Marine Futures
In partnership with

Seagrass Restoration Project Report

Project Short Title: Seagrass Restoration Potential in Morecambe Bay.

Full Project Title: Seagrass meadow recovery in Morecambe Bay: investigating restoration potential and techniques for a highly tidal environment.

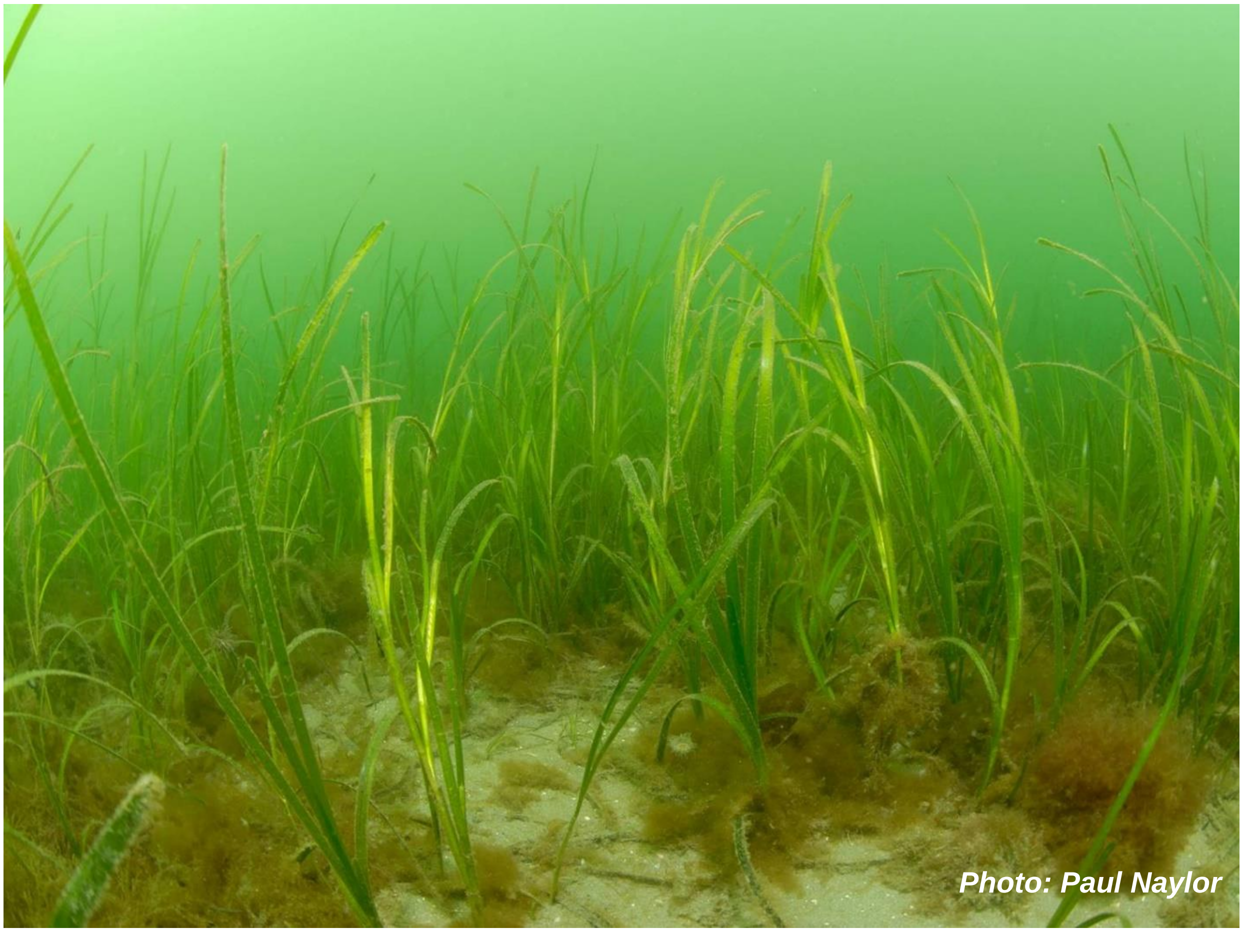
Photo: Paul Naylor

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Marine Futures Intern 2020 - 2021

Project Details

Foreword

This report details the research project ‘Seagrass meadow recovery in Morecambe Bay: investigating restoration potential and techniques for a highly tidal environment‘ which was carried out in collaboration with the North West Wildlife Trusts and Natural England as part of the Marine Futures Internship.

This report should be cited as:

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Introduction

Project Background

Our estuarine and coastal environment has declined substantially from its natural state and, although existing measures help in many ways, the reality is that our current efforts all too often do little more than maintain a degraded status quo.

Seagrasses are the only flowering plants that are able to live in seawater and pollinate while submerged. Seagrass meadows are highly productive and diverse ecosystems providing: a complex habitat for creatures such as worms, molluscs and algae; nursery and refuge areas for fish; a food source for overwintering geese, eiders and shelducks; sediment stabilisation; and a carbon sink.

Up to 92% of the UK’s seagrass has been lost through disease and human activities. Seagrass meadows are declining at an unprecedented rate and remain under threat from various pressures. Seagrass meadows were once abundant and widespread in Morecambe Bay but now only a few small areas remain. There are ongoing pressures, such as scouring from boat moorings, and past pressures, such as poorly placed outfall pipes. In both cases (even in the latter where the pressure has been removed), the seagrass meadows have not recovered.

With every loss in seagrass area, there is a consequent loss in the ecosystem services this habitat provides: carbon and nutrient sequestration, biodiversity and fish nurseries etc. This presents a significant cost to all of us - even if we don’t acknowledge it or we are unaware of it.

What challenge will this project address?

Seagrass restoration and research has been conducted for over 50 years, normally through a process of replanting or reseeding. However, success rates are normally low. This project will address the potential for active seagrass restoration in Morecambe Bay through researching relevant past and ‘cutting edge’ current restoration projects.

What environmental benefits will this project have?

Seagrass meadows are able to store carbon up to 35 times faster than terrestrial forests. Active seagrass restoration is emerging as a potentially meaningful climate change mitigation strategy. Under the Paris Climate Accord and the Katowice Climate Package, seagrass restoration can be considered to be part of “defined emissions reduction targets or traded for carbon credits”. If this project could lead on to a largescale restoration project in Morecambe Bay, this would help to increase the amount of carbon dioxide sequestered in coastal sediments, in addition to the other environmental benefits provided by the ‘rewilding’ of this coastal habitat - i.e. supporting biodiversity and fisheries.

Project Aims and Objectives

Project Aim: To evaluate the current extent of seagrass species within Morecambe Bay and produce key recommendations for the future development of a seagrass restoration plan.

Project Objectives:

1. To produce maps of the historic and current presence and extent of seagrass species in Morecambe Bay, and potential restoration sites.
2. To review seagrass restoration methods for highly tidal environments.
3. To produce recommendations for a future seagrass restoration plan for Morecambe Bay.
4. To form and hold a meeting with a seagrass stakeholder working group.

The Value of Seagrass

Seagrasses support a whole range of highly valuable ecosystem services that rival those of many well-know ecosystems such as mangrove forests (Unsworth *et al*., 2019b). They a create three-dimensional habitat, providing shelter to a rich diversity of fish and invertebrate life. Recent estimates suggest seagrass meadows support the productivity of 20% of the world's biggest fisheries through nursery habitat provision (Unsworth *et al*., 2018), supporting coastal livelihoods.

They filter water in costal environments, removing nutrients and bacterial pathogens (Unsworth *et al*., 2019b), and there's growing evidence they capture microplastics (Jones *et al*., 2020; Carmen *et al*., 2021).

Seagrasses are highly productive, representing one of the largest global carbon sinks, despite occupying only 0.1% of the ocean floor (Green *et al*., 2021). They contribute to stabilizing our climate by storing and sequestering carbon within their sediments (Unsworth *et al*., 2019b), increasing shoreline stability. It's estimated 19.9 Pt carbon is stored in the top 1m of seagrass worldwide, the equivalent to the carbon dioxide emissions from fossil fuel and cement production in 2014 (Green *et al*,. 2021).

Seagrass Growth & Ecology

Taxonomy

Two species of *Zostera* occur in the UK, dwarf seagrass *Zosteria noltei* (synonymous to *Zostera noltii*) and seagrass *Zostera marina*. *Z. noltei* is broadly considered an intertidal species, found highest on the shore, often adjacent to lower saltmarsh communities, while *Z. marina* is predominately found in the sublittoral. Mixed beds of *Z. noltei* and *Z. marina* eco. *angustifolia* (see below) often occur on the shore, with each species occupying a niches; *Z. noltei* occurring on hummocks of free draining sediment and *Z. marina* eco. *angustifolia* occupying hollows that retain standing water at low tide (Tyler-Walters, 2005).

A third species, the 'wide leafed' intertidal *Zostera angustifolia* is frequently cited as either a distinct species, a variant or a synonym of 'narrow leafed' *Zostera marina*. Several genetic comparisons have found that specimens identified as *Z. angustifolia* are genetically indistinguishable from *Z. marina* and that leaf width does not correlate with molecular data delineating species (Coyer *et al*., 2013; Olsen *et al*., 2013). Variations in leaf width may be classed as ecotypes but leaf width is a stable phenotypic characteristic and cannot be attributed to morphological plasticity (Olsen *et al*., 2013). The current consensus is that *Z. angustifolia* is a taxonomic synonym of *Z. marina*. Thus, for this study any historic records of *Z. angustifolia* are referred to as *Z.marina eco. angustifolia*.

Growth & Natural Dynamics:

Seagrasses have two reproduction methods; sexual reproduction via the pollination of flowers which produce sexual seeds and asexual reproduction, colonizing sediment via rhizomes. Seagrass species can disperse and recruit existing/new areas via pollen, seed, floating fragments or reproductive structures, vegetative growth (via rhizomes), and via biotic vectors such as wildfowl and fish. While it has been suggested that vegetative reproduction exceeds seedling recruitment, genetic analysis suggest a more complex process. New leaves and seedlings appear in spring, with meadows developing over intertidal flats in summer (D'Avack *et al*., 2019). Leaf growth stops in September/October and leaves are shed, with *Z. noltei* keeping its leaves for longer than *Z. marina* in winter. Plants are reduced to their rhizomes within the sediment until regrowth occurs the following season. The rhizome of *Z. noltei* is thinner than *Z. marina* and it's growth is rapid and ephemeral in nature, taking advantage of seasonal increases in light and nutrients, rather than metabolites stored within the rhizome (Tyler-Walters, 2005).

Seagrass meadows are highly dynamic ecosystems. In semi-annual populations, seed production, dispersal, germination and seedling survival determining the bed dynamics. The semi-annual *Z. marina*, and perennial *Z. noltei* have high inter-annual variability in extent and location, with local extinction and recolonisations/colonisations being part of their life strategy, typical of r-strategy species (Valle, *et al*., 2013).

Sexual Reproduction – Pollination of Flowers and Sexual Seeds

Zosteria species flower and release pollen in long strands that are dense enough to remain at the depth they were released for several days, increasing their chance of pollinating receptive stigmas. Pollen are long-lived with estimated dispersals of 10m for *Zostera noltei* and 15m for *Zostera marina*, although most are thought to be intercepted by the canopy within 0.5m. Pollination mostly occurs within the same or adjacent meadows, with a high level of outcrossing. (D'Avack *et al*., 2019)

Seeds develop within a membranous wall that photosynthesises, developing an oxygen bubble within the capsule, eventually rapturing the capsule to release the seed. The seeds generally sink due to their negative buoyancy (D'Avack *et al*., 2019) and may be dispersed by currents, waves and birds (Tyler-Walters, 2005). *Z. noltei* seeds are much smaller than *Z. marina*, at about half the size of a sesame seed (Jayes, 2021).

Seedling mortality is extremely high (D'Avack *et al*., 2019; Tyler-Walters, 2005). Reports of the viability of seeds with age vary; McMahon et al. (2014) noted that *Zostera* seeds are dormant and viable for 12 months or more. However, Dooley et al. (2013) reported that the viability of one-year-old *Zostera marina* seeds was 77% but that viability dropped to only 32% in four-year-old seeds. Similarly, 68% of one-year-old seeds in their study germinated but only 15% in three-year-old seeds and successful seedlings resulted from only ca 5% of fresh seeds (Dooley et al., 2013). The extent of the biotic dispersal of seeds is unclear (D'Avack *et al*., 2019).

Asexual Reproduction – Rhizome Colonisation:

Zostera marina plants are monomorphic, restricted to horizontal root growth, unable to grow rhizomes vertically. This makes the recolonization of adjacent bare patches difficult and explains why large beds are only found in gently sloping locations. *Z. marina* rhizome growth has been reported at a rate of 26cm per year (D'Avack *et al*., 2019).

If pieces of rhizome or shoot become displaced, they may take root if they settle on suitable substratum (Tyler-Walters, 2008).

Environmental Conditions/Habitat:

Z. noltei is more tolerant of high light intensities, available at low tide, than *Z. marina*, presumably as an adaptation to life higher on the shore and in the more turbid environments of intertidal flats (Tyler-Walters, 2005). *Z. noltei* prefers areas sheltered from wave exposure on the upper or mid shore, in muddy sand or sandy mud sediment (D'Avack *et al*., 2020). It grows in scattered clumps, dense beds or meadows on intertidal mud or detritus rich fine intertidal sand. Its upper and lower limits shift down shore with decreasing salinity, and in brackish waters, it may become permanently submerged (Tyler-Walters, 2005).

Zostera marina is found on the lower shore (between 0-10m) in areas sheltered from wave exposure in sediment ranging from mud to sand (D'Avack *et al*, 2019).

Symbiosis

A three-way symbiotic relationship exists with the small lucinid bivalves and their endosymbiotic sulfide-oxidising gill bacteria. Experiments have show the gill bacteria of *Loripes lacteus* reduced sediment sulfide levels and enhanced the productivity of *Z. noltei*, while the oxygen released from the roots of *Z. noltei* benefited *Loripes* (D'Avack *et al*., 2019).

Epiphytic grazers remove fouling epiphytic algae that would otherwise smother seagrasses. *Hydrobia ulvae* and *Lacuna* species have been show to reduce the density of such epiphytes on both *Z. noltei* and *Z. marina*, enhancing the productivity of seagrass (D'Avack *et al*., 2019).

Infauna

The distribution of *Z. noltei* may be affected by infaunal deposit feeders, being excluded from sediment dominated by *Arenicola marina* (blow lugworm) or *Hediste diversicolor* (ragworm; Tyler-Walters, 2005).

Threats/Pressures

In general, the resilience of seagrasses to external pressures is low, as demonstrated by the very slow or lack of recovery after the epidemic of a wasting disease in the 1930s (D'Avack *et al*., 2019).

Seagrasses are thought to be sensitive to marine heatwaves, sea level rise, physical changes to their habitat/the seabed, including abrasion and penetration, changes in suspended solids and nutrients in the water column and the introduction of invasive non-native species/pathogens. The removal of associated species, such as filter-feeders, may also significantly impact seagrass beds (D'Avack *et al*., 2019).

Evolutionary change in seagrasses can occur within a few generations, suggesting genetically diverse populations would be more resilient to changes in environmental conditions than genetically limited populations (D'Avack *et al*., 2019).

As *Z. marina* rhizomes can only grow horizontally, a depression of the seabed by disturbance of the sediment can restrict meadow expansion. The size and shape will influence resilience, with larger denuded areas are likely to take longer to recover than smaller areas due to the greater edge to area ratio and the related availability of plants for recolonisation. Large, non-fragmented meadows are thought to have a higher persistence than small, fragmented meadows and hence, smaller patches are thought to be more vulnerable to disturbance (D'Avack *et al*., 2019).

Declines in the UK

Qualitative data suggests that before World War One seagrass would have been found across a large proportion of subtidal mud- and sandflats and on the lower ranges of most intertidal flats throughout the UK, especially in Estuaries. An estimated 44% of seagrass in the UK has been lost since 1936, 34% since the 1980s (Green *et al*., 2021).

Protection in the UK

Seagrass habitats are protected at local, national and international levels; they are listed as named components of Annex 1 features under the EU Habitats Directive, as features of Sites of Special Scientific Interest (SSSIs) within the intertidal, as supporting habitats for Ramsar wetlands and Special Protection Areas (SPAs) and as Features of Conservation Interest (FOCI) in Marine Conservation Zones (MCZs). Seagrass beds (*Z. marina* and *Z. noltei*) are UK Biodiversity Action Plan (BAP) Priority Habitats (JNCC, 2019).

Protection measures are often based upon the actual distribution of *Zostera* within a particular monitored year, thus harmful activities may be permitted occur around seagrass, damaging the unoccupied habitat of these dynamic populations (Valle *et al*., 2013). Studies have shown the dynamic nature of seagrass beds, with shifting contours, 'pulsing' extents and the formation of new beds where others disappear, emphasizing the need to protect suitable seagrass habits in addition to existing beds (Valle *et al*., 2013).

Protection in Morecambe Bay

Within Morecambe Bay, seagrass beds are a key feature of the South Walney and Piel Channel Flats Special Site of Scientific Interest (SSSI).

Historic & Current Records of Seagrass within Morecambe Bay

Historic Records of Damage and Recovery

The only known seagrass meadows within Morecambe Bay are located in the north west around Walney, Roa and Foulney Islands. While few historic records exist, three gas pipelines have been constructed though the Concle Bank seagrass beds; two in 1993 (with a bare strip created in 1992) and one in 2003 (available to view under infrastructure and pipelines on the Marine Management Organisation database here), with subsequent surveys of the saltmarsh and seagrass community recovery.

Davidson and Hughes (1998) report the presence of *Zostera*, potential destruction and restoration within Morecambe Bay in the early 1990s:

"*Between 1992 and 1997, work has been undertaken on the intertidal Zostera beds in the Barrow and Walney Island areas of Morecambe Bay, relating to the construction and laying of two gas pipelines. During this work, areas of Z. angustifolia* [i.e. *Z. marina* eco. *angustifolia*] *and Z. noltii were destroyed by the clearance of a 150 m wide swathe and the excavation of a trench. To assist recovery, the surface sediments of the Zostera bed were removed, stored and consequently replaced. The recovery has been monitored. Populations to the north of the pipelines have been recovering, albeit slowly and patchily. However, populations to the south of the pipeline have decreased or disappeared (I. Tittley, pers. comm.).*"

Surveys in 2007 of the second pipeline corridor (constructed in 1993) by Evans *et al*., (2007), report a noticeable boundary of denser growth of *Zostera* beyond the working width of engineering still persisted, with slow, patchy recovery.

They also noted that surveys in 2003, post construction of the third pipeline, recorded a pipeline corridor devoid of *Zostera* compared with healthy growths and common presence in 2001. By 2007, four years post construction, *Zostera* was recorded present within the corridor, with a patchy occurrence both within and outside the corridor and cover varying considerably. The maximum offshore limit of *Zostera* along the pipeline corridor contracted with reports of 580m, 450m, 475m and 350m in 2004, 2005, 2006 and 2007 respectively. The reasons for this retraction of extent are unknown.

Z. angustifolia [i.e. *Z. marina eco. angustifolia*] was reported in 2007 mainly in shallow standing water, rarely exposed at low tide, while *Z. noltei* was reported occupying slightly raised mounds of sand and mud. Reports outside of the pipeline corridor record abundant populations, thinning out with increasing distance offshore and a patch-dynamic, with populations appearing and disappearing year by year (Evans *et al*., 2007). This distribution and dynamic nature is still thought to occur (see below).

It was also noted in 2007 that very little seagrass occurred within the impact zone of the wastewater outfall, which was dominated with ephemeral green algae *Enteromorpha* species (Hubble *et al*., 2007). Since these surveys, this outfall pipe has been moved in order to avoid damaging the seagrass. However, it does not appear that this area has recovered (see below).

Analysis of the Historic & Current Distribution & Main Bed Areas:

Historic survey data infrequently collected between 1998 and 2017 is available to analyze recent changes in distribution and extent of the seagrass bed areas. To avoid repetition, please see Natural England (2013) for a summary of the survey methodologies used between 1998 and 2013. The two most recent surveys completed in 2016 and 2017 follow the same methodology as used in 2013.

Distribution

Figure 1 and Figure 2 depict the available data from surveys of the beds. The 1998 survey (Figure 2) recorded the presence of *Zostera* (species unknown) with an apparently large bed running parallel to the coastline between Roa Island and Roosecote Sands, thinning and becoming patchy at the north-west end, a bed between Roa and Foulney Islands, a bed in Slitch Bay between Foulney Island and Slitch Ridge and a bed on Snab Sands, to the west of South Walney Island.

Since the 2010 APEM/UU study, the presence of seagrass at the north-western end of the bed between Roa Island and Roosecote Sands has not been recorded and thus it appears this area has been lost. It is thought this loss was due to a outfall pipeline which discharged directly onto the beds. This has since been moved. The other beds seem to have remained within similar extents.

There have been few surveys of the Snab Sands bed, however it was last recorded as present in the Gateway/AMEC 2012 survey.

Seagrass Bed Areas/Extents

A record of 224 ha of seagrass is cited by Green (Green, 2019/Green *et al*., 2021) and is thought to have occurred at Barrow-in-Furness in Morecambe Bay pre-1998, however it has not been possible to locate the original source of this data. Recent survey estimates of the areas of the main *Zostera* beds are detailed in Table 1, it should be noted that no surveys have been completed since 2017 (4 years ago). Taking the most recent complete estimates for each main bed (highlighted in bold and underlined in Table 1; representing the minimum area of *Zostera* as these are the main beds and do not include all small outlying patches), it is estimated 69.453 ha of seagrass beds currently exists within Morecambe Bay. This represents an estimated 69% loss from the 224 ha pre-1998 figure cited by Green (Green, 2019/Green *et* al., 2021).

Since 2013, it appears the areas of the main beds (Rooscote Sands, Concle Bank, Roa Island Bay North, West of Foulney 1 (top bed), West of Foulney 2 (middle bed), West of Foulney 3 (bottom bed) and Slitch Bay), appear reasonably stable, with changes in extent as would be expected with the natural dynamics of seagrass beds. More frequent surveys would greatly assist in monitoring the beds.

*Table 1 - Zostera main bed area estimates (ha) from historic surveys, either as reported or as calculated from GIS layers in ArcPro (p = presence recorded but extent/area not mapped). Bold and underlined figures indicate those used to calculate a most recent total area of seagrass beds. Note these represent the minimum area of Zostera present. * = there were some minor discrepancies between the figures reported in the Natural England 2013 report and those calculated using ArcPro, where this occurred the figures listed are those calculated in ArcPro. **Mapping of the full extent of some of the seagrass beds during the 2017 Natural England surveys was not possible, thus this data is incomplete for some of the beds. This is indicated within the table by calling the area of the beds either 'complete' i.e. the whole bed was mapped and thus the figure can be used to estimate the area of that bed, or 'incomplete' i.e. mapping of this bed was not finished and cannot be used to estimate an entire area for the bed.*

	Survey:			
Bed	2012 Gateway/AMEC	2013 Natural England*	2016 Natural England	2017 Natural England**
Roosecote Sands	7		**20.673**	Mapping incomplete (minimum of 9.914 incomplete main bed + **1.383** complete most northern outlying patch mapped in this area)
Concle Bank	22		36.907	**34.332** (6.337 + 27.995 beds divided and mapped separately)
Snab Sands	**5.5**	*Not surveyed*	*Not surveyed*	*Not surveyed*
Roa Island Bay North		3.3171	**4.058**	3.001 (incomplete)
West of Foulney 1 (top bed)		0.6731	**1.649** (beds combined)	1.721 (beds combined, incomplete)
West of Foulney 2 (middle bed)		0.4517		
West of Foulney 3 (bottom bed)		0.6172	**0.588**	*Not surveyed*
Slitch Bay		1.1435	1.730	**1.044**
Outlying Small Beds (total)		*p at Rampside sands*	0.0962	**0.2262**
Total area from survey:	34.5	6.203	65.7015	51.621

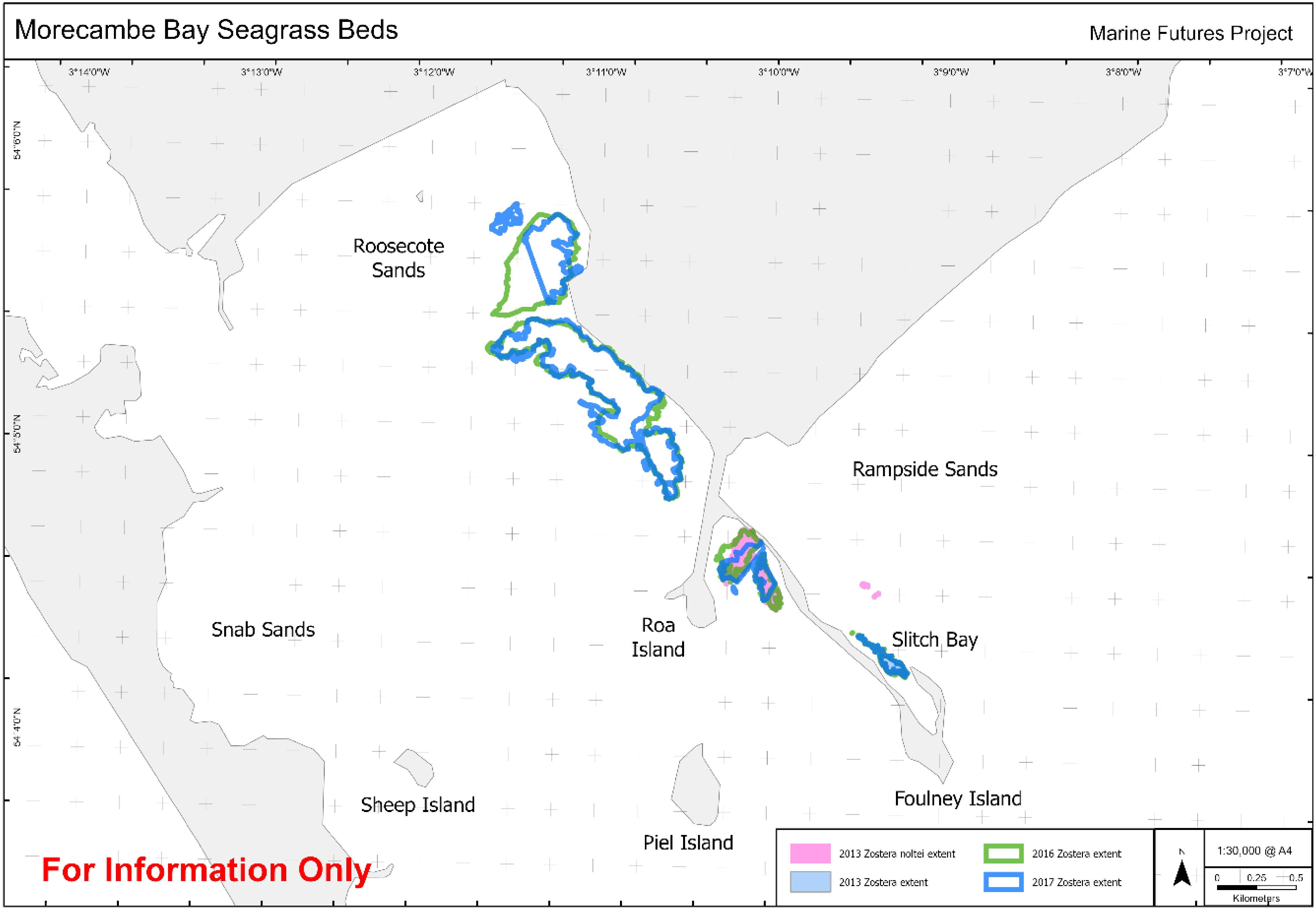


Figure 1 – Seagrass beds of Morecambe Bay and surrounding area nomenculture (survey data from Natural England). NOTE: The 2017 survey data is incomplete (there is not a straight line of seagrass).

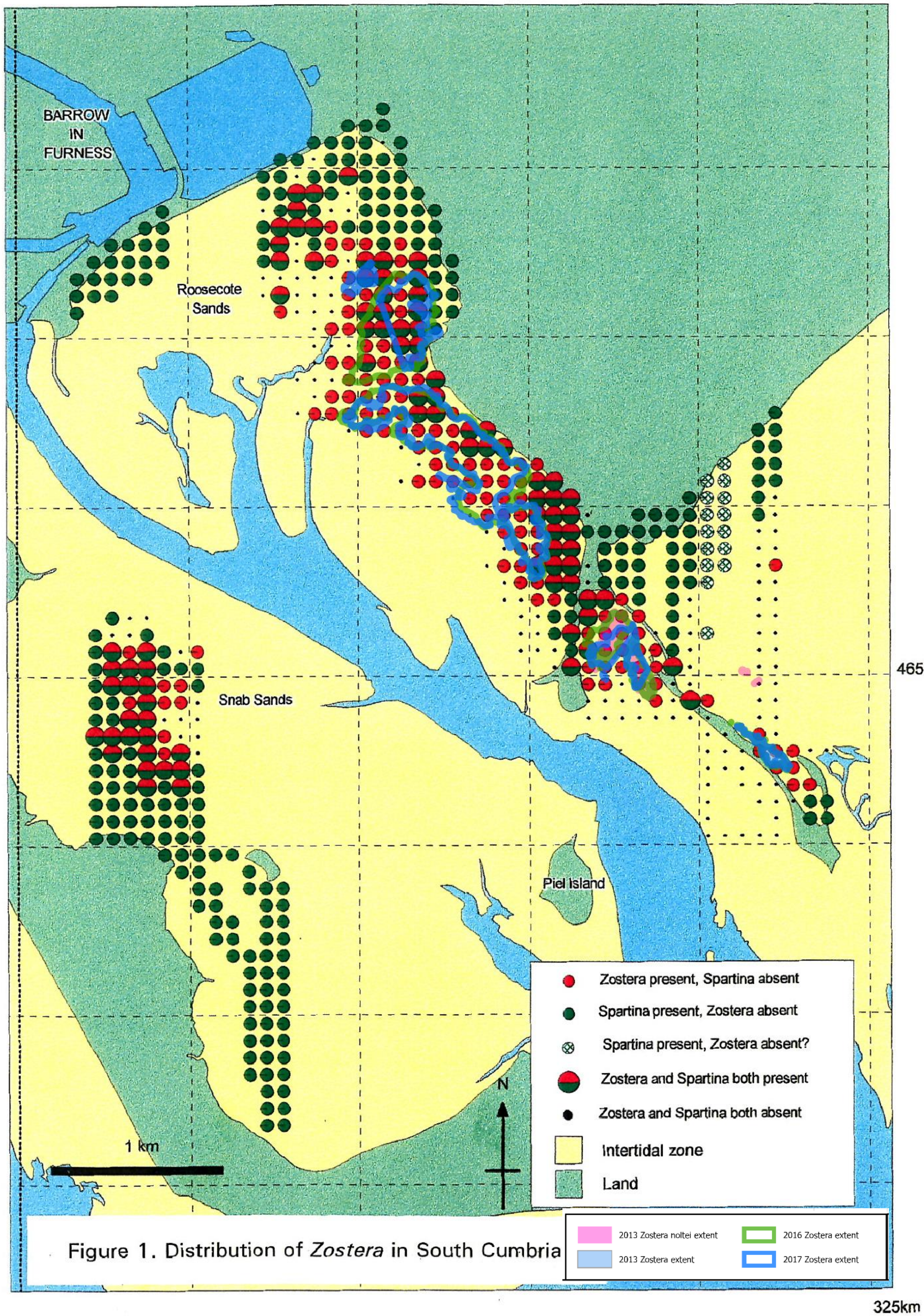


Figure 2 – Seagrass data from 1998 (reproduced from Tittley et al., 1998) with Natural England 2013, 2016 and 2017 survey data overlaid. NOTE: The 2017 survey data is incomplete (there is not a straight line of seagrass).

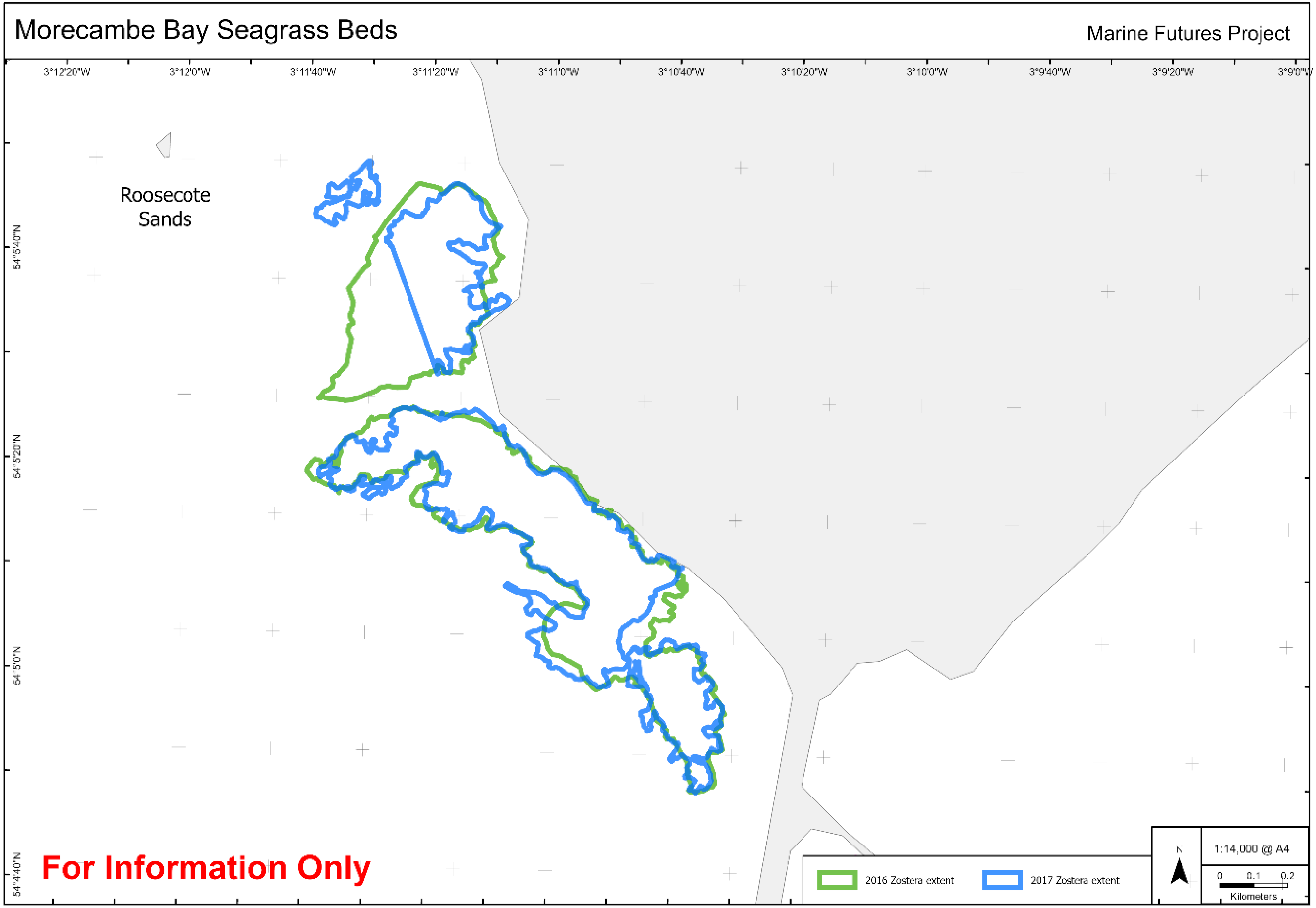


Figure 3 - Roosecote Sands and Concle Bank seagrass beds surveyed by Natural England in 2016 and 2017. NOTE: The 2017 survey data for the Roosecote Sands seagrass bed is incomplete (there is not a straight line of seagrass).

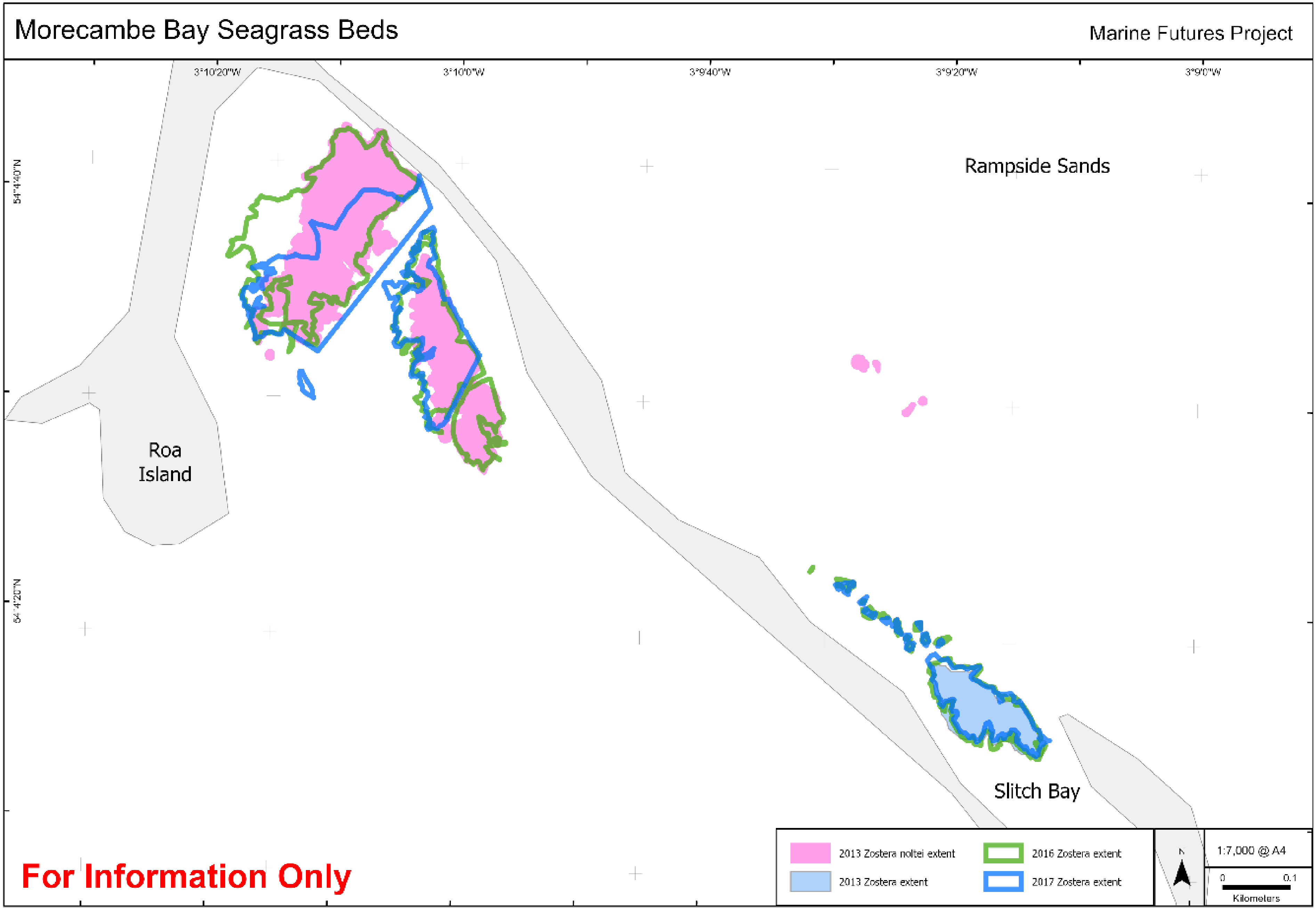


Figure 4 –Roa Island Bay North, West of Foulney 1 (top bed), West of Foulney 2 (middle bed), West of Foulney 3 (bottom bed), Slitch Bay and Outlying Small seagrass beds, surveyed by Natural England in 2013, 2016 and 2017. NOTE: The 2017 survey data is incomplete (there is not a straight line of seagrass).

Threats to the Current Beds and Restoration Success

Removal of threats prior to re-planting is important for restoration success (van Katwijk *et al*., 2016) and an overall meadow management strategy should be in place for the whole bay/region in which the seagrass beds and any potential restoration projects occur (Boudouresque *et al*., 2021).

The following threats currently exist:

Boat Moorings

Private boat moorings between Roa and Foulney Island are currently damaging and fragmenting areas of the seagrass beds here (Natural England, 2013). Natural England is currently working to move these moorings to protect then beds. As these moorings occur within the middle of beds, it is thought once the pressure is removed, these will naturally be re-colonised by roots and seeds from surrounding seagrass plants.

Water Quality

Water quality is an issue in the area of the *Zostera* beds. The areas near/around the beds are identified as high or medium priority areas of water quality issues due to faecal indicator organism issues, phosphate issues and nitrate issues. It was not possible to analyse Water Framework Directive data within the scope of this project, however this should be analysed prior to any restoration work.

Biotubation can lead to severely reduced initial trial survival and long-term population expansion (van Katwijk *et al*., 2016), this should be also be analysed from the WFD data.

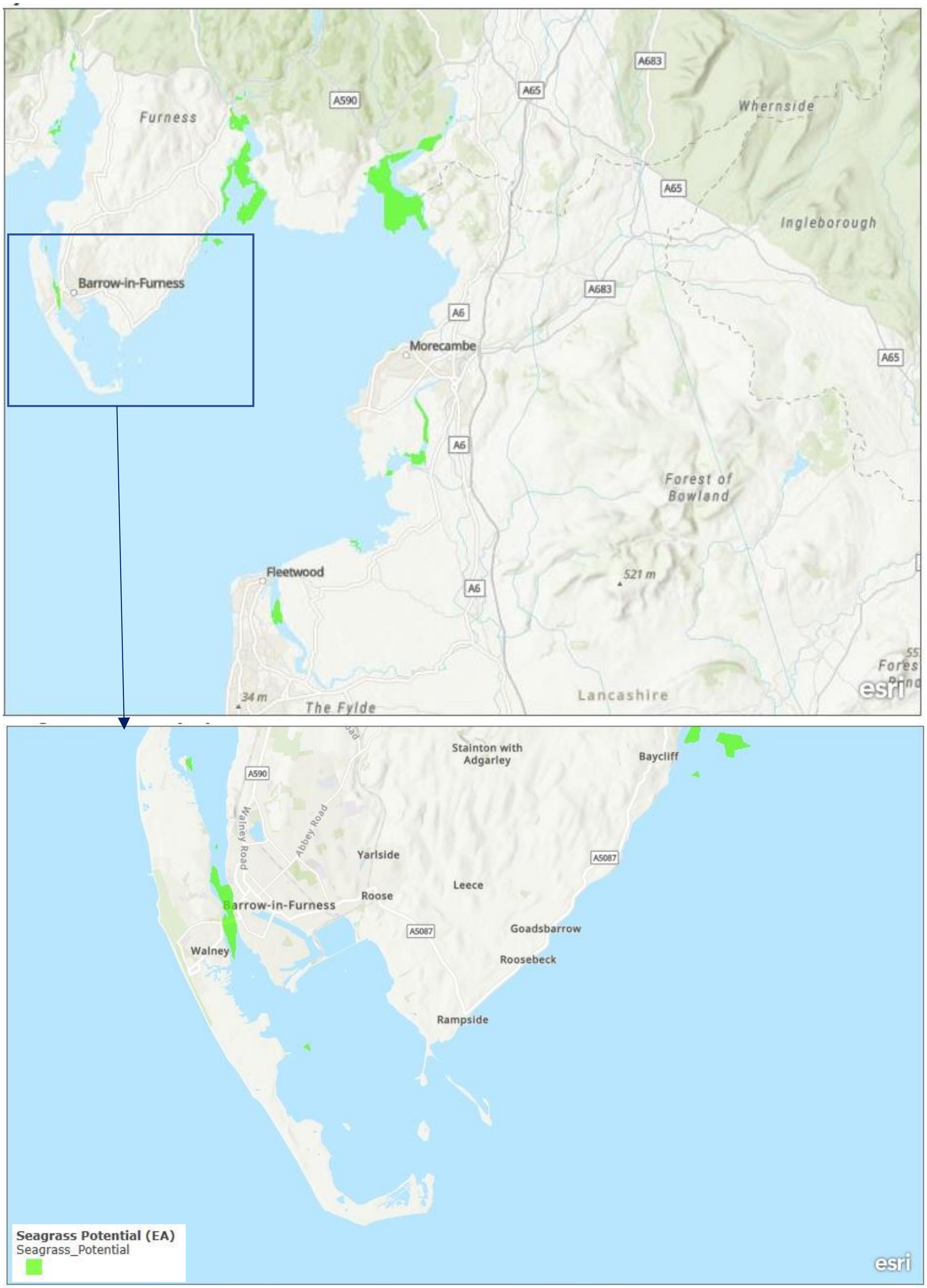
Poor water quality is one of the main reasons for limited restoration success (van Katwijk *et al*., 2016). Therefore, the any water quality issues need to be addressed prior to a future restoration project.

Potential Distribution: EA maps

The Environment Agency have produced maps of potential seagrass areas, based on habitat suitability defined as areas with low wave energy (<11.41 Nm-2), low current energy (<130 Nm-2), of an elevation between -10m to 5m above sea level and salinity >10 (Figure 5; Environment Agency, 2020).

While these high-level maps show the habitat potential for seagrass within the north of Morecambe Bay, Natural England have not recorded *Zostera* here. It is thought that the beds documented above are the only seagrass beds within Morecambe Bay.

It is interesting to note that the area where *Zostera* beds are known to occur do not match with the Environment Agency's analysis of potential areas based on habitat suitability. However, it should be noted these are very broad analysis of habitat suitability, limiting their suitability on a smaller scale. The presence of stable seagrass beds within the area is a far better indicator of habitat suitability.



Seagrass potential areas for restoration derived from wave and current energy, elevation and salinity criteria.

Figure 5 – Potential Seagrass Areas © Environment Agency copyright and/or database right 2015. All rights reserved.

Potential Restoration Area – Where to Restore

Seagrass should only be restored where there has been it was historically present, where a real decline has occurred from human impacts and where it is based on real needs at the local level. Targeting dead matte of historic seagrass is a prime example of where transplanting attempts should occur. Furthermore, restoration attempts should only occur where the cause of decline has ceased (Boudouresque *et al*., 2021).

While there are limited mapped records of the extent of seagrass beds within Morecambe Bay, it is thought that the main area of seagrass decline has occurred on Roosecote Sands, where an outfall pipe used to discharge. The 1981 data shows that at least some seagrass was historically present in this area. While the outfall pipe has been moved so that it no longer damages the seagrass, it is likely recovery of this area will be slow, if at all. It is therefore recommended that any future restoration projects focus on this area.

The proximity to and recovery of donor beds is positively correlated with trial performance by demonstrating the suitability of the habitat for seagrass growth (van Katwijk *et al*., 2016). Therefore, while the moorings have created areas of damage to the seabed, due to being surrounded by seagrass, when the pressure is lifted these should naturally recover. It is not thought that this will happen at Roosecote Sands within a reasonable timeframe, if at all.

A suggested maximum restoration area is outlined in Figure 6. It's estimated a maximum area of 49.330 ha (493305 m^2) is available for restoration. However, this should be ground-truthed to ensure saltmarsh has not covered any of this area. This area is in line with the current seagrass beds and next to a current seagrass bed of a reasonable size, which should indicate environmental suitability and assist with restoration due to close proximity to a donor bed. If it is not possible to restore this whole area, it is recommended the side closest to the current seagrass bed is focused on, due to the positive influence of close proximity to a donor bed.

Key Recommendations from Reviewing the Seagrass Beds:

1. A seagrass meadow management strategy is needed. This should be focused at the regional level, including all the known beds (including Snab Sands) with consistent monitoring of; (i) the total surface area of each meadow; (ii) the area lost due to decline and cause of the decline; (iii) the area reclaimed each year through natural regeneration (if this occurs). Infrequent monitoring is likely to incorporate the core areas, frequently occupied by seagrass, but likely also to exclude large areas that are only occupied occasionally, therefore underestimating the overall seagrass habitat. If only the core areas of seagrass are protected, a large part of the total distribution could be lost (Valle *et al*., 2013).
2. Threats to the seagrass should be minimized as much as feasibly possible in order to enhance chances of restoration success.
   - **a.** Potential water quality issues require further investigation. It was not possible to analyse Water Framework Directive data during this project, but this is available and should be analysed prior to a restoration project. If water quality is found to be an issue for the seagrass, this should be improved prior to a restoration project.
   - **b.** It is recommended that boat users are positively encouraged to moor elsewhere to avoid damaging the seagrass beds.
3. Restoration should focus within the area outlined in Figure 6.

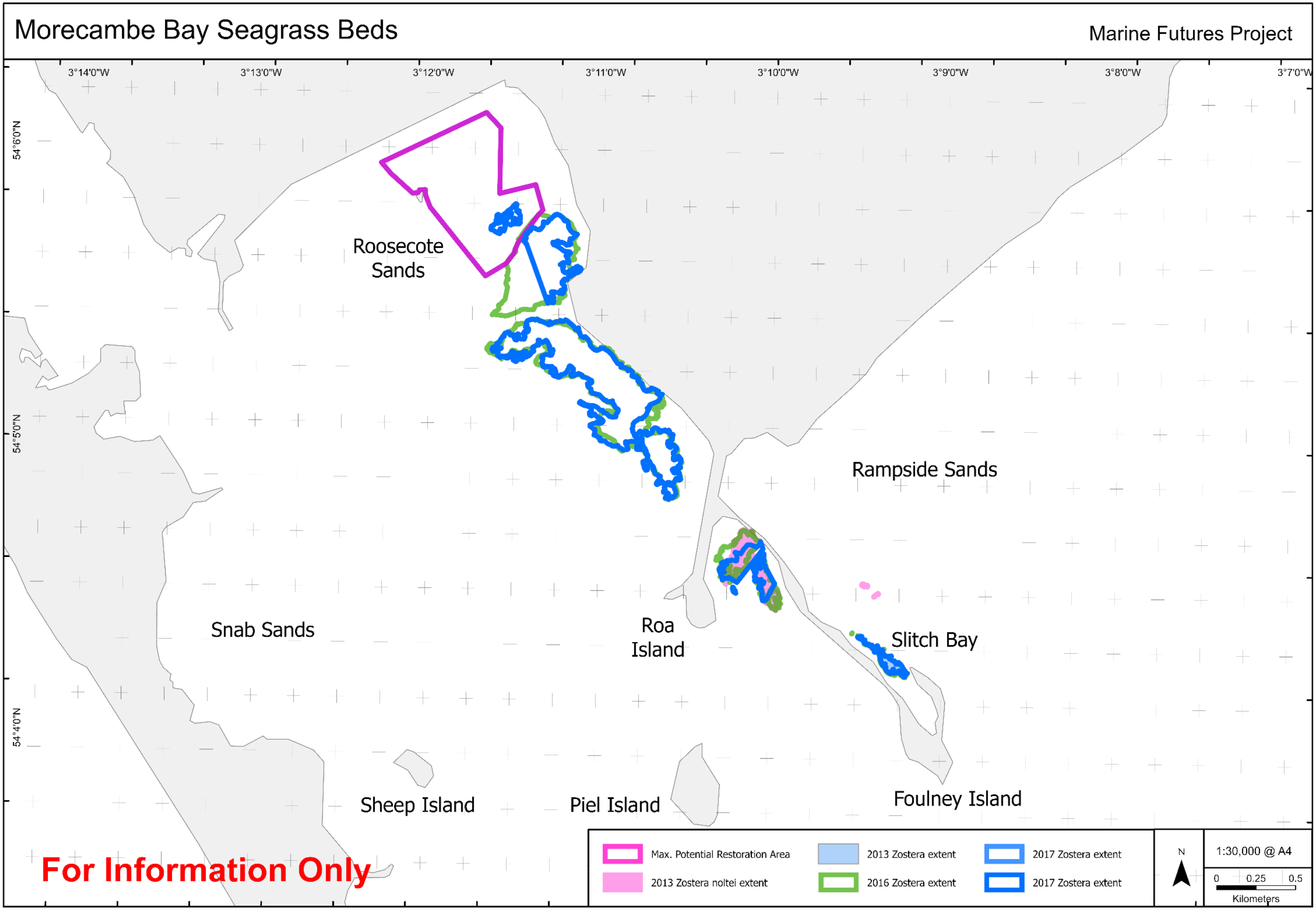


Figure 6 – Potential Restoration Area and historic seagrass data (2013, 2016 and 2017).

Restoration Methodologies

This section summarises the potential methods that can be used to restore seagrass, drawing on the knowledge of experts and literature[1]. There are three main materials that can be collected and planted for restoration; seeds, seedlings and rhizomes:

Seeds

The majority of modern restoration projects collect and deploy seeds to restore seagrass meadows. This is thought to be the most ecologically friendly restoration technique (Boudouresque *et al*., 2021).

Seed Collection

Seed collection involves collecting seed fronds when they are ready to pick, often around August, although individual beds do vary in timing. As *Z. noltei* is intertidal, the only suitable collection method is hand picking to avoid damaging the existing beds. Jayes (2021) estimates it can take one person about 8 hours to collect about 1,000 seeds.

The seeds can then either be separated from the frond by hand (one person can approximately separate 100 seeds in an hour (Jayes, 2021)) or by putting the fronds in tanks with an aerated flow and allowing the fronds to go through the rotting phase, releasing the seeds sink to the bottom due to their negatively buoyancy (Unsworth *et al*., 2019a). Invariably some fronds will also sink, in which case a plankton net can be used to allow the seeds to fall though but collect most of the fronds that would otherwise sink (Jayes, 2021). After this, seeds can be separated out for storage. This is a reasonably low-skilled task that can be done by volunteers or trainees.

Seed Storage

There is still a lot of uncertainty about the storage of both *Z. noltei* and *Z. marina*. Temperature and full saltwater can keep seeds dormant and bluelight can halt germination, however the effects of these on seed viability is unknown (Jayes, 2021). Jayes (2021) has found that *Z. noltei* seeds will germinate if they have been stored in 3ºC of clean saltwater (although the rates of germination are unknown; Yorkshire Wildlife Trust are hoping to research this in 2021).

Seed Deployment in Hessian Bags

While there are a range of methods for planting seeds (including spreading by hand, the use of seed buoys (Pickerell *et al*., 2015), planting in coconut matting (Sousa *et al*., 2017)), the majority of current restoration projects deploy *Zostera* seeds in hessian bags. As such, it has become the tried and tested method for seagrass restoration. Using hessian bags helps to anchor the seeds in place during germination, thus minimizing the impacts of water movements in areas where there is a large tidal range (Unsworth *et al*., 2019a). This makes it a suitable method for the environment of Morecambe Bay.

The bags also provide protection from potential predators, enabling protected germination and growth through the hessian fabric. Bags must be made of 100% natural fibers (avoiding hessian bags where the fibers are coated in silicon (Unsworth *et al*., 2019a) or include plastic (Jayes,

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[1] A seagrass restoration handbook is currently being written by several seagrass experts and practitioners in the UK as part of the ReMeMaRe project. This is due to be published this year and will be extremely valuable for any progression of this project. When published, the document will be available here.

2021)), making them environmentally-friendly as they break down within a few months of deployment, allowing rhizomes to establish and embed into the sediment (Unsworth *et al*., 2019a).

Using bags, each filled with 100 seeds, linked by hessian rope and anchored to the seabed with metal pins, Unsworth *et al*., (2019a) have demonstrated that when deployed in a suitable environment 94% of bags develop into mature seagrass shoots. This study planted *Z. marina* seeds; however this method has also been used for *Z. noltei*. Other projects have shown the bags can either be linked with rope and anchored with metal pins, or simply filled with enough sand to sufficiently weigh them down on the seabed.

It's best to use donor sediment from the same area to avoid introducing invasive and non-native species and diseases (Jayes, 2021). If this is not possible, a heavy compost may be used, however algal growth may become problematic. Sediment should be added to the bags with seagrass detritus (fronds) to provide nutrients and microbes (Unsworth *et al*., 2019a).

As each rhizome can reach 50cm from the plant, planting one bag per square meter is thought to be the optimal planting distance. Jayes (2021) uses a pottieputki to make holes and insert the bags, sending them down the tube and gently brushing sediment overtop, estimating a planting time of about 8hrs for 1 acre (0.405 ha). The seeds don't want to be pushed too deep, just below the surface, and the anoxic layer of sediment must be avoided (Unsworth *et al*., 2019a). To limit water movement, seeds should be planted after the spring storms (around March), on neap tides.

Seedlings

Planting seedlings can reduce the risk of morality as you are planting established seedlings (Jayes, 2021). This is an ecologically friendly and low-cost technique that has been successfully used worldwide (Boudouresque *et al*., 2021).

You can force germination of *Z. noltei* and *Z. marina* with commercially available freshwater, as this draws water into the seed, ruptures the seed and allows germination. Jayes (2021) has found that placing seeds in a jug of freshwater, at around a pH of 8.1/8.2, for 36 hours initiates germination in *Z. noltei*. While germination may occur from tap water, it's best to use distilled or de-ionised water to avoid chlorine. pH may influence germination.

Seedlings can be grown in the hessian bags placed in temperature- and salinity-controlled tanks of water under a maximum of 3-4 inches of water. Growing these in sunlight is probably best for photosynthesis, however if this is unviable, fish tank lighting around 8.5 thousand kelvin (i.e. a warm light) and avoiding bluelight works (Jayes, 2021).

Seedlings can be planted in hessian bags to help anchor the seedlings in place; trials by Yorkshire Wildlife Trust have determined this is the best method (Jayes, 2021). Seedlings should be planted after the spring storms (around March), on neap tides, with one seedling per square meter (as each rhizome can reach 50cm from the seedling).

Sods/Rhizome Fragments

Simply cutting and moving sections of seagrass meadow is thought to be one of the best ways to restore seagrass. However, this method is not as widely accepted by funders and regulators and is unsuitable for small seagrass beds (Jayes, 2021).

Cement slabs or cement frames around wire mesh has been used to retain cuttings, however this is not thought to be environmentally friendly as the cement will persist for centuries. Furthermore, planting on cement structures is thought to limit restoration success. Similarly, metal or plastic grids have also been used for other seagrass species. Fixing cuttings to the seabed with stakes or staples has been used at a number of sites worldwide (Boudouresque *et al*., 2021).

Cylindrical plugs (of plant, roods and sediment) have been used to transplant *Z. noltei* in Provence and a range of seagrass species in other locations. The transportation of large clods may be advantageous as large numbers of shoots can be transplanted simultaneously and the shoot's and root's invertebrate fauna can be preserved and transferred with the clod (Boudouresque *et al*., 2021).

Things to Consider

Anchoring & Planting

Planting techniques influence restoration success. The most important factors affecting success is thought to be the anchoring technique and plant material. Anchoring of seedlings or rhizome fragments using weights (sand bags, stones or shells) enhances survival compared to restoration projects which have not used any anchoring (van Katwijk *et al*., 2016).

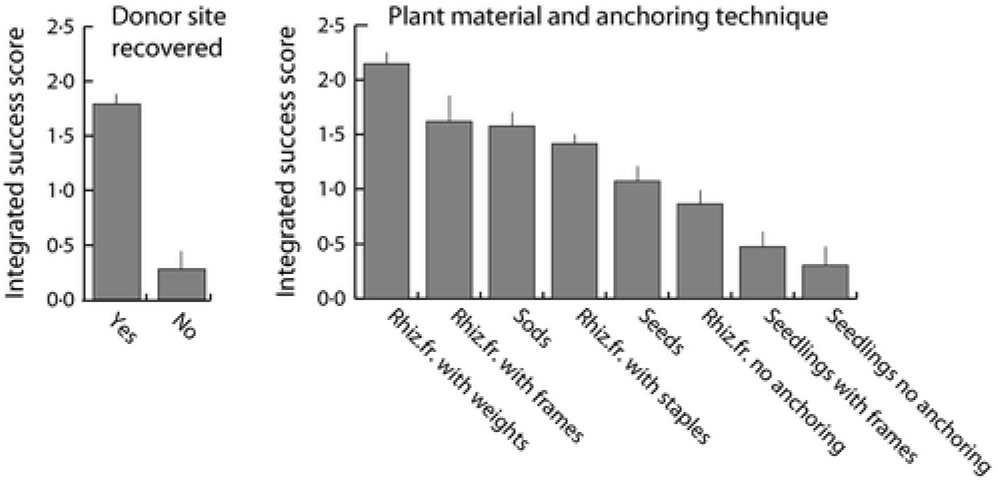

Figure 7 - Performance of seagrass restoration trials in relation to plant material and anchoring techniques. The semi-quantitative integrated success score and its standard error of the mean were calculated from initial survival and long-term performance after initial survival. Rhiz.fr. = rhizome fragments (reproduced from van Katwijk *et al*., 2016)

Manual planting is thought to be more successful in the long term than mechanical planting methods (van Katwijk *et al*., 2016).

Donor Beds

The proximity of the donor bed (the one from which materials are collected for restoration) is positively correlated with restoration success (Figure 8). Collecting material from local beds may be beneficial due to the presence of locally adapted gene complexes (van Katwijk *et al*., 2016).

Collecting from local beds may also reduce the time and thus physiological stress the material goes though prior to planting (van Katwijk *et al*., 2016).

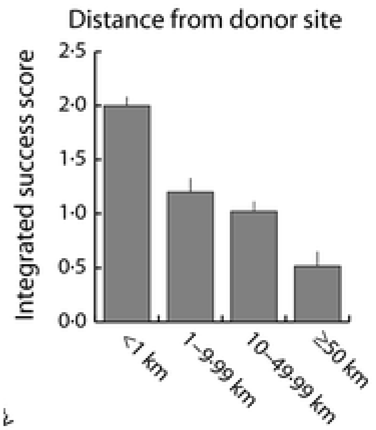

Figure 8 - Performance of seagrass restoration trials in relation to distance from the donor site. The semi-quantitative integrated success score and its standard error of the mean were calculated from initial survival and long-term performance after initial survival (reproduced from van Katwijk *et al*., 2016).

The Effect of Scale

Large-scale planting increases trial survival and seagrass population growth rates because with increasing numbers of initially planted individuals; (1) the survival percentages increases, relating to the spreading of risks to overcome environmental variability (i.e. planting over a larger area increases the range of environmental conditions experienced and hence the likelihood of encountering suitable conditions for growth); and (2) the population growth rate increases, due to positive feedback (Figure 9; van Katwijk *et al*., 2016).

A large investment in high numbers may be needed for dynamic systems to capture windows of opportunity generated by spatial heterogeneity and to reach a threshold required to initiate self-sustaining feedback. Evidence suggests a threshold of scale of the restoration trial required for restoration progress is between 1,000 and 10,000 shots/seeds, although this will vary over time and in space depending on factors such as stress levels and natural variability (Figure 9van Katwijk *et al*., 2016).

Where investment and the number of plants is limited, there is a trade-off between investing more in either spatial extent or in planting density (Figure 10). In highly dynamic systems with large unpredictable disturbances, environmental forcing will overrule benefits from restoring feedback and thus the spreading of risks is of paramount importance. A focus on large spatial extent is therefore preferable (van Katwijk *et al*., 2016).

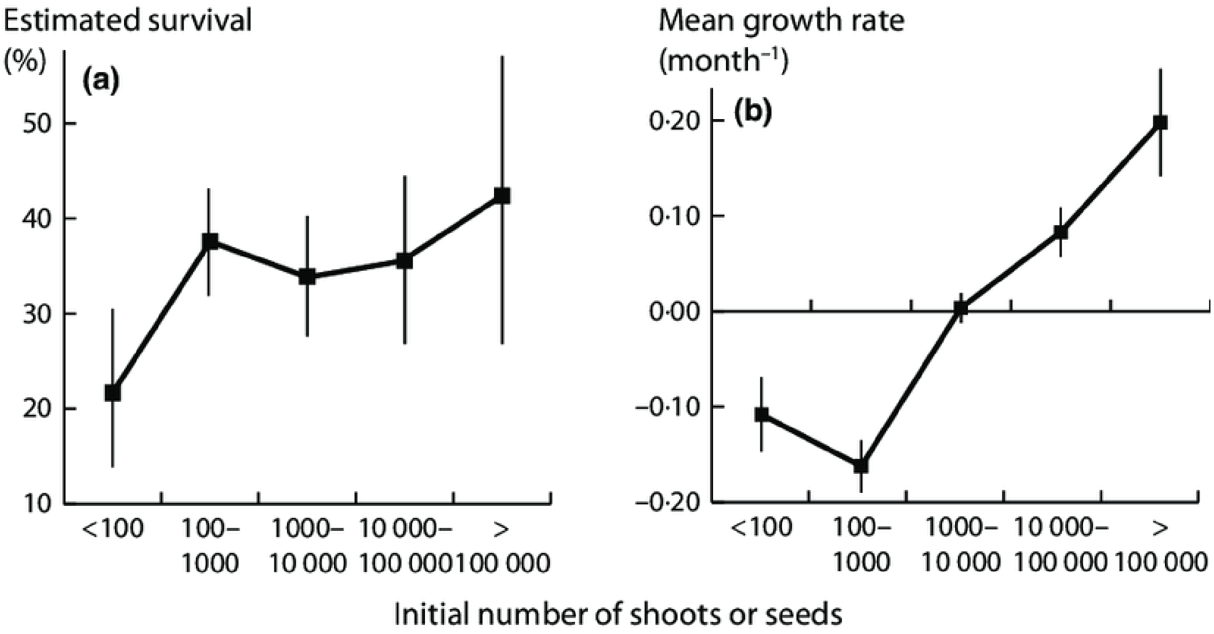

Figure 9 - Positive effects of restoration scale (number of initially planted shoots) on trial survival and population growth rate of seagrass in trials that survived. (a) Kaplan–Meier-estimated trial survival after ≥ 23 months, ± confidence interval (proportional hazard model over entire period: P = 0.0070); (b) Log mean population growth rate (log of increase in number of shoots mo-1) ± standard error of the mean, ANOVA P < 0.0001, d.f. = 4 (reproduced from van Katwijk et al., 2016).

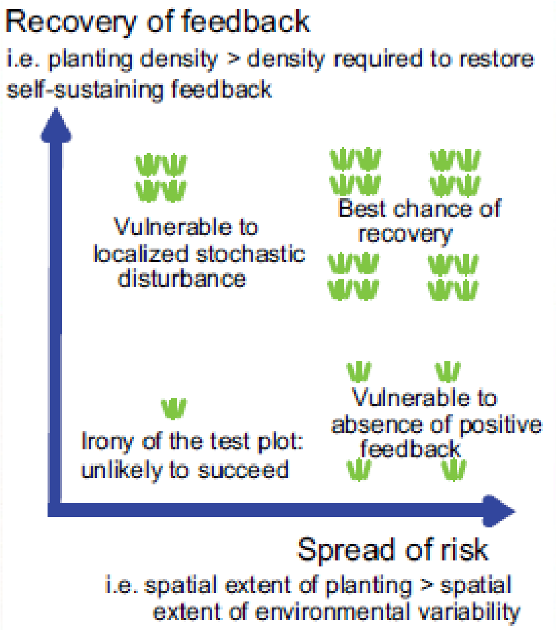

Figure 10 – The synergy in spatial extent and planting density and the trade-off between investing in spatial extent or planting density (reproduced from van Katwijk et al., 2016).

Permissions and Marine License Requirements

Any restoration project must gain the permission of the landowner. Marine licenses will be required for the project, due to the collection of seeds and sediment. Many restoration projects have found that as the projects require the extraction and deposition of sediment, they need to apply for a marine license similar to those used by the aggregates industry. Further to this, the extraction of seeds is likely to require a license.

Cost Considerations

While planting a larger area may be beneficial (see The Effect of Scale, p.25) it is recognized that this is costly due to the large amount of resources required to extract donor material and the operational costs.

Costs can be substantially reduced by collaborating with an organisation which already has suitable facilities. Local businesses or aquariums in the area may be able to supply these. Aquariums will have knowledge of aquaculture and are often very keen to collaborate on conservation projects due to requirements for licensing schemes (e.g. BIAZA - the British and Irish Association of Zoos and Aquariums). Working with these can also help to meet funding targets for the number of people to reach.

Key Recommendations for a Future Seagrass Restoration Project

Identified Location to Focus Restoration Efforts

Restoration should focus on Roosecote sands within the area identified in Figure 6. It's estimated a maximum area of 49.330 ha (493305 m^2) is available for restoration

Further details can be found under Potential Restoration Area – Where to Restore (p.20).

The Most Appropriate Restoration Technique

While planting of sods/rhizome has been shown to be the most successful, this is not thought to be appropriate for Morecambe Bay due to the small size of the beds and their protection as a feature of the South Walney and Piel Channel Flats Special Site of Scientific Interest (SSSI).

Planting seeds in hessian bags seems to be the most appropriate method for highly intertidal environments as the bags protect and anchor the seeds to the seabed. This is the most ecologically-friendly and tried and tested of all the restoration methods, with proved success, making it the most likely method to attain funding for.

To restore the whole 49.3305 ha area a minimum of 493,305 seeds would be needed to plant at the absolute lowest effective density of one seed per square meter. Planting 100 seeds per square meter is recommended for restoration success and would require 49,330,500 seeds for the whole restoration area. A balance needs to be met between planting the largest area possible and planting at an effective density. When determining the number of seeds to plant, the space available for storage and resources (funding, time and number of people) available for planting also need to be considered.

The amount of seeds the existing beds produce will depend on factors such as temperature, salinity, current density and trampling, and may vary in different areas. A lot of the literature is based on healthy beds, assuming a high fecundity. It is therefore very difficult to estimate the amount of seeds a bed will produce. Jayes (2021) notes that areas of the Yorkshire *Z. noltei* beds will only produce a few seeds, despite full density, and some areas could potentially produce much higher than estimates in the literature. With this in mind, an average of three papers in the literature (cited in Zipperle *et al*., 2009) estimates an average of 1665 potential seeds per meter square of *Z. noltei* (further research into the average potential seed production would be beneficial). If this is multiplied by the area of the existing beds combined, this equates to 1,156,395,780 seeds and thus collecting 493,305 and 49,330,500 would equate to 0.04% and 4.2% of this total seed production estimate respectively.

It is likely restoration of this whole area will not be possible due to limited resources (especially finances), in which case, the area closest to the current seagrass beds should be restored, due to the influence of proximity to donor beds on restoration success.

Community and Organisation Involvement

A lack of awareness of what seagrasses are and a limited societal recognition of the importance of seagrasses in costal ecosystems is though tot be one of the biggest global challenges for seagrass conservation (Unsworth, *et al*., 2019b). In order to enhance restoration success, the community should be engaged to in order to prevent damaging activities on the seagrass beds and restoration area.

Due to limited resources it was not possible to officially form and hold a seagrass stakeholder working group meeting within the timescale of this project, however this is recommended for the future.

Blue Carbon Value of the Beds & Maximum Potential Restoration Area

Seagrass meadows are a significant source carbon sink. Using an average net sequestration rate for seagrass of 83 g C m-2 yr-1 (Duarte *et al*., 2005; Laffoley and Grimsditch, 2009, p.26), estimates for the current and potential restoration area carbon capture of the beds within Morecambe Bay are presented in Table 2. This represents a conservative carbon capture rate. It should be noted, research into the carbon sequestration rate of *Z. noltei* is still developing.

Table 2 – Blue carbon calculations for the current and estimated potential restored seagrass area.

	m2 extent	g C m-2 yr-1	C g per annum	C kg per annum	C tonnes per annum	50 year carbon capture (tonnes)
Current area of beds	694532	83	57646156	57646.16	57.64616	2882.308
Potential seagrass restoration area	493305	83	40944315	40944.32	40.94432	2047.216

Questions for Further Research:

1. While this project has highlighted potential threats to the seagrass, a full in-depth review should be carried out prior to restoration. A particular question is whether the water quality is detrimental to the seagrass and may thus limit restoration success? A full analysis of Water Directive Framework data around the seagrass beds is required.
2. Consistent monitoring of the seagrass is needed (see p. 20). A current map of the extent of seagrass would be greatly beneficial to document if the seagrass bed is naturally extending into the potential restoration area at all.
3. Can you plant Z. *marina* for restoration of *Z. marina eco. angustifolia*? Will the plant grow into the ecotype because of where they are?
4. As *Z. noltei* is an intertidal species, will *Z.noleti* therefore germinate in damp conditions (rather than full water tanks)?
5. What are the optimal conditions (pH, temperature etc) for seed germination?

Note: Many of the questions above are currently unknown as this is an emerging field.

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