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Restored saltmarshes lack the topographic diversity found in natural habitat

Peter J. Lawrence[a], Graham R. Smith[a], Martin J.P. Sullivan[b], Hannah L. Mossman[a,*]

[a] School of Science & The Environment, Manchester Metropolitan University, Chester Street, Manchester M1 5GD, UK
[b] School of Geography, University of Leeds, Leeds LS2 9JT, UK

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ABSTRACT

Saltmarshes can be created to compensate for lost habitat by a process known as managed realignment (MR), where sea defences are deliberately breached to flood low-lying agricultural land. However, the vegetation that develops on MR sites is not equivalent to natural habitat. In natural sites, surface topography and creek networks are drivers of vegetation diversity, but their development on restored sites has not been well studied. We investigate the topographic characteristics of 19 MR areas, and compare these to nearby natural saltmarshes (representing desired conditions) and to coastal agricultural landscapes (representing conditions prior to MR). From high-resolution LiDAR data, we extracted values of elevation, six measures of surface topography (although two were later excluded due to collinearity), and three measures of creek density. MR and natural marshes differed significantly in all surface topographic indices, with MR sites having lower rugosity and more concave features, with greater potential for water accumulation. MR sites also had significantly lower creek density. MRs and coastal agricultural landscapes were more similar, differing in only one topographic measure. Importantly, there was no relationship between age since restoration and any of the topographic variables, indicating that restored sites are not on a trajectory to become topographically similar to natural marshes. MR schemes need to consider actively constructing topographic heterogeneity; better mirroring natural sites in this way is likely to benefit the development of saltmarsh vegetation, and will also have implications for a range of ecosystem functions.

1. Introduction

Saltmarsh is a valuable intertidal ecosystem that provides habitat for rare species, as well as important ecosystem services such as water regulation, wave attenuation, and recreation (Barbier et al., 2011). Loss of saltmarsh, particularly due to agricultural reclamation, has been substantial, with less than 50% of the extent of historic habitat remaining worldwide (Adam, 2002; Barbier et al., 2011). Although land claim still occurs, one of the major threats currently affecting saltmarsh is sea-level rise (Adam, 2002; Hay et al., 2015; Nicholls et al., 1999), exacerbated by the construction of static, hard sea defences, which prevent the natural landward migration of marshes, so that marshes are trapped between sea defences and rising sea-levels. This coastal squeeze results in loss of saltmarsh (Morris et al., 2004).

New saltmarsh is being created to combat this loss of habitat (Callaway, 2005; Zedler, 2004), partially motivated by legislation requiring its replacement (e.g. European Commission, 2007, USA Clean Water Act). Saltmarsh can be created through the process of managed realignment (MR), where sea defences are deliberately breached following the construction of new defences further inland, to allow tidal waters to flood the land between (French, 2006). Low-lying, coastal agricultural landscapes provide a key location for the restoration of saltmarshes, because much of this was saltmarsh prior to land claim.

Saltmarsh plant and invertebrate species can quickly colonise newly established MR sites (Garbutt et al., 2006; Mazik et al., 2010; Wolters et al., 2005), but community composition and function are often different to that found on natural saltmarshes. For example, plant communities that develop on MR sites are not equivalent to those found on natural saltmarshes (Mossman et al., 2012a). Furthermore, the vegetation on sites established on agricultural land accidentally breached during storm surges remains different to that on natural marshes, even 100 years post flooding (Mossman et al., 2012a). These differences in plant assemblages reduce biogeochemical functions such as carbon storage (Moreno-Mateos et al., 2012) and are likely to have knock-on effects on other plant-influenced ecosystem functions such as wave attenuation (Möller and Spencer, 2002; Rupprecht et al., 2017) and sediment erosion/ deposition dynamics (e.g. Ford et al., 2016), meaning that restored marshes are unlikely to satisfy legal requirements for biological and functional equivalency with natural marshes (Mossman et al., 2012a). Elevation (height above sea-level) is a key determinant of

* Corresponding author.
E-mail addresses: p.lawrence@mmu.ac.uk (P.J. Lawrence), g.r.smith@mmu.ac.uk (G.R. Smith), m.j.sullivan@leeds.ac.uk (M.J.P. Sullivan), h.mossman@mmu.ac.uk (H.L. Mossman).

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the vegetation communities that colonise restored sites because saltmarsh plants have clear elevational niches (Masselink et al., 2017; Sullivan et al., 2017; Zedler et al., 1999). Some restored sites were initially at low elevations because of relative sea-level rise and shrinkage of the land during the years of reclamation, and this may have limited vegetation colonisation (Garbutt et al., 2006).

Plant species also vary in their tolerance of poorly drained, waterlogged sediments (Davy et al., 2011; Huckle et al., 2002), with these conditions more frequent in some MR sites (Sullivan et al., 2017). However, the drivers underlying this increased waterlogging are poorly understood, although in some sites this appears to be due to poor drainage (Masselink et al., 2017). Local variation in surface elevation and shape, i.e. topography, can influence sediment drainage, with flat surfaces draining poorly. Increased topographic variation and complexity could increase the range in potential niches available and thus increase plant diversity (Kim et al., 2013; Moffett and Gorelick, 2016; Morzaria-Luna et al., 2004), which could influence the provision of ecosystem services such as flood defence (Rupprecht et al., 2017). Furthermore, topographic features such as creeks are important to saltmarsh functioning, as they supply sediment and water across the marsh, and provide nursery habitat for juvenile fish (Cavraro et al., 2017; Desmond et al., 2000; Peterson and Turner, 1994). Topography on natural saltmarshes can take many forms, such as hummocks, pans, creeks and levees (Fig. 1; Goudie, 2013). Land management during reclamation, such as ploughing, trampling and channelization of creeks, may reduce surface topography prior to restoration. For example, research at one MR site found reduced heterogeneity in surface elevation compared to natural marshes (Brooks et al., 2015). However, little is known about the topographic diversity of other restored marshes or how this topography develops over time.

We assess the surface elevation, topography, and creek network density and diversity of 19 MR areas, comparing these to natural saltmarsh and local agricultural reference sites. To do this, we use remote sensing (specifically, Light Detection And Ranging [LiDAR]) derived digital elevation models (DEMs), from which we calculate a range of topographic indices and creek network measures that describe the characteristics of the marsh surface. Using this data, we investigate the following questions: (1) Does topography differ between natural saltmarsh, restored saltmarsh (MR), and adjacent agricultural landscapes; (2) Does topography vary with age since restoration and with former land-cover; (3) Are any differences in topography between MR and natural saltmarshes consistent across the intertidal elevational range?

2. Methods

2.1. Study sites

Seventeen MR sites, ranging from 4 to 23 years since the date of breach, were selected along the south and east coasts of the UK (Fig. 2 and Table A1). Two of the MR sites were divided into two hydrologically distinct areas by sea walls or other landscape features, which resulted in a total of nineteen MR areas. MR sites were identified using the ABPmer online database (ABPmer Online Marine Registry, 2014) and aerial photography, and later selected based on the availability of LiDAR data after restoration, as well as to ensure coverage of a range of geographic locations and site ages. Twelve natural saltmarshes and fourteen agricultural plots were sampled as reference sites, representing respectively the desired end-conditions and likely starting conditions of

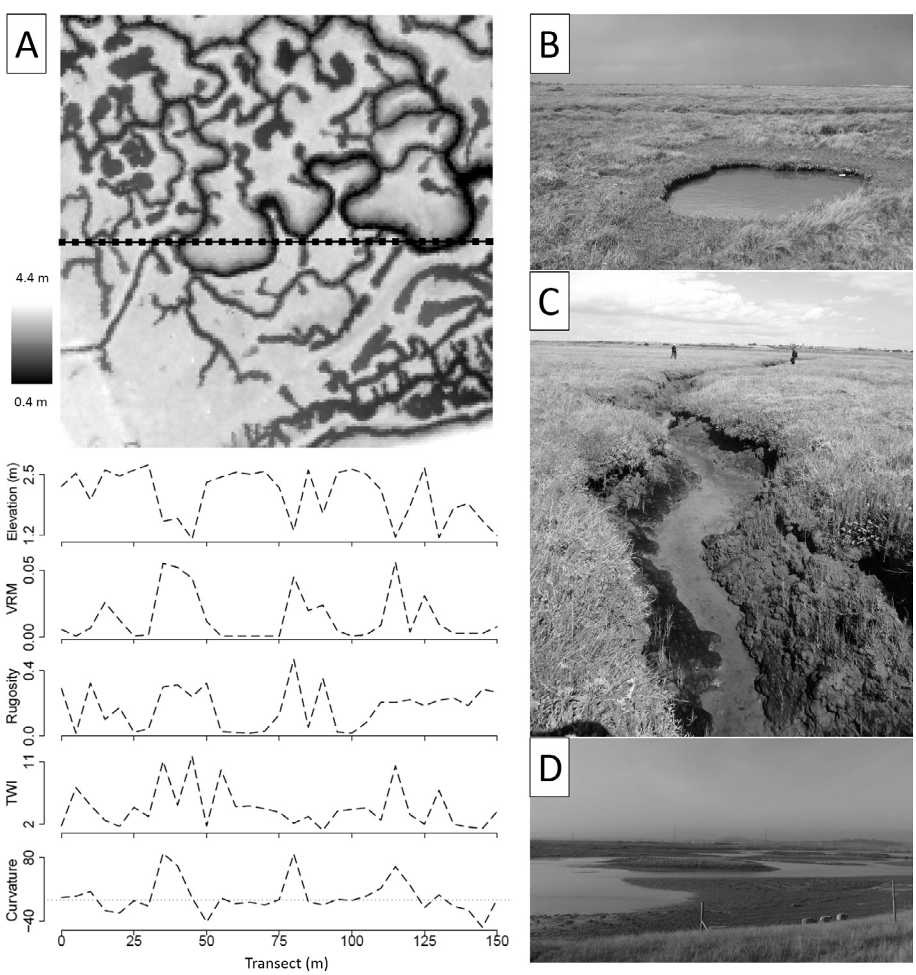

Fig. 1. (A) A sample digital elevation model from Tollesbury (Essex) showing elevation (m ODN). Topographic variables have been illustrated along a seaward transect represented by a dashed line. The five plots below show measurements every 5 m along this transect. From top to bottom these are Elevation, vector rugosity measure (VRM), rugosity (s.d. elevation), topographic wetness index (TWI) and profile curvature. For profile curvature, the dotted line separates convex (−ve) and concave (+ve) scores. Photos illustrate (B) a concave salt pan with high TWI and low rugosity; (C) a creek with variable TWI, concave profile curvature and high rugosity; (D) a constructed hillock at a MR that has low TWI, higher rugosity and convex profile curvature.