately 98 km^2. It is home to around 250 permanent inhabitants (**Figure 1**) who rely on subsistence agriculture, commercial fishing, and food imports from the UK and South Africa.

Figure 1: View of Tristan da Cunha from satellite, with the main settlement plain in the northwest clearly visible.

Over the last few years, Tristan has suffered some major events of soil erosion. These events have destroyed a significant area of the pasture land upon which the inhabitants rely, and are a potential threat to water security and safety of the settlement. The mechanism for this erosion is not clear, however it is thought that that vegetation at the top of the cliffs (the edge of The Base) is becoming saturated and the water is seeping in between the soil and the unconsolidated layers of volcanic material, pooling until it reaches a sheer zone, causing the soil to slump (**Figure 2** & **Figure 3**)[1]. Factors effecting the distribution and severity of these events include the geology, biophysical properties, land use, ecology and climate found on the island.

[1] Following discussions with Tristanians, BGS and RSPB.

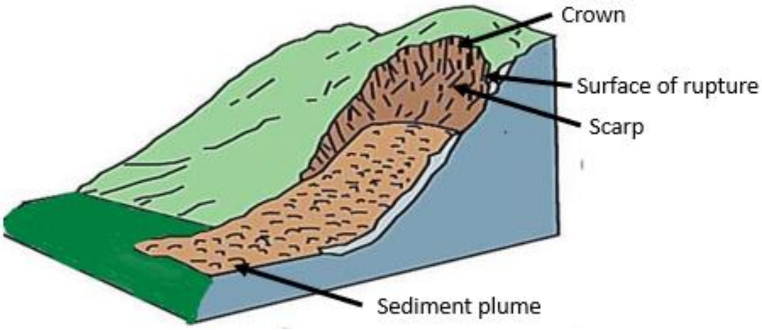

Figure 2: Diagrammatic representation of slump. These types of landslides start at the interface between the steeper slopes and the shallower plateau tops. On Tristan da Cunha this represents the cliffs and The Base.

Figure 3: Recent slump on Tristan da Cunha (imagery supplied by Tristan da Cunha Government).

Geology of Tristan da Cunha

The island is a large oceanic stratovolcano which is formed of alternating layers of volcanic ash and lava flows. If measured from the sea floor, the volcano is 5,500 m high, with only the top 40% rising above sea level (Creswell 2016). The volcano is active and lies on the Walvis Ridge. It last erupted in 1961. It is classed as an aseismic feature with a very low level of earthquake activity. The island formed where a tectonic plate moved over a stationary upwelling of magma and burned a hole in the overlying crust. It has a distinct morphology probably due to different volcanic products:

- the central cone is made of pyroclastic material, subject to quick erosion resulting in the formation of scree. This area is a steady 30° slope to the summit of Queen Mary's Peak at 2,062 m, with a central heart-shaped crater lake near the Peak crater (often snow covered). There are steep erosion gullies radiating downwards on all sides.
- The slopes of the basal plain are predominantly made of lava flows.

- There are numerous cinder cones across The Base with occasional crater lakes.
- The main cliffs are made up of alternating layers of lava flows and pyroclastic material, locally interspersed with parasitic centres.
- The Settlement Plain, which represents just 5.2% of the island area (Scott, 2017), was formed by a massive collapse of 'The Base' which was then infilled by lava flows (Hicks et al 2012). The most recent volcanic eruption of 1961 was on the north of this plain, just east of the settlement itself. This destroyed the fish factory and necessitated evacuation of the island, but fortunately the lava flows stopped just short of the settlement.
- In the marine environment the shallow, shelf waters are generally no more than 2 km wide. Below 250 m, the slope becomes much steeper down to 1000 m (Creswell 2018).

An extensive study by Hicks et al (2012) found that eruptions were much more frequent and recent than previously suspected. These relatively frequent eruptions can occur from a wide variety of vent locations across a broad range of compositions, making it impossible to predict, with any accuracy, when the next eruption might occur. Islanders have recently upgraded their emergency action plan based upon more recent studies.

Around most of the island, coastal erosion has resulted in steep cliffs arising straight from the sea. The more detailed profile of the island above water is therefore of a girdle of extremely steep and often inaccessible cliffs rising to around 500 m, with a less steep area above this (which islanders refer to as The Base).

Biophysical description of Tristan da Cunha

Topography

Topographically, Tristan is roughly divided into four key areas (**Figure 5**);

- **Peak**: a classic volcanic cone with a central crater. The upper slopes of the peak are predominantly bare of vegetation and mainly comprise loose volcanic ash or cinders.
- **Base**: the plateau area that slopes gently away from the central Peak towards the sheer cliffs which encircle Tristan. It is intersected by steep ravines (known as gulches) that radiate from the central peak down to the coast, and volcanic features including three explosion craters now filled with water and known as 'The Ponds'.
- **Cliffs**: an almost continuous ring of cliffs encircle the island reaching up to 300 m in height. These cliffs provide nesting spots for seabirds.
- **Lowland plains**: in several places, between the cliffs and the sea, the lowland plains (or coastal strips) can be found. The three most important of these are:
    - Settlement Plain in the north west; the most extensive plain on Tristan that lies on the north west of the island approximately 4 km in length and up to 1.5 km wide (less than 5 km^2) This area forms the whole extent of the human habitation of the island.

- Sandy Point at the east.
- Stony Hill and Cave Point in the south.

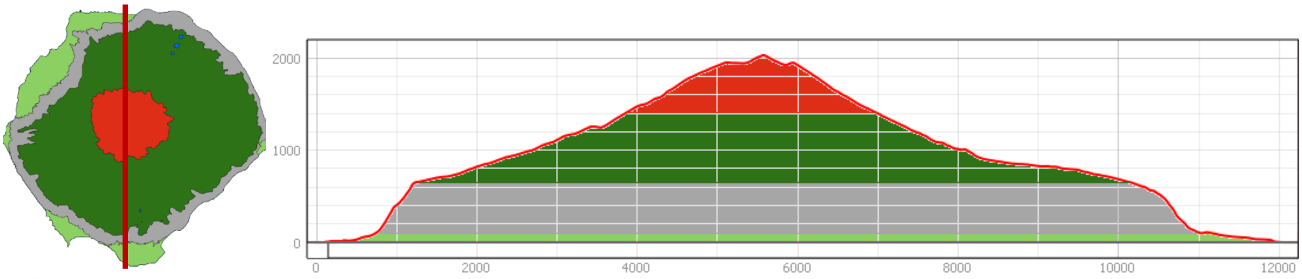

Figure 4: Profile of Tristan da Cunha as delineated by the red line.

Land use on Tristan da Cunha

Very little land is available for agriculture, the majority of which is raising cattle and sheep and growing potatoes, along with some vegetables and fruit. These are grazed and grown on the far end of Settlement Plain in what is known locally as 'Patches', although sheep are also grazed on The Base.

Terrestrial ecology

The islands have never been linked to a continental land mass, this isolation has resulted in a large number of endemic species evolving in both the terrestrial and marine environment (Glass *et.al*. 2005). This gives the island a great importance in terms of their natural history.

The vegetation of Tristan da Cunha is zoned by the geology / topography and altitude:

- The lower areas along the Settlement Plain are now pasture land which are dominated by non-native grasses and occasional small arable areas where potatoes are grown. On some of the other low-lying plains the native vegetation persists which is dominated by tussock grass *Spartina arundinacea*, or thickets of island tree *Phylica arborea* growing amongst a mass of ferns.
- The Base above Sandy Point and in the southern half of the island is dominated by fern bush.
- Between 600 and 750 m, the dwarf tree fern *Blechnum palmiforme* is dominant
- From 750–900 m, the tree ferns are replaced by low herbaceous vegetation.
- Above this zone extensive mats of the crowberry *Empetrum rubrum* and the moss *Rhacomitrium lanuginosum* occur.
- Above 1,500 m the vegetation becomes very sparse.

Many non-native plants have become established on Tristan. Some are considered invasive as they have become pests in the agriculture areas and gardens, others have become dominant in several natural habitats. For example, New Zealand Flax *Phormium tenax* was introduced to Tristan as a thatching material and is still used as windbreaks. However, it has now established itself in other areas and would be hard to eradicate (Glass *et.al*. 2005).

Climate of Tristan da Cunha

The Subtropical Convergence, the boundary between the warm Atlantic gyre and cold water to the south, lies approximately over the Tristan top islands, with residual currents from west and northwest. The climate of the islands is therefore described as cool temperate. Temperatures are relatively stable due to the influence of the ocean. The average temperature at sea level is 15ºC. Frost is rare on the plain however, snow is common on the peak especially in December. Rain falls on average 250 days a year with slightly more in winter (60%) at the Settlement where average rainfall is 1,615 mm/year (Scott 2017). Rainfall is mostly linked to the passage of cold fronts; these can bring 180 mm of rain in a few hours and it is this factor that contributes to the risk of erosion events on the island. Gales and the residual swell from gales are common restricting access to the sea in both summer and winter. Climate change could alter physical factors including seawater temperatures, the speed and direction of currents around the island and the rainfall amount and pattern.

Aims

The aim of this project was to provide an estimate of soil erosion risk across the island, and to identify areas most susceptible to slumping.

Project Approach

Task 1: Build time series of the data

Using freely available data (Landsat and Sentinel-2), a time-series of images were obtained and processed. This enabled an investigation into vegetation changes / landform relationships at the top of the island, establishing a picture of the erosion mechanisms and risks.

A number of historical images were captured by the Landsat satellites. However, a failure in the Landsat 7 sensor resulted in no usable imagery captured after 31/05/2003 accounting for the gap in the time series (Figure 5). In addition, optical imagery is susceptible to cloud, and given the location and topography of Tristan, cloud is often present in satellite imagery. Fortunately, the area of interest (AOI) was the north western corner of the island, therefore a number of cloud-free images were available.

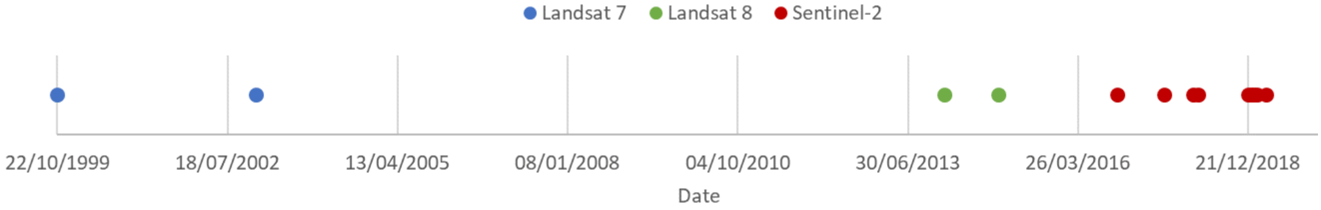

Figure 5: Illustration of the time series of imagery acquired for mapping the extent of the current habitats.

Note, the revisit frequency of Sentinel-2 provides a means to continuously map and monitor the distribution and extent of habitats on Tristan going forwards. This means that the habitat map generated for this project can be regarded as a basis for a ‘living map’, which can be improved upon and updated as more imagery and field data become available.

Task 2: Upgrade habitat map

The interaction between vegetation, soil, geology and landform is the primary driving force behind soil erosion risk. It was therefore necessary to update the habitat map of the island to provide the best data possible to feed into the erosion model. This habitat map has not been validated with dedicated fieldwork on island, however, once this has been done it can stand as a new baseline against which to record change, and feed into a wide range of other projects.

The habitat map was updated using remote sensing methods. This provides an up-to-date and rapid assessment of the type of land cover in an area. The benefits of remote sensing include:

- **Coverage**: Remotely sensed Earth Observation (EO) imagery captures large areas. This is particularly useful for capturing a temporally consistent image of the whole of Tristan.
- **Access**: EO is particularly useful for observing and monitoring areas which are dangerous to access on foot such as those found on Tristan (e.g. The Base).
- **Repeatability**: EO imagery can be captured regularly to identify and monitor changes in the environment. Given the suspected increase in landslide activity on Tristan, this means that past and future landslides can be identified and monitored in order to understand the cause.

Remote sensing cannot be used on its own to create habitat maps. Ideally, ground data are collected in parallel to help train and validate the habitat map. Unfortunately, this was not possible because of the remote nature of Tristan and its lack of accessibility. Therefore, in order to update the existing habitat map, previous habitat studies were consulted to provide context.

Habitats found on Tristan

Tristan has nine broad habitat types, each defined by a dominant vegetation type, which are determined by altitude, aspect and topography. However, the majority of the habitats are mosaics of the plant species, where generally one species will be more common than the others. The nine habitat types are described below (Glass *et.al*. 2005).

1. **Lowland grassland**: The lowland plains are dominated by alien grasses which are grazed by cattle and sheep. These grass species are found in patches across The Base and up towards The Peak.
2. ***Blechnum penna-marina* heath/sward**: The heath is dominated by a low-lying fern, which thrives on the steepest of slopes. It is most common on the sea cliffs and the sides of gulches that intersect The Base.
3. ***Blechnum palmiforme* heath/scrub**: This habitat is dominated by small tree ferns. It occurs at intermediate altitudes, from the upper levels of the sea cliffs to the steeper gradients on The Base where it is replaced by grasses and mosses. The size of the ferns varies according to age and exposure; in sheltered areas they will grow to about a metre in height whereas those on exposed ridges are much reduced in size.
4. ***Phylica* woodland**: *Phylica* trees dominate this habitat. They are found at similar altitudes to the tree ferns, and are often found growing together. They tend to thrive in slightly

sheltered situations, and are commonly found at the bottom of gulches and throughout the side of the island sheltered from the prevailing westerlies, where they form an almost continuous cover. In unusual circumstances *Phylica* will grow to a considerable size (up to ~10 m), but are usually no more than 2 or 3 m in height. In exposed positions they will adopt a recumbent habit, growing small creeping branches that rarely extend more than 30 cm above the ground.

5. ***Empetrum rubrum* heath**: This procumbent plant dominates some areas on The Base and is also found at low altitudes, particularly at the south of the island. It produces large numbers of berries which are collected by Islanders.
6. **Wet heath and bog**: A small number of places are permanently waterlogged and consequently support a different flora, dominated by mosses. The area known as Soggy Plain is the largest occurrence of this habitat type.
7. **Upland grassland**: The main species occurring here is *Rumex acetosella*, locally known as 'sour-grass'. It is particularly abundant in the higher-mid altitudes, between the bogfern/*Phylica* habitats and the *Rhacomitrium* moss habitat, which is common higher on the mountain. While some areas will be dominated by *Rumex* plants, it is usual to find introduced farm grasses mixed in with, and at times completely replacing it.
8. ***Rhacomitrium* moss/ *Rhacomitrium-Empetrum* heath**: Large areas of the higher reaches of the mountain are covered with this pale green moss which is able to colonise, and appears to stabilise, some of the cinder slopes. It also occurs in small patches on rock outcrops at these high altitudes and has been found at the highest point of the peak. Its habit of colonising loose substrates means that it is easily dislodged by walkers and sheep; the few human visitors to this altitude tend to follow fixed routes and are therefore unlikely to create any significant impact at the present rate of usage but the impact of sheep at higher altitudes is noticeable.
9. **Cinders**: The majority of the Peak is dominated by a cinder cone; a steep conical hill of loose pyroclastic debris. As such, the area is dominated by highly mobile scree slopes sparsely colonised by hardy lichens and mosses adapted to the extreme climatic conditions experienced at these altitudes.

In addition to the nine broad habitats outlined above, there are additional areas of non-native grassland and woodland on the Settlement Plain. There is also a plantation of pine and eucalyptus trees on the eastern side of the island close to Sandy Point.

A 2018 habitat map was generated predominantly using a Sentinel-2 image captured on 03/03/2018. Additional Sentinel-2 images captured on 01/02/2018 and 18/12/2018 were used to analyse the areas obscured by cloud in the 03/03/2018 image. A pre-existing simple habitat map, produced as part of the Darwin Initiative project 'Empowering the people of Tristan da Cunha to implement the CBD' (Appendix 1), was used to guide the classification since ground data were not available. Given the remote nature of Tristan, accompanying fieldwork was also not possible.

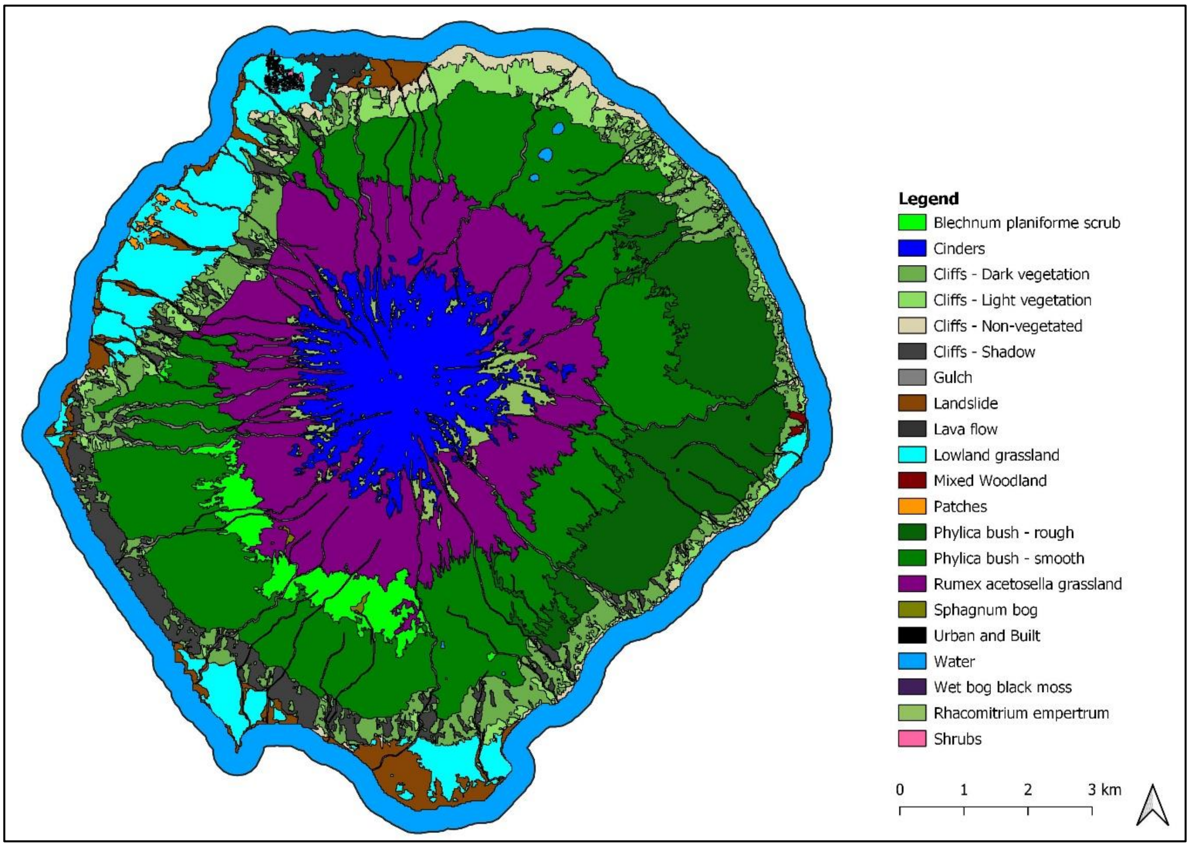

Figure 6: Updated habitat map of Tristan de Cunha (2018).

The imagery was segmented within eCognition (a software application) and an ecological rule base was then created. Building the rule base involved understanding both the ecology of the habitats, their situation in the landscape, and the manifestation of the different phenotypic variation of the habitats in the imagery. This fusion of disciplines allows information to be extracted from multi-spectral (Sentinel-2) and radar (Sentinel-1) imagery to create a classification.

Topographic attributes were generated based on a high-resolution digital terrain model (WorldDEM) including aspect, slope and elevation. While this assisted with the classification of certain habitats, the nature of the topography of Tristan also created some issues:

- With optical imagery, there are areas in shadow, which resulted in some habitat attribution being uncertain.
- With radar imagery, steep topography distorts the information that the satellite 'sees'.

Updated habitat map

A pre-slump habitat map was generated utilising imagery acquired in 2016. This allowed for a pre and post-slump comparison of vegetation between 2016 and 2018 (Figure 6) and assess the erosion risk before and after the 2017 slump (Figure 7).

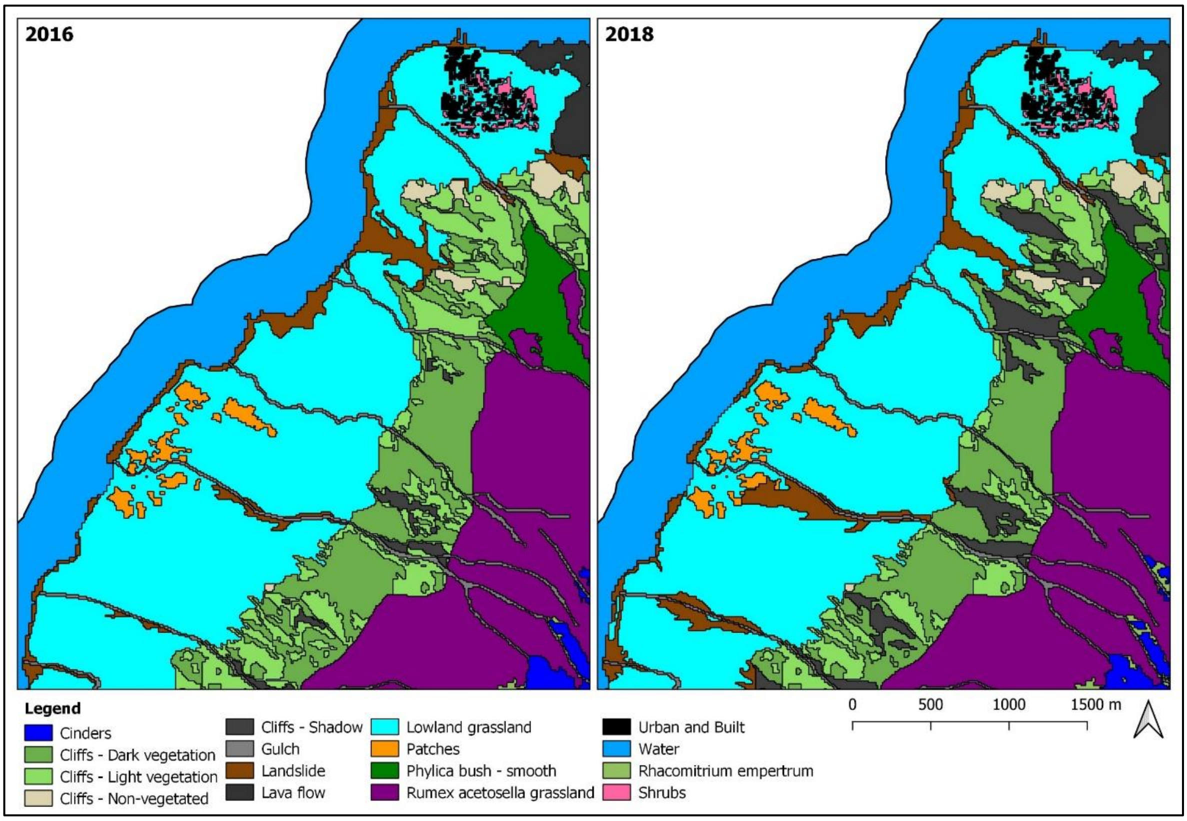

Figure 7: Land cover in 2016 (left) and 2018 (right).

Task 3: Model erosion risk

In order to assess the susceptibility of an area for a slope failure, the following information is necessary:

- **Land cover**: vegetation can play an important role in holding soil structures together. Changes in land cover can affect the likelihood of landslides.
- **Topography**: the steeper and higher a slope, the more likely gravity can act on weakened materials.
- **Precipitation**: Water can trigger landslides because it alters the pressure within the slope, leading to slope instability. Excessive water is thought to be one of the most common triggers for landslides.

Detailed topography of the island was created using a high-resolution digital terrain model (WorldDEM) which was available from a previous study funded by JNCC (Williams et.al, 2018; Figure 8). These data have a pixel spacing of 12 m with vertical accuracy of < 4 m and horizontal accuracy of < 6 m. This study also found that the vertical accuracy is actually, on average, much better than this. Since the digital terrain model was generated using radar, each point has an accurate height, however the 12m spacing means that small and potentially significant features might not be picked up. A full airborne LiDAR (Light Detection And Ranging) survey of the island is recommended, particularly of the area above the Settlement Plain, to ensure that no small features that could add to risk have been missed.

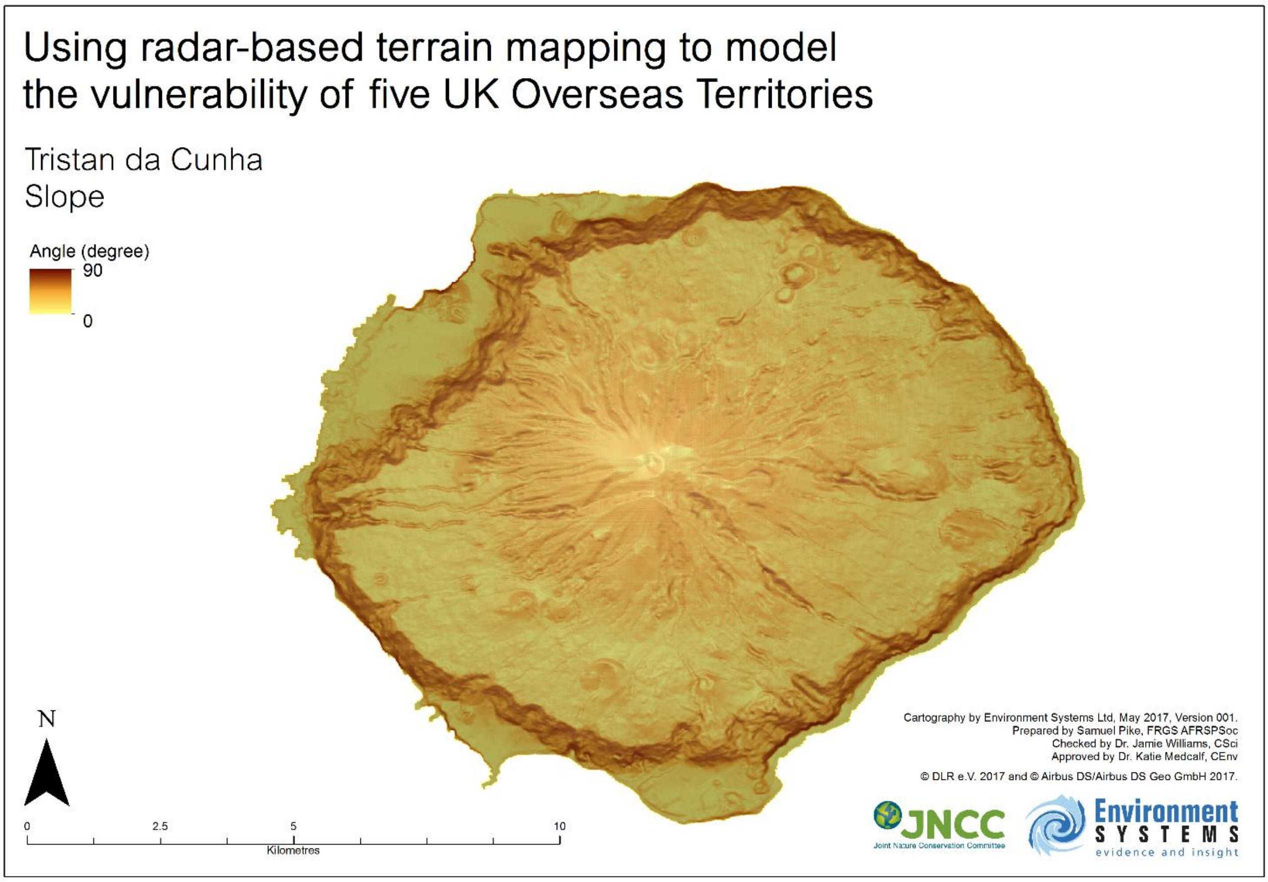

Figure 8: World DEM model of Tristian da Cunha

Four years' worth of precipitation data were supplied by the Tristan da Cunha Government to use in the erosion risk model. For the climate change scenarios, precipitation data were obtained from the UKCP18 global dataset - RCP8.5. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies. Compared to the total set of Representative Concentration Pathways (RCPs), RCP8.5 thus corresponds to the pathway with the highest greenhouse gas emissions."

The UKCP18 global dataset is sampled to 60 km grid squares. Monthly averages were used, obtained from the UKCP18 global dataset. Given that Tristan is 207 km^2, it only represents 5% of the 60 km grid square. Ideally, precipitation data that better reflects the distribution and intensity of rainfall across the island of Tristan would be desired however, this is not currently available. Consequently, a network of weather stations installed across the island would help to understand the rainfall intensity and distribution and would subsequently improve current and future model runs.

Risk modelling

SCIMAP, developed between the universities of Durham and Lancaster, is a fine sediment risk model that gives an indication of where the highest risk of sediment erosion risk occurs in a catchment. This is achieved by;

1. identifying locations where, due to land use, sediment is available for mobilisation,
2. combining this information with a map of hydrological connectivity.

SCIMAP can be carried out over large areas and has much reduced input data requirements, compared to most conventional models, thereby making it more feasible for data poor areas and initial investigations.

SCIMAP outputs include an erosion risk layer which shows the risk of soil being transported off the land by water (erosion by wind is not considered). The inputs required for the production of the erosion risk layer are:

- Elevation (Digital Terrain Model (DTM))
- Precipitation (in mm/year)
- Erodibility (scored between 0 and 1, with 0 being least and 1 being most erodibility)

The updated habitat map was used to create the erodibility scores (Appendix 2). These, and the outputs, were preliminarily assessed by the Project Lead from SAERI, however these will need to be quality assured by on-island experts.

The resulting outputs from SCIMAP indicate that erosion risk is high along the steep gulches that radiate out from the Peak as well as on the coastal cliffs of Tristan (**Figure 9** and **Figure 10**).

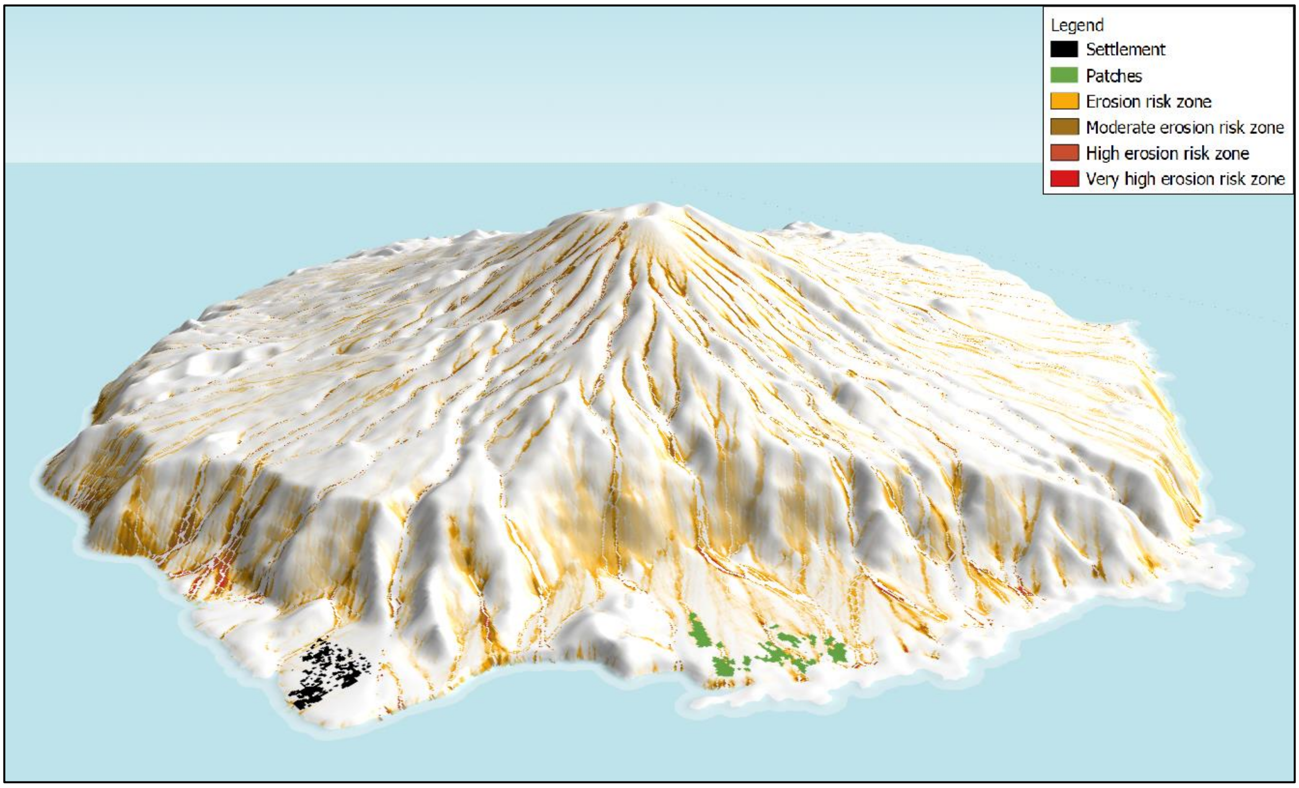

Figure 9: 3D representation of erosion risk (2020) along the Settlement plain. The erosion risk shows a boundary at the break of slope with the base and along the gulches.

As SCIMAP is based upon the soil erosion risk, areas with fine soil material, little vegetation cover and on steep slopes are scored as the highest erosion risk. This is why the edges of recent slumps and the steep slides of the gulches are showing as highly erodible. Material in these areas is likely to be carried down the water channels in storm events. Those areas on the cliffs below The Base with the highest erosion potential are both the steepest and those with least vegetation holding the slope together. The angle of slope is also a key factor (Figure 10).

Figure 11 shows the island's water supply and associated infrastructure above the settlement. It reveals both are sited within an erosion risk zone and therefore vulnerable to possible damage and disruption of the settlement's only water supply. This risk should be investigated as a priority in any further assessments and mitigation plans developed.

Figure 13 shows areas of older slips which are becoming vegetated and the erosion risk is being reduced, whilst other areas are becoming less stable and the erosion risk is increasing. It also shows the change in erosion risk as parts of the island slump and new soil and vegetation develops. This leads to a change in erosion risk over time. It is therefore advised to regularly monitor vegetation on the island using remote sensing techniques and Sentinel 2 imagery, which is readily available. In addition, the erosion risk model should be re-run to keep an up to date view of where key significant risk points are developing.

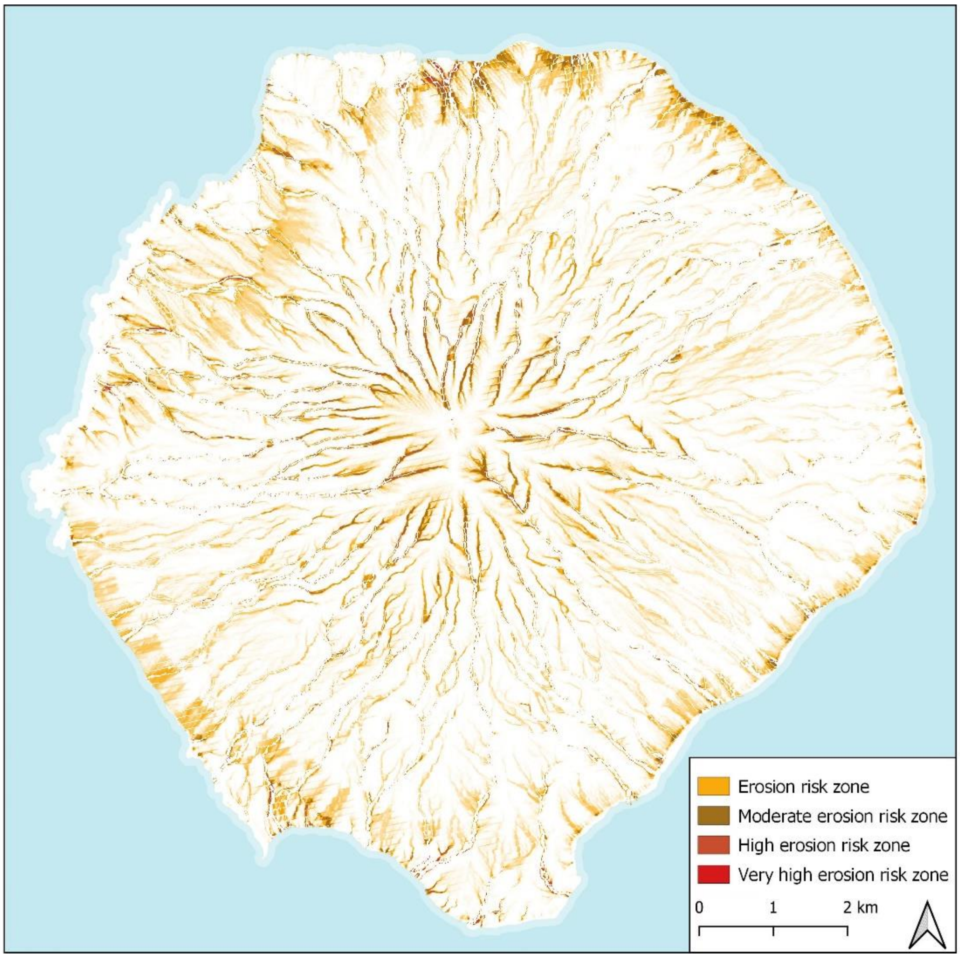

Figure 10: Erosion risk Tristan da Cunha.

Climate change predictions suggest that rainfall will fall in increasingly heavy and prolonged storms in the South Atlantic/over Tristan. This might have the effect of saturating the deeper soil profile on The Base, further leading to an increased risk of slumping in the future. An erosion risk model was run using the 2050 predicted precipitation data from UKCP18 GCM. The same land cover map was used (2018) since it is not possible to predict future vegetation change. No perceptible change was detected between the 2020 and 2050 model runs, despite an increase in precipitation. This indicates that changes in vegetation extent affects risk to a greater extent and highlights the importance for ongoing monitoring.

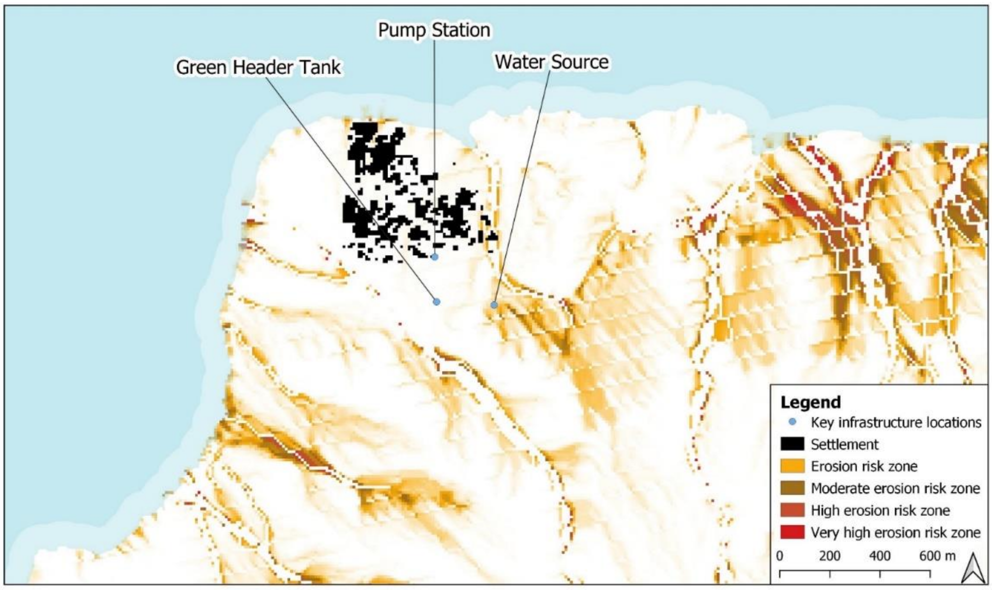

Figure 11: Erosion risk (2020) around the main water source and its infrastructural features

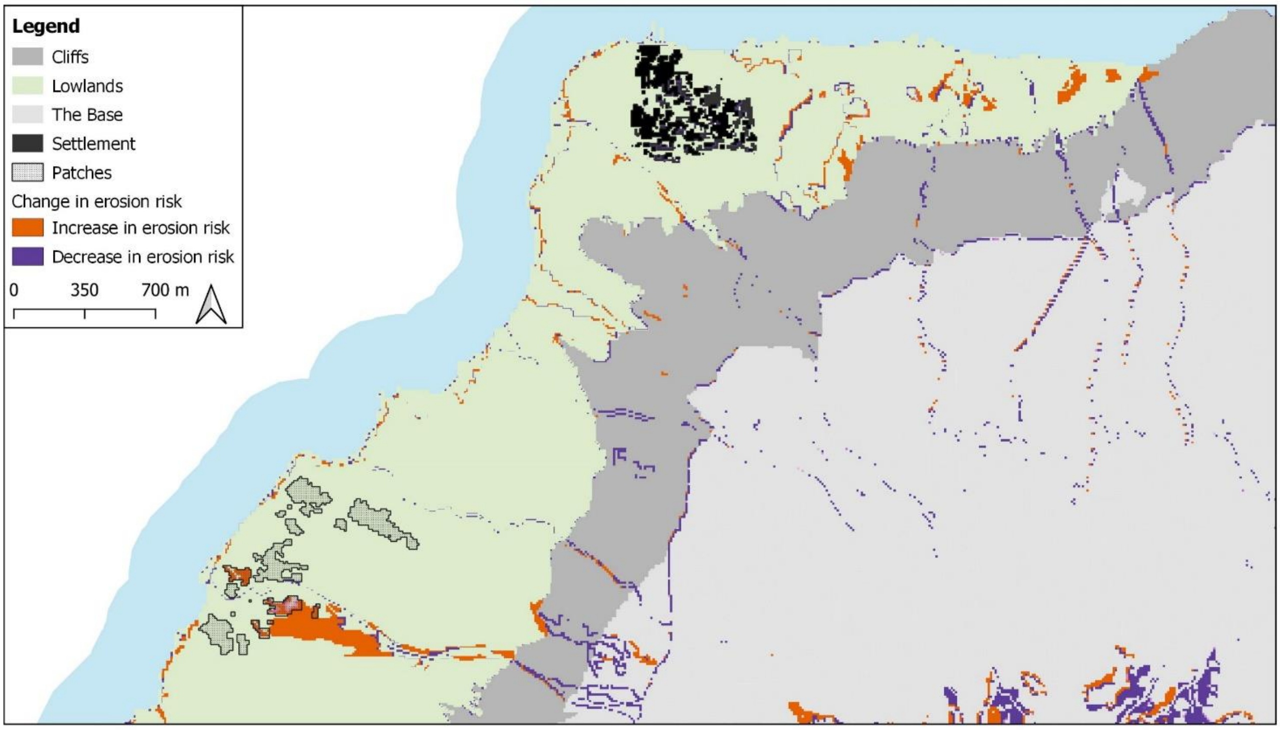

Figure 12: Erosion risk prior to 2017 slump (purple) that is no longer an erosion risk, and erosion risk that has developed since 2016 (orange).

Conclusion and next steps

This project has used a time-series of imagery to update the habitat map of Tristan da Cunha to show the current boundaries of the main different types of land cover. It is a baseline map which can form the basis of a living map for the island, the boundaries being updated over time using both satellite imagery and field surveys. The DTM was created using the satellite-derived World DEM; this gives good accuracy for the vertical precision but only has a record every 12 m. Therefore, small changes in landform which might be significant are not picked up. An airborne LiDAR survey at a higher resolution is strongly recommended.

The SCIMAP soil erosion risk model was run for the island. It showed a number of areas with soil erosion risk concentrated around the gulches and on the steep cliffs, with particular risk present where these interface with The Base. The time-series analysis showed that the erosion risk is changing over time. This can result in both a positive, reduction in risk as the slumps vegetate over, or negative increase in risk found on very steep areas with increasing rainfall. This project is the first attempt to quantify erosion risk on the island, and further work should be carried out focusing on:

- The erosion risk zones and models verification on-island, with a full geological survey to confirm the main risk zones particularly on the Settlement Plain and where the water source for the settlement is located.
- The establishment of mitigation measures by an on-island survey.
- The re-run of remote sensing techniques on an annual or biannual basis to further establish and verify risk areas.
- The deployment of a network of weather stations to improve the understanding of rainfall intensity and distribution.

Erosion risk is a very serious issue on the island, the Settlement Plain being key for the island's survival and at high risk from future erosion events. Erosion risk around the water supply is also a high concern. This report is a useful first step in understanding and mitigating these risks.

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Appendix 1 – Existing habitat map of Tristan de Cunha

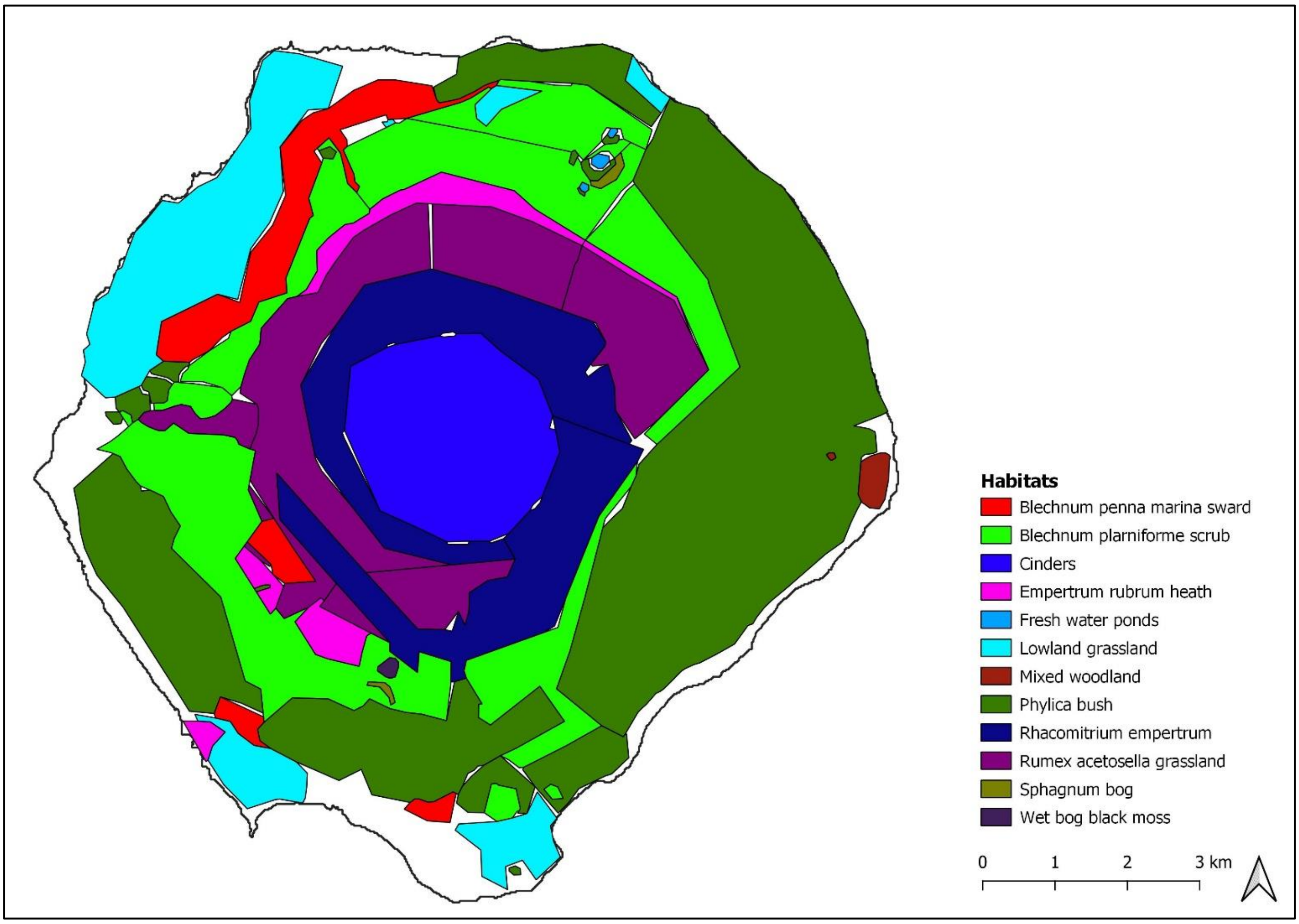

Figure 13: Existing habitat map of Tristan de Cunha.

Appendix 2 - Erodibility scores

Land cover class	Erodibility score
Blechunum planiforme scrub	0.3
Cinders	1
Cliffs - dark veg	0.3
Cliffs - light veg	0.4
Cliffs - non-veg	1
Cliffs - shadow	0.4
Empertrum rubrum heath	0.1
Gulch	1
Landslide	1
Lava flow	0.8
Lowland grassland	0.3
Mixed woodland	0
Patches	0.7
Phylica bush - rough	0.1
Phylica bush - smooth	0.2
Rhacomitrium empertrum	0.6
Rumex acetosella grassland	0.5
Shrubs	0.3
Sphagnum bog	0.2
Urban and built	0
Water	0
Wet bog black moss	0.2