SPATIAL DISPLACEMENT OF NEARSHORE VEGETATION IN RESPONSE TO ARTIFICIAL CHANGES IN COASTAL MORPHOLOGY

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Abstract – The species composition of nearshore plant communities represents a continuous biological response to environmental gradients perpendicular to a marine shoreline. This response integrates individual adaptations, competition, abiotic variability, and chance events resulting in a definite 'optimum' band where a particular species attains highest density. Ultimately, this variation creates distinct vegetation zones where groups of species coincide in their optimum density. This study evaluated possible changes to nearshore plant communities in response to a change in shoreline. Surveys of vegetation assemblages were carried out in six coastal sites. Measurements of soil salinity and exposure to wind were also taken from each site. All six sites outcropped on the same bedrock and had a comparable overall seaward slope. Previous studies indicated that the species sequence was predictable: *Arthrocnemum macrostachyum* closest to the shoreline, with a *Limonium-Crithmum maritimum* zone adjacent in the inland direction. This was succeeded by a broader band of *Limbarda crithmoides* subsp. *longifolia*. Further inland, the subhalophilous assemblage dominated by *Thymbra capitata*, was the dominant cover. The perpendicular distance from the shoreline at which peak density of *L. crithmoides* was recorded, was taken as an indicator of the 'location' of the vegetation sequence. The variation in density of *L. crithmoides* perpendicular to the shoreline was unimodal and was modelled using a Gaussian 3-parameter distribution for each study site. The distance from the shore of the peak *L. crithmoides* density was positively correlated with the Thomas Exposure Index (adjusted $R^2 = 0.563$). These models were subsequently used to simulate the predicted shift of the vegetation sequence in response to a modified shoreline. The displacement in vegetation distribution following land reclamation is not necessarily subject to linear predictability. The abrupt change in shoreline morphology would modify the effects of environmental stressors, driving a displacement of nearshore plant communities towards the new shoreline. This displacement is unlikely to be either uniform or symmetrical, as the infill may have different sedimentological characteristics from the original substratum and initially will not have a persistent soil seed bank.

Introduction

The variation in species composition of nearshore plant communities represents a continuous biological response to environmental gradients perpendicular to the marine shoreline. This response integrates individual adaptations of vegetation, outcomes of competition, variability of environmental factors, and the occurrence of chance events, resulting in a definite 'optimum' band where a particular species attains highest density. The

variation in selection pressure perpendicular to the shoreline creates distinct vegetation zones where different species coincide in their optimum density. This vegetation sequence, in terms of lifeform and adaptations, is broadly present throughout the Mediterranean littoral and differs from site to site in terms of species richness, identity of the characteristic species, substratum, and rate of change in abiotic gradients. The relative position and compression of the sequence is directly related to effective distance from the shoreline and sequence displacement has been observed or inferred following changes in coastal morphology. As such, this ecologically-predictable perpendicular zonation of vegetation would be expected to displace in response to changes in the position of the shoreline, migrating upshore in contexts where shoreline erosion exceeds deposition of sediment and vice-versa. This, in turn, can be used to construct broad predictions about changes in the conservation status of communities and species, if the position of the shoreline changes. The upshore or downshore migration of coastal communities is not a straightforward process, as different species will 'migrate' at different rates based on their dispersal, colonisation and establishment mechanisms. The present communities are the result of a dynamic equilibrium of species composition that can be shifted into a new stable state leading to possible extirpation of species. Whilst gradual changes in coastal conformation are often the result of natural cycles, the responses to anthropogenic processes are usually much more rapid. These include the redirection of rivers, and, therefore, of their sediment, for energy production, agricultural purposes and other reasons. In locations with limited land area, this also includes the deliberate reclamation of land from the marine environment. In such cases, the formation of a new shoreline displaced seaward relative to the previous one, would represent an abrupt modification of abiotic parameters, followed by migration of plants into the 'new' reclaimed areas. This study uses the central Mediterranean island of Malta as a case study for the characterisation of the coastal community and prediction of its responses. Malta is small, relative to its population size (316 km^2; 516000 persons), with its high population density ($>1600 \text{ km}^{-2}$ in December 2020) exerting extreme pressure on all its resources, including land area. There have been several recent indications that the island's government would consider land reclamation favourably, and, if implemented, this would occur along the shallower north-eastern coast of Malta. The vegetation sequence in Malta, syntaxonomically within the *Crithmo maritimi-Limonietea* alliance [4], occurs along much of the rocky coastline of the island. The band closest to the shore is colonised by halophytes and small chasmophytes whilst with increasing perpendicular distance this assemblage is replaced by a subhalophilous pulvinate assemblage. As such, this study aimed to predict the probable effects of changing coastlines on the distribution of halophytic communities and of protected species that occur in these zones. More specifically, the study aimed to accomplish the following:

(a) Determine the optima and limits of tolerance (in terms of perpendicular distance from the shoreline) of *Limbarda crithmoides*, an indicator species, in various areas along the coastline of Malta.

(b) Quantitatively predict plant community change in response to given changes in coastline extension.

The results of the study would subsequently inform conservation and restoration initiatives that should be associated with any land reclamation strategy.

Materials and Methods

The study was carried out in three coastal areas in Malta: Ghallis, Pembroke and Qalet Marku. These three sites were selected as they have been identified as possible sites for land reclamation by the Environment and Resources Authority of Malta. Where possible, sample sites with different aspects within the same area were identified and utilised, two such sites were selected at Ghallis, and three at Qalet Marku, giving six sample sites in total (Ghallis 'northwest', Ghallis 'east', Qalet Marku 'A', 'B' and 'C', and Pembroke). These sites will henceforth be referred to as Gh-NW, Gh-E, QM-A, QM-B, QM-C and PMB respectively.

The authors had access to detailed species occurrence and distribution records from three sites (QM-A, QM-B and QM-C) over a 5-year period (2015-2020) and this was used as a comparative baseline for the present study. A review of these previous studies indicated that the species sequence was predictable: *Arthrocnemum macrostachyum* colonising rock closest to the shoreline, with a *Limonium-Crithmum maritimum* zone adjacent in the inland direction. This was succeeded by a broader band of *Limbarda crithmoides* subsp. *longifolia*. Further inland, the subhalophilous assemblage dominated by *Thymbra capitata*, accompanied by *Crucianella rupestris*, *Cichorium spinosum* and other sprawling forms was the dominant cover. The nearshore community comprises several species with a restricted local distribution including endemic species (*Limonium zeraphae*, *L.melitense*, *Anthemis urvilleana*).

The surveys associated with this study required greater resolution of species distribution than was available in the baseline studies. Given the area of the sample sites, it was deemed feasible to carry out vegetation analysis using 'whole-site' orthophotos rather than limited linear transect samples. This necessitated detailed aerial surveys and photography for each study site. Aerial surveys were conducted using a DJI Mavic 2 Pro drone equipped with a Hasselblad L1D-20c camera, 1" CMOS, 20 million effective pixels sensor and lens of 35 mm Format-Equivalent 28 mm with Field of View (FOV) of approximately 77° and an f/2.8 aperture. The images produced by the drone were each 5472 x 3648 pixels in size. The flight plan was pre-programmed on Litchi Flight Planner [12]. Pilot studies indicated that photos taken at an altitude of 20 m retained sufficient ground resolution to permit individual large shrubs to be identified to species based on their habit and colour. The flight path constructed virtual transects 10 m apart or less to ensure an adequate area of overlap facilitating the accurate alignment of photos. The separate aerial photos were combined into an orthophoto using Agisoft Metashape Professional v.1.6.3 [1].

The regularity and predictability of the sequence of vegetation over the baseline period (2015-2020) suggested that the use of an indicator species to 'locate' the sequence was justified. The most suitable species for this purpose was *Limbarda crithmoides* subsp. *longifolia*. This plant was present in all study sites across all years of the baseline period, it is large and distinctive enough to be identified easily from aerial photographs, and it is sufficiently abundant and dense to form a well-defined zone. The population density of *L. crithmoides* in each study site was obtained from the orthophotos. The orthophotos were calibrated in FIJI [10] and a virtual grid of 1 m^2 squares overlain on each image. Random squares were used as the origin for a virtual 10 m^2 x10 m^2 quadrat in which all *L. crithmoides* individuals were counted. As many non-overlapping virtual quadrats as possible were taken for each site. The perpendicular distance from the shoreline at which peak density of *L.*

crithmoides was recorded in each site, was taken as an indicator of the 'location' of the vegetation sequence. These peak values were estimated by fitting a 3-parameter Gaussian distribution model to the data relating the density of the *L. crithmoides* population with distance from the shoreline:

$$f = ae^{-0.5(\frac{x-x_0}{b})^2}$$

In this model, *f* is the density of the *Limbarda crithmoides* population at distance *x* from the shoreline, *a* is the 'peak density', x_0 is the distance from the shoreline at which the peak density occurred and *b* is the width or 'tolerance' of the zone occupied by the species. These parameters were subsequently correlated with the values of the environmental factors measured from each site to assess the contribution of each of the plant's distribution. The principal environmental factors that were measured at each site included variation of soil salinity, slope, geographical aspect and exposure to wind and wave action. The geographical aspect of each site was read off from maps. The slope at each site was measured using a clinometer, with all required procedural precautions taken. The slope was measured at every break of slope perpendicular to the shoreline and an overall value for the slope in each site was obtained. For the assessment of soil salinity (measured as electrical conductivity), several samples of surface soil were collected from each of the study sites, at different perpendicular distances from the shoreline. Soil samples were taken to the laboratory immediately after collection and frozen at -20°C until processed. In the first step of processing, the soil samples were allowed to thaw at 25°C for 36 hours, after which 20g of soil from each sample was weighed and suspended in 100 mL deionised water. The suspension was mixed for 30 minutes and allowed to settle for a further 15 minutes. The electrical conductivity was then measured by taking several replicate readings using a TPS 90-FL desktop conductivity meter. The entire procedure was repeated twice per soil sample, and all necessary procedural precautions were taken [7]. The exposure of each site to wind and wave action was estimated using the Thomas Exposure Index (TEI) [11] which assumes that wave action can be predicted from wind direction, wind duration and velocity and accounts for direction, shape, and angle of exposure of the shore. It also accounts for wind fetch and bathymetry of the seabed. This was carried out using a 12-division, wind rose, overlain on a map of each site of study. The centre of the wind rose was placed over the point of interest. The parameters noted to determine the TEI were the Wind Energy (W) obtained from meteorological tables, Fetch (F), the distance from the shoreline to the nearest headland in nautical miles, calculated using the Navionics webapp online portal [9]. For open shorelines this was taken to be 100 nautical miles. The third parameter was the critical depth for shallow water, the distance in nautical miles from the shoreline to the 6m bathymetric line (Cs). These were also read from the Navionics webapp online portal [9]. The TEI was subsequently calculated using the following:

$$TEI = \sum logW \, log\left(1 + \frac{F}{C_s}\right)$$

Results

  The variation in peak density (a), peak distance (x_0) and tolerance (b) of the *Limbarda crithmoides* population in each of the six study sites is given in Figure 1 and Table 1. As can be seen from the graphs, the peak distance x_0, varied from 28.7m (QM-A) to 51.5 m (QM-C). The tolerance of the fitted model was narrowest at PMB, Gh-E and QM-C, whilst it was much broader at the other sites.

  The variation in TEI with peak distance and tolerance across sites is given in Figures 2 and 3. These data suggest that higher TEI is negatively correlated with tolerance (r = -0.553; P = 0.255) and positively correlated with peak distance (r = 0.81; P = 0.052)

  The variation in the electrical conductivity of the surface soil across all sites is given in Figures 4 and 5. These data suggest a trend of decreasing median electrical conductivity and decreasing variance in the values of this parameter with greater distance from the shoreline even over such a narrow distance range. Although the median electrical conductivity varied across sites, there was no discernible pattern that correlated with any of the environmental factors considered during this study. In general, when taking all samples from all sites together, a distinct negative correlation between electrical conductivity and distance from the shorelines is evident (r = -0.433; P < 0.0001; n = 328).

Discussion

  The data collected during this study confirmed the predictable sequence of the vegetation zones of the sloping rocky coasts of the Maltese Islands, but also established a relationship between the peak density and tolerance of the fitted distribution with the exposure to wind and wave action. The predictability of the vegetation zones is related to the degree of specialisation of the plant species concerned. Smooth, non-hirsute photosynthetic surfaces, such as those of *A. macrostachyum*, *L. crithmoides* and *Crithmum maritmum*, allow any saline aerosol that reaches the surface of the leaves to drain off rapidly. This avoids the risk of the plant retaining high levels of salt on the surface of the leaves, which would ultimately result in further osmotic stress. The reduction of leaves is evident in many species found in these areas including *A. macrostachyum*, where leaves are reduced to scales and in which the principal photosynthetic organ is the stem. The photosynthetic output of stems has been shown to be comparable to photosynthesis from leaves [3], however a photosynthetic stem also reduces the surface area to volume ratio compared to photosynthetic leaves. Reduction of leaves, and consequently of stomatal leakage, is an adaptation against dry conditions. On assessing succulence in the different species of interest it was noted that *L. crithmoides* had a much higher succulence than any of the other four species investigated for succulence. *A. macrostachyum* is a stem-succulent [8] unlike *C. maritimum* and *L. crithmoides* both of which are leaf-succulent species. The stem of *A. macrostachyum* is anatomically complex, with several structures requiring space [6]. Therefore, succulence in this species is limited by space. *C. maritimum* and *L. crithmoides*, both being leaf-succulents do not have the same restriction as *A. macrostachyum*, both recording a similar median water loss. However, the variation range of *L. crithmoides* was much larger than that of *C. maritimum* indicating that the former has a much larger range of tolerance as succulence is varied depending on the conditions present at the site in which the species is thriving [2].

Land reclamation studies which have been conducted in the past have shown that the coastal vegetation is somewhat altered following the process of land reclamation and immediately after the process of land reclamation, the seed bank and vegetation change from that originally established [5]. As a result, the coastal zone would undergo serial modifications as the vegetation starts to encroach into the new area from various zones, with some species outcompeting others. The trends shown by the fitted models suggest that any modification in the position of the shoreline would be accompanied by a corresponding shoreward shift of the vegetation sequence, indicated by the position of x_0, in all sites. The principal determinant seems to be the variation in TEI, which would also influence the median electrical conductivity of the soil at every given point. As such, the former shoreline areas would, following reclamation, have lower TEI, lower median electrical conductivity and less variability in this parameter. The authors' unstructured observations of colonisation processes involving plants from the coastal community suggest that *Limbarda crithmoides* is generally the pioneer species in a regenerant primary succession whilst the other characteristic species only establish much later. As such, the most likely proximal outcome of extending the shoreline seaward is a shoreward migration of the *Limbarda crithmoides* zone and the subhalophilous xerophyte zone (*Thymbra capitata* and other species). This would lead to gradual replacement of the existing Crithmo-Limonietum formation as the relative fitness advantage of the halophytes and chasmophytes in this zone would be reduced. Physiological constraints would limit the shoreward migration of the subhalophilous xerophyte-*Limbarda crithmoides* formation leaving a broad bare zone. This would later be colonised by extreme halophytes such as *Arthrocnemum macrostachyum*, chasmophytes such as *Limonium* spp. and succulent species including *Crithmum maritimum*. The stochasticity associated with this colonisation has not been evaluated. However, the migration/extirpation/recolonisation sequence related to the reclamation process might lead to the local extirpation of potentially vulnerable species, such as the endemic *Anthemis urvilleana*.

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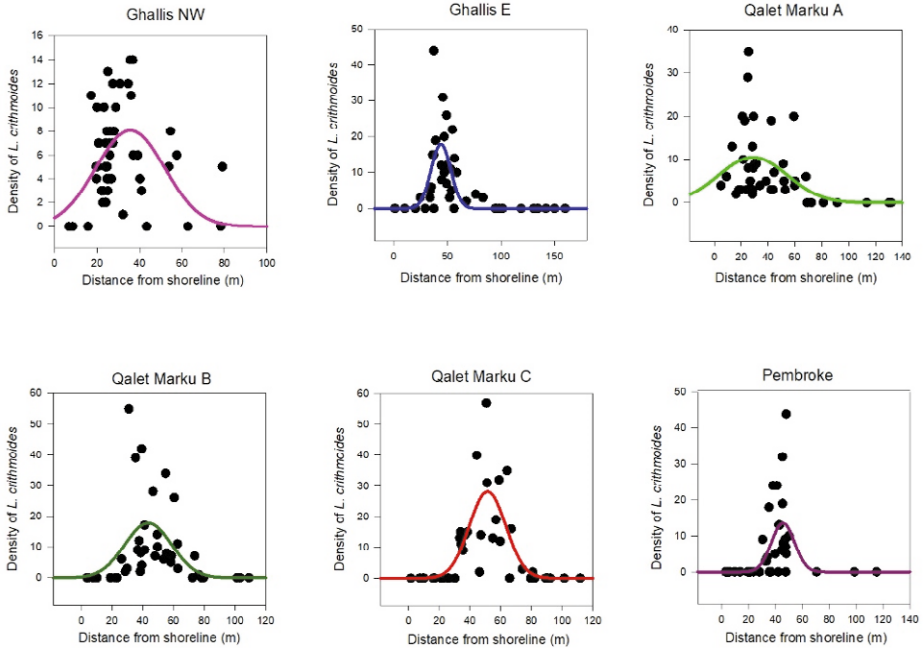
Figures and Tables

Figure 1 – Variation in population density of the *Limbarda crithmoides* population in each of the six study sites. The data points are measured values whilst the lines represent the fitted 3-parameter Gaussian model.

Table 1 – Summary of Gaussian model parameters (a, b, x_0) and TEI for each study site.

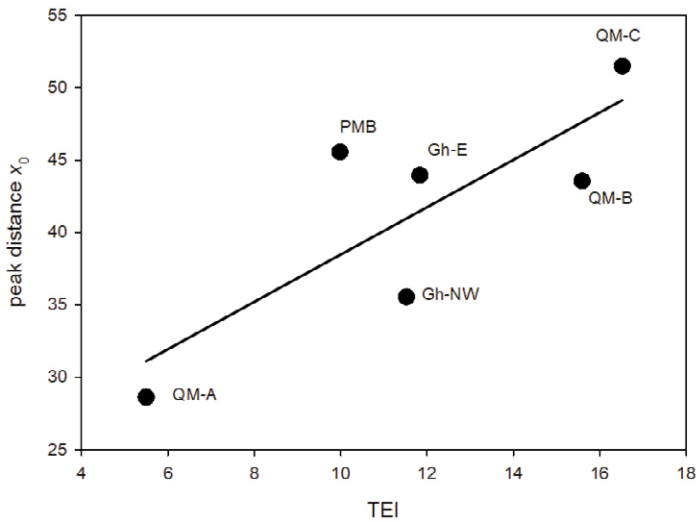| Site code	TEI	Peak density (a)	Tolerance (b)	Peak distance (x_0) (m)
Għ NW	11.52	8.1	16.3	35.6
Għ E	11.83	17.9	9.2	44.0
PMB	9.98	13.5	8.6	45.6
QM A	5.49	10.5	25.5	28.7
QM B	9.21	17.6	15.2	43.6
QM C	16.52	28.1	11.9	51.5

Figure 2 – Variation of peak distance (x_0) with TEI for all sites. R = 0.81; P = 0.052. Site codes – QM-A, Qalet Marku A; QM-B, Qalet Marku B; QM-C, Qalet Marku C, QM-C; Gh-NW, Ghallis northwest; GH-E, Ghallis east; PMB Pembroke.
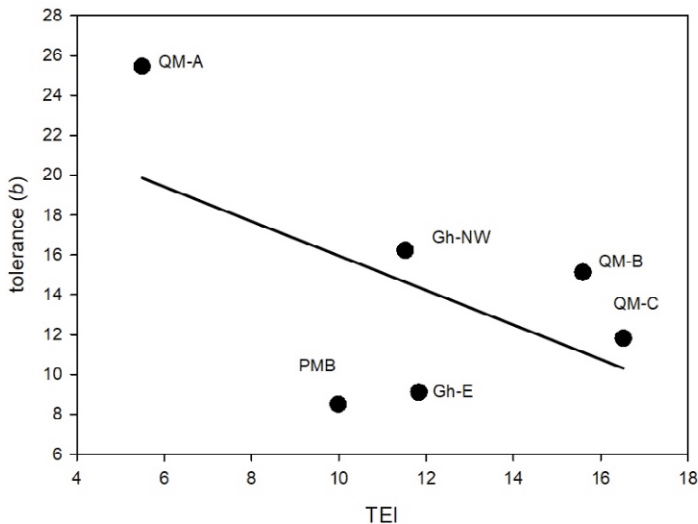

Figure 3 – Variation of tolerance (*b*) with TEI for all sites. r = -0.553; P=0.255. Site codes – QM-A, Qalet Marku A; QM-B, Qalet Marku B; QM-C, Qalet Marku C, QM-C; Gh-NW, Ghallis northwest ; GH-E, Ghallis east ; PMB Pembroke.
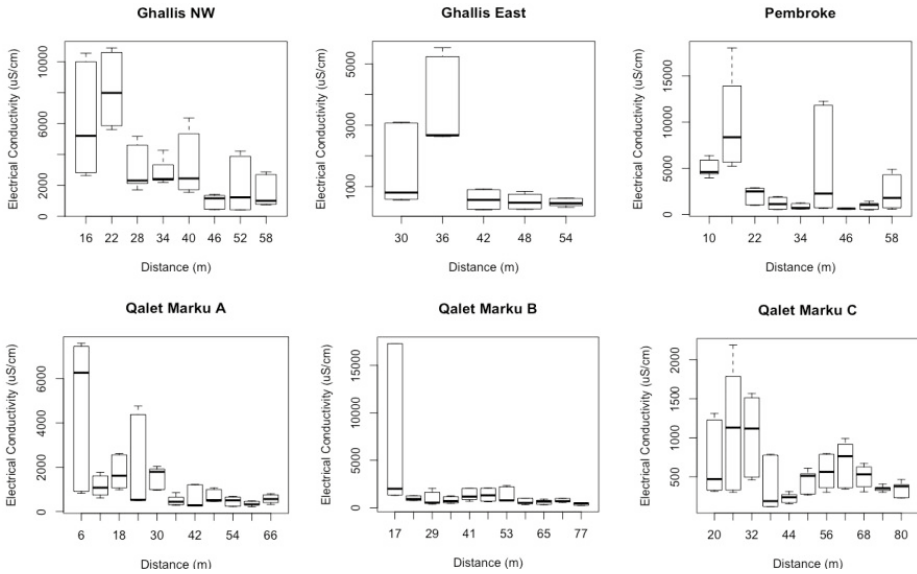
Figure 4 – Variability of median electrical conductivity in each site with distance from the shoreline. The upper and lower bounds of each boxplot represent the 75th and 25th percentiles respectively. Upper and lower error bars are situated at the 95th and 5th percentiles respectively.
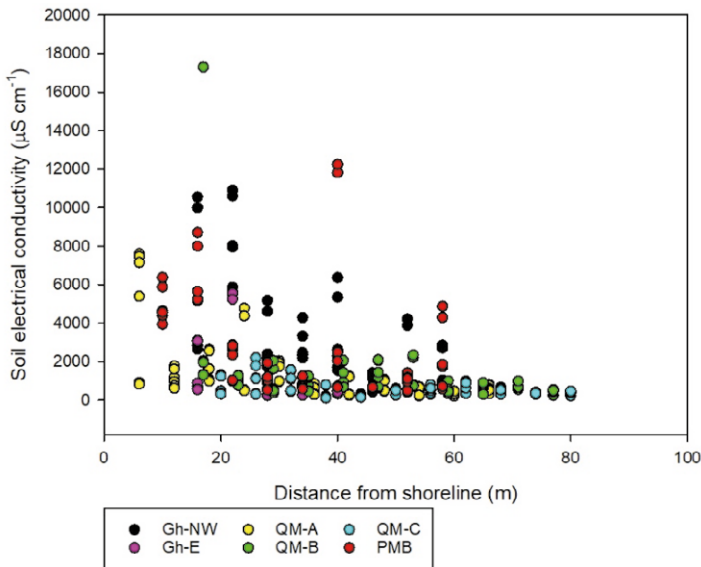

Figure 5 – Variation of electrical conductivity with distance from shoreline for all sites.