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Intertidal morphology change following *Spartina anglica* introduction, Tamar Estuary, Tasmania

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ABSTRACT

The surface morphology and sediment characteristics of introduced *Spartina anglica* marshes of the Tamar Estuary were analysed using a combination of spatial mapping, land-based topographical surveys, sediment coring and identification of the pre-introduction surface. Such a morphological investigation of estuarine change following *Spartina* introduction has not been attempted elsewhere before. A difference was found between marshes in upper and lower estuary. Surface topography of Type-1 marshes of the upper estuary was found to be independent of the pre-*Spartina* surface morphology, with deeper vertical development and exhibiting a flat to slightly concave upper marsh, a convex ridge in the outer mid marsh, and a relatively steeply graded convex lower marsh. Type-2 marshes of the lower estuary were thinner in vertical development, and with surface topography dictated by the underlying pre-*Spartina* surface. The difference was found to be due to variations in environmental conditions in sediment supply and wave/current exposure between the two regions rather being an indication of relative maturity. The seaward edge of marshes was found to be 0.5 m lower at the seaward end of the Tamar relative to the landward, reflecting tidal amplification up this confined estuary. While *Spartina* marshes are accretionary, surveys demonstrated retreat of the seaward margins throughout the estuary over the past 17 years, and the development of erosional scarps in Type-1 marshes. Spatial mapping identified 374 ha of *S. anglica* infestation within the Tamar Estuary, with Type-1 marshes occupying 240 ha and Type-2 marshes occupying 134 ha. Topographic profiles and stratigraphic data were used to estimate total sediment volumes trapped by *Spartina* in the Tamar Estuary, finding approximately 1,193,441 m^3 of material to have been trapped beneath *Spartina* since its introduction in 1947, of which between 14 and 28% has been *Spartina*-derived organic matter.

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1. Introduction

Spartina species were widely introduced to intertidal areas from the early 1800's owing to their role as ecosystem engineers (Jones et al., 1994, 1997; Strong and Ayres, 2009), influencing habitat change through promoting accretion. Dense *Spartina* swards of stiff stems and fleshy interwoven leaves work to slow the velocity of tidal waters, trapping suspended sediment in the axes of leaves (Thompson, 1991). Flow velocities across unvegetated flats increase exponentially with height from the bed surface (Leonard and Luther, 1995; Shi and Chen, 1996; Shi et al., 2000; Bouma et al., 2005a, b). However, dense *Spartina* vegetation causes frictional drag that reduces hydrodynamic forces such as turbulence (Leonard and Luther, 1995; Shi et al., 2000; Bouma et al., 2005b; Wang et al., 2008) as well as wave height and velocity (Strong and Ayres, 2009) to enhance deposition. By reducing turbulence and by trapping sediment, recently developed salt marsh canopy can also suppress re-suspension in comparison to non-vegetated areas (Shi et al., 2000). Stiff vegetation such as that of *Spartina* is therefore viewed as an adaptation to promote sedimentation, which increases marsh elevation (Bouma et al., 2005b).

The fertile allopollyploid F2 species *Spartina anglica* was first observed at Southampton, UK in the late 1800's (Baumel et al., 2001), and had spread to all suitable habitats along the coast of France, Netherlands, Germany and Ireland during the early 20th century (Strong and Ayres, 2009). The establishment of successful populations at these early sites demonstrated the ability of *Spartina* to accrete sediment and increase intertidal marsh elevation. European claims of its value in converting intertidal 'wasteland' into valuable farming and grazing areas resulted in the encouragement of further spread throughout the UK and the Netherlands (Hubbard and Stebbings, 1967; Boston, 1981) and deliberate introductions

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worldwide occurred in New Zealand, China and Australia (Boston, 1981; Partridge, 1987; An et al., 2007). Benefits have included reclamation, coastal protection (Chung, 2006; Strong and Ayres, 2009; Wan et al., 2009) and negative consequences have included threats to native species (Strong and Ayres, 2013), degrading coastal infrastructure and reducing productivity of industries such as aquaculture (Hedge and Kriwoken, 2000; Wan et al., 2009).

Salt marsh topography has been investigated in Europe and North America to show how native marshes evolve relative to controlling factors such as sea level change (Kirby, 1992; French, 1993; Schwimmer and Pizzuto, 2000; Schwimmer, 2001; van der Wal et al., 2002; Smith et al., 2004). Kirby (1992) showed that cross-sectional shape of mudflats directly relates to their erosional or depositional state, compiling profiles from the Humber, Medway, Wash and Severn Estuaries in the UK, to show that accretional mudflats exhibit a high, convex-upward profile, while erosional mudflats are relatively low and concave-upward.

Incorporating stratigraphy with topography, a conceptual model of macrotidal minerogenic salt marsh development (French, 1993) showed successive stages of marsh infilling from a shallow convex marsh surface upon a pre-existing surface, developing upwards with a flat-concave surface to reach Mean High Water Springs levels where raised banks along creek margins bring concavity to marsh surfaces. This followed the cross sectional model for intertidal flat to salt marsh development of earlier European research in macrotidal settings (Beeftink, 1966; Steers, 1977; Beeftink and Rozema, 1988). An actual model from a microtidal organogenic marsh showed three stages of evolution from an initial sequence of transgression of the marsh/inland border accompanied by erosion of the marsh shoreline, followed by continued transgression of the adjacent inland along with progradation of the marsh shoreline; and then transgression of the marsh/inland border accompanied by rapid shoreline erosion (Schwimmer and Pizzuto, 2000).

Net sedimentation rates following the establishment of *Spartina* have been established to be high, ranging from around 10 mm a^{-1} (Lee and Partridge, 1983; Long et al., 1999; Wang et al., 2008) up to over to 100 mm a^{-1} (Oliver, 1920; Ranwell, 1964; Chung, 1990). Greater stem density increases substrate buildup rates (Gleason et al., 1979; Callaway and Josselyn, 1992), and organic carbon in sediment accumulation increases under *Spartina* relative to pre-existing surfaces (Gao et al., 2012). While extensive work is available on such impacts of *Spartina* infestation on sedimentation rates, as well as nutrient and biogeochemical changes, alteration in habitat conditions and associated faunal changes (Daehler and Strong, 1996; Levin et al., 1998; Hedge and Kriwoken, 2000; Zhou et al., 2008; Cui et al., 2011; Gao et al., 2012) there has been no overall assessment of changes to estuarine geomorphology.

This study investigates the three-dimensional morphology and physical characteristics of *Spartina* marshes of the Tamar Estuary, Australia's largest infestation, using a combination of land-based spatial mapping, topographic surveys, sediment coring, and analysis of organic and inorganic sediment characteristics. Such a comprehensive investigation of whole system estuarine change following *Spartina* introduction has not been attempted elsewhere before, and allows estimation of sediment volumes trapped under *Spartina* marshes, the respective contribution of organic and lithic material in that sediment and net accretion rates.

The research objectives are:

1. To update the Tamar's extent of *Spartina* infestation through spatial mapping;
2. To determine the morphological change that has occurred following *Spartina* infestation by comparing recent profiles to the pre-existing surface, and earlier surveys (Phillips, 1975; Pringle (nee Phillips), 1993);
3. To determine the nature of organic and lithic sediment trapped by *Spartina* in the estuary, and estimate the total volume trapped since establishment.

2. The study area and *Spartina* introduction

Spartina anglica was first introduced to Australia in the 1920s at Corner Inlet, Victoria (Boston, 1981), and plantings in all states occurred shortly after. Only the coastal embayments of the south-eastern states proved climatically suitable, with populations persisting in Port Gawler, South Australia, Bass River and Western Port Bay, Victoria and estuaries and inlets of northern and eastern Tasmania. After management of many smaller infestations in the last 15 years, two major infestations remain today in Tasmania, the largest in Australia is the Tamar Estuary (Fig. 1), and a second large infestation occurs to the west in the Rubicon (Beasy and Ellison, 2013).

Tasmania is the southernmost state in Australia, extending across a latitudinal range of 39° 40′-43° 20′ S. The Tamar Estuary is one of Tasmania's largest estuaries (100 km^2) (Pirzl and Coughanowr, 1997), with a catchment area of approximately 10,000 km^2, about 20% of Tasmania. The majority of freshwater inflow into the Tamar Estuary is at the estuary head where the North and South Esk Rivers provide significant suspended sediment, and tributary outflow further north into the Tamar being minor (Ellison and Sheehan, 2014). The narrow drowned river valley is confined by bedrock, causing tidal amplification with distance inland, with a mean tidal range of 2.34 m at George Town and 3.25 m at Launceston (Foster et al., 1986), which are some 70 km apart. Mean daily temperatures are between 5 and 25 °C, and annual rainfall about 675 mm, with a winter wet season (Ellison and Sheehan, 2014). Water temperatures in the areas of the estuary occupied by *Spartina* vary from 10 to 23 °C through the year, and salinities 16–22°/oo (Attard et al., 2011).

Wave action within the estuary is driven by winds, and Bureau of Meteorology wind rose data shows that the dominant wind directions are north–westerly through to northerly, with some south-easterly influences. This suggests that the sinuous and incised nature of the estuary and the alignment of the valley influences wind direction throughout the *Spartina*-affected sector of the estuary. Wind speeds are relatively consistent, with average annual wind velocities ranging from 0.5 to 23.1 m s^{-1}. There is substantial diurnal variation in wind speeds, with 49.5% of wind speeds below 2.1 m s^{-1} at 0900 h, 21.6% percent of which are calms (<0.5 m s^{-1}). Conversely, 51.2% of wind velocities are between 3.6 and 8.8 s^{-1} for 1500 h with only 3.7% calms, reflecting afternoon land-sea breezes.

While wind direction and velocities are consistent throughout the estuary, the proximity of the *Spartina* marshes to the active channel varies significantly (Fig. 1). Sections such as Whirlpool Reach and south of Dilston are narrow with strong tidal currents, with the main channel located within 10–20 m of the *Spartina* marsh. However in the mid and lower estuary, several hundred meters of shallow water and mudflat occur between the *Spartina* marshes and the main channel. In these areas, wave energy is attenuated before reaching the intertidal marshes.

Prior to the introduction of *Spartina* the intertidal areas of the mid to upper estuary were almost completely bare of vegetation with the exception of a narrow 1–2 m fringe of native salt marsh vegetation at high water (Phillips, 1975). *Spartina* colonised mudflats in the upper estuary and intertidal rocky areas of dolerite or basalt, or beaches of gravel or sand (Pringle, 1993). Native salt marsh was limited to the innermost upper parts of protected bays in the lower estuary near high water mark (Phillips, 1975), habitats

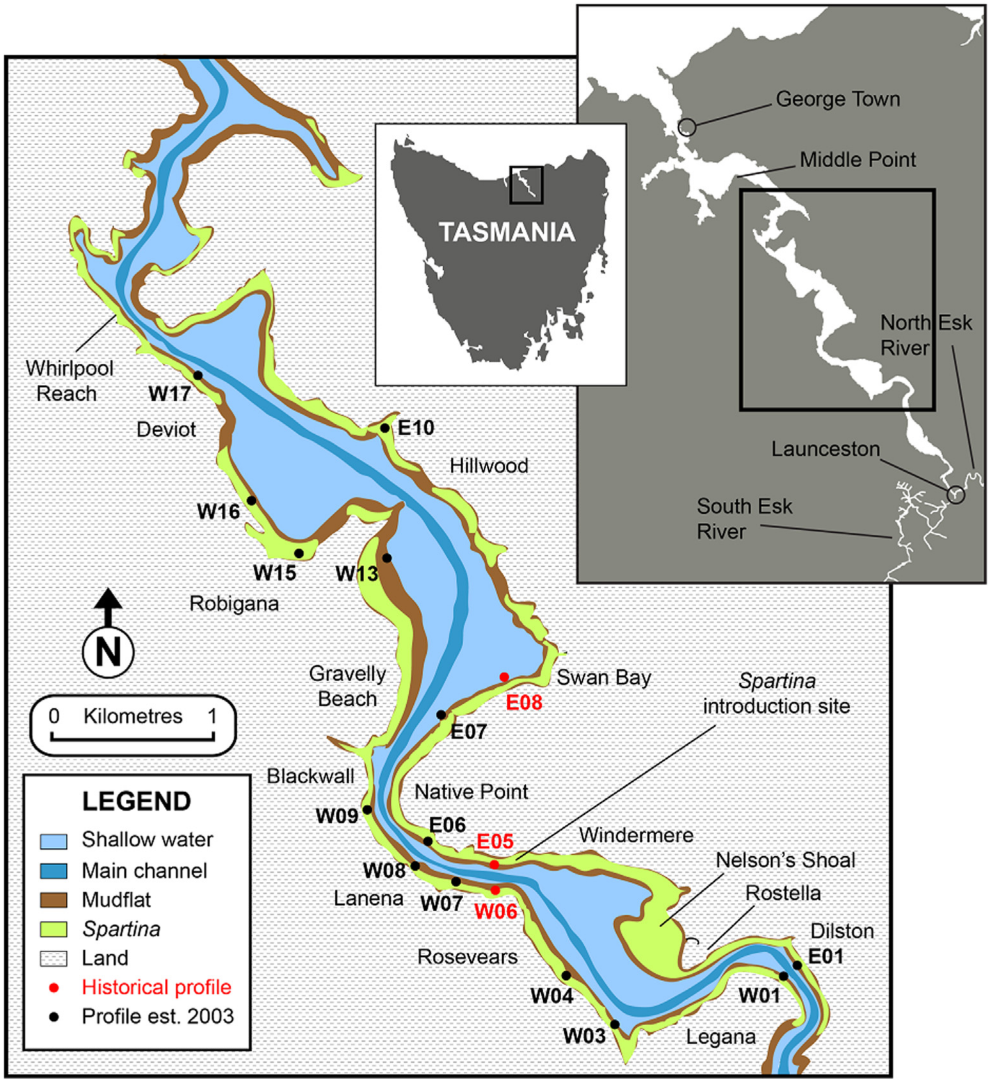

Fig. 1. Map showing the Tamar Estuary, extent of rice grass and locations of survey transects.

where it is found today (Ellison and Sheehan, 2014). *Spartina anglica* was introduced in 1947 at Windermere (Fig. 1) in an attempt to stabilise channel sediments and reduce estuarine siltation problems, by concentrating tidal flow in the shipping channel (Ranwell, 1967; Phillips, 1975; Pringle, 1993). Additional plantings were made soon after and in close proximity to the initial plantings, with a further 4047 m^2 planted in 1955 (Phillips, 1975). By 1998 the area of infestation had increased to 420 ha (Kriwoken and Hedge, 2000), at which time *Spartina* was continuing to spread towards the estuary mouth (Hedge, 1998), and the 2006 infestation size was estimated to be greater than 450 ha (DPIW, 2006).

Early work on the effects of *S. anglica* on the intertidal morphology of the Tamar Estuary included topographic analysis by Phillips (1975) and Pringle (1993). Profiles of the intertidal zone at the three initial planting sites of Rosevears, Windermere and Swan Bay (Fig. 1) were intermittently surveyed by the Port of Launceston Authority, showing development of these marshes over time (Phillips, 1975; Pringle, 1993). These surveys showed an increase in marsh elevation of 0.4 m at the lower part of the Rosevears marsh between 1977 and 1991, 0.1 m at the lower part of the Windermere marsh between 1983 and 1991, and 0.1–0.2 m at the upper part of the Swan Bay profile between 1983 and 1991 (Pringle, 1993). Pringle (1993) interpreted marsh maturity on the basis of outer edge type, with marshes having continuous outer margins and no isolated clumps or shoots seaward of this margin being described as having reached maturity. Conversely, marshes with relatively less accumulated sediment and undefined outer margins made up of isolated clumps of vegetation were described as young. Based on these definitions, Pringle (1993) identified that mature marshes occupied intertidal areas landward of Gravelly Beach, closest to initial *S. anglica* plantings, while maturing marshes were found in seaward sections of the estuary. *Spartina* marsh development in the Tamar Estuary has not been reassessed since 1993.

3. Methods

3.1. Spatial area assessment

Spartina extent in the Tamar was assessed using GIS (geographic information system) analysis of the most recent aerial photographs available from August 2006, which were rectified to a collage of ortho-photos taken in 2000 supplied as a single enhanced compression wavelet file, using an affine transformation. Due to the errors in the enhanced compression wavelet collage, the root mean squares values of the rectifications ranged from between 4 and 7 m, with a mean value of 6.48 m for all the photos. Polygons depicting the areas of *Spartina* marsh in the Tamar Estuary were constructed, and verified by ground truthing during topographic surveys in relation to permanent survey markers and datums.

3.2. Surveying of the intertidal zone

Obtaining surface data to assess the geomorphic state of salt marshes has included remote sensing techniques such as LIDAR (light detection of ranging) imagery (van der Wal et al., 2002; Blott and Pye, 2004; Rosso et al., 2006; Schmid et al., 2011), and hyperspectral and near infrared imagery (Smith et al., 2004). While GIS analysis of remote sensing imagery can produce errors (Cipolletti et al., 2012), an advantage of remote techniques is that they reduce the reliance on ground-based observations in salt marshes (Civille et al., 2005), which are difficult to access and work in. Hyperspectral imagery was found to give a good representation of ground-based topographic data in a marsh of the Westerschelde Estuary, Netherlands (Smith et al., 2004). However, remote techniques have some limitations, particularly in densely vegetated marshes, where the elevation can be interpreted as the height of the foliage rather than the sediment surface (Paine et al., 2004; Rosso et al., 2006). Topographic data are still widely collected using electronic total stations for the topographical and morphological assessment of salt marshes (Keim et al., 1999; Neira et al., 2005), and while they are time consuming and labour intensive, they provide high resolution data combined with intensive field observations of the conditions being surveyed.

A total of 16 shore-normal transects were surveyed across the intertidal zone spaced approximately every two kilometres throughout the *Spartina* sectors of the estuary, each adjusted to the centre of larger embayments (Fig. 1). These transects included the three historical surveys from the 1980s at Windermere, Rosevears and Swan Bay, to provide a comparative temporal study of morphologic development and topographical change.

Existing survey control data along the Tamar Estuary coastline were poorly positioned for this study and new benchmarks were kindly created by the State Government's Department of Primary Industries and Water (DPIW). These were established above high water mark in view of transects, and positions and heights derived using real time differential GPS based on existing Geocentric Datum of Australia control marks. The accuracy of the new benchmarks was verified by reoccupying them using different base stations, and shown to be 1 cm in the horizontal and 2 cm in the vertical. The observed ellipsoidal heights were converted to the Australian Height Datum (AHD) 1983 using the geoid model AUSGeoid98 (Geoscience Australia, 2013), and the AUSGeoid98 model was checked by occupying AHD benchmarks on both sides of the Tamar Estuary.

The mud surface along transects was surveyed from high tide mark to the low-tide extent of *Spartina* using a Topcon GTS-603 total station. A 1 mm depth aluminium sheet was placed on the marsh surface to prevent the reflector pole point from sinking into the mud. Surface elevation across transects was recorded approximately every 3 m or where there was a visible change in surface elevation. Point data (longitude, latitude and elevation) were downloaded to create marsh profiles along the surveyed alignment.

Historical profile data from marshes at Swan Bay, Windermere and Rosevears surveyed by A. Pringle and G Waldschmied between 1972 and 1989 were obtained from the Port of Launceston Pty. Ltd., and were adjusted to the Australian Height Datum 1988. Cross sectional profiles surveyed were overlayed with the recent survey to assess temporal change in morphology, relative marsh elevation and *Spartina* cover.

3.3. Determination of the pre-Spartina surface

The depth of the level at which *Spartina* colonised pre-existing surfaces was determined across all transects, collecting a total of 48 cores, 3 collected from each transect in the centre of the *Spartina* extent, and the upper and lower quartile. A side sampling Hiller corer was used, which avoids sediment compaction so is suited to research questions where elevation is critical (Ellison, 2008). In addition a stainless steel rod of 6 mm diameter was used to probe the depth of the pre-*Spartina* surface at all points across each transect. The calibrated rod was inserted until there was textural change in the substrate. Boulder beach and bedrock substrates were impenetrable by the rod, while the sandy gravels showed changed resistance compared to the overlying muds.

In the upper estuary and other bays where *S. anglica* had colonised existing mudflats, the depth of the pre-*Spartina* surface was determined from sediment characteristics in core stratigraphy. Prior to the introduction of *Spartina*, these intertidal areas were unvegetated (Phillips, 1975; Pringle, 1993; Bird, 2008). Compound specific stable carbon isotope measurements of salt marsh sediments of Poole Harbour have shown that *S. anglica* contributed between 37 and 100% of its biomass to salt marsh sediments (Bull et al., 1999), therefore the organic content of the underlying pre-*Spartina* mudbanks was likely to be lower than sediments accumulated by *Spartina*. Macrofossil evidence in cores was also used, the preserved root-stem morphology indicating at depth the level of *Spartina* colonisation of mudflats (Li and Gao, 2013). The pre-*Spartina* surface was therefore interpreted as the depth at which there was a marked decline in organic matter coinciding with a change in macrofossils from leaf axis, and stem remains relative to rhizomatous root and nodal root macrofossils.

Cores from the centre of each transect were subsampled for laboratory analysis at 10 cm intervals. Sediment samples of approximately 3 g wet weight were oven dried at 65 °C until consistent weight was achieved (24 h). Triplicate sub-samples from each slice were prepared for loss-on-ignition (LOI) analysis of organic content. Samples were crushed and a sub sample of approximately 1 g dry weight obtained. Samples were then combusted in a muffler furnace at 375 °C for 16 h based on the procedure of McKeague (1976). Other LOI procedures of 420 °C for 1.5 h (McKeague, 1976) and 550 °C for 4 h (Heiri et al. (2001) were also carried out, but it was found by digesting the residue in 30% H_20_2 after 375 °C for 16 h, that there was negligible reaction even when heated to 90 °C. The percentage LOI was calculated from the weight loss as a percentage of the oven-dried crushed sub sample weight. Results from the rice grass sediment were averaged to give a mean organic content for each transect.

3.4. Data analysis for calculation of sediment volume

Volumetric estimates of gains and losses of sedimentary material from a marsh system in the Bay of Fundy, Canada, were derived using a combination of GIS marsh margin mapping and sediment depth data (van Proosdij et al., 2006). This combination of methods was used to calculate sediment volume trapped by *Spartina* in the Tamar. On transect profiles a second alignment to the surface survey with identical longitude and latitude values was created, on which pre-*Spartina* surface elevation data were entered. Digital terrain models for both the surface and basement alignments were then created from which cross sections and long sections could be extracted, allowing a profile of the marsh surface and the pre-*Spartina* surface between high water mark (HWM) and low water mark (LWM) to be obtained.

Using the polygons created to depict *Spartina* cover derived from the aerial photographs, avenue script in GIS was used to calculate the area of marsh. It was found that average marsh depths for a given transect were representative of marsh depths in the vicinity of that transect. The area of each polygon was multiplied by the estimated average sediment depth to give the volume of material under the marsh. Volume estimates for each polygon were then compiled to obtain an estimate of the total volume of sediment trapped beneath *Spartina* swards, and as the corer used was a sidewall sampler then compaction during coring was negligible. Nelson's Shoal (Fig. 1) was not included in the volume calculations as there were no surveys or depth estimates obtained from this inaccessible area. Compaction of historical sediments was not assessed, hence volumes calculated would be an underestimate of sediment accumulated over time. LOI data were combined with the volume estimates to determine the proportion of material that was *Spartina*-derived organics.

4. Results

4.1. Spatial area assessment

GIS analysis of aerial photographs identified approximately 374 ha of *S. anglica* infestation within the Tamar Estuary based on cover estimates interpreted from the 2006 photographs, which is depicted in Fig. 1. Fieldwork observations confirmed that *Spartina* cover is expanding in the lower reaches of the estuary; however these colonising regions consist of very small clumps and individual shoots and, therefore, are not visible on aerial photography or otherwise have established since 2006.

4.2. Surface morphology of *Spartina* marshes

Profiles of typical *Spartina* marshes are shown in Figs. 2–5, with each located in Fig. 1, representing examples of the marsh topographies, edge types and substrates observed throughout the Tamar Estuary. Detailed profiles and survey data of the other 12 transects are given in Sheehan and Ellison (2007).

Profiles from the upper estuary were all found to be concave to flat in the upper marsh and convex-up in the lower seaward section, terminating at a seaward micro-cliff. Within the marsh were well-developed deep creek systems of various orders and, in many instances, creek channels were cut down to the pre-*Spartina* surface. The profile of mature sward on the eastern shore at Dilston near the inland extent of *S. anglica* is shown in Fig. 2A, upon a pre-*Spartina* basement of dolerite boulder beach. This is a narrow sector of the estuary in close proximity to the well-defined estuarine channel, and the sward is regularly dissected by narrow, deep tidal creeks which run perpendicular to the shore and consequently are not represented by the profile. A similar profile from the western bank of the estuary at Rosevears is shown in Fig. 2B, which also occurs on a pre-*Spartina* dolerite boulder beach, with a more extensive mudflat seaward of the sward.

In contrast to profiles shown in Fig. 2, lower estuary marsh profiles are exemplified by Fig. 3 from Deviot and Fig. 4A from Swan Bay. The intertidal zone was found to be wider than those of the upper estuary and not restricted by the channel, the estuary being broader in its seaward sector. The marsh surface also has low gradient, with marshes typically extending up to 150 m from MHW, although the Deviot profile in Fig. 3 is a narrower section. Profiles of the marsh surface were found to have less shape than those of the upper estuary, being flat in the upper marsh (Fig. 3B), and flat to convex-up in the lower seaward section, terminating irregularly at a prograding seaward margin (Fig. 3C).

4.2.1. Temporal change in marsh morphology

Surveys of *Spartina* marshes from Swan Bay, Rosevears and Windermere were each superimposed on the historical surveys of Phillips (1975) and Pringle (1993), shown in Figs. 4–5. The Rosevears survey is opposite the original *S. anglica* planting site at

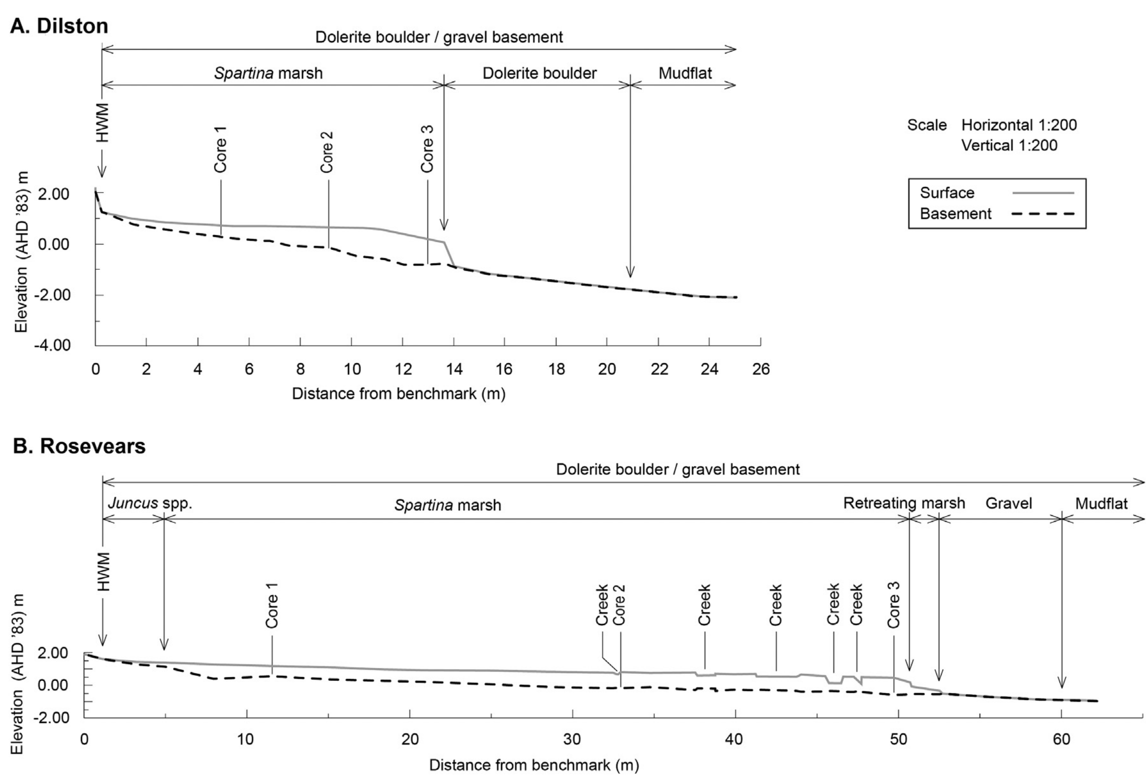

Fig. 2. Cross sectional profiles from the upper Tamar Estuary. A) Dilston (E01). B) Rosevears (WO4).

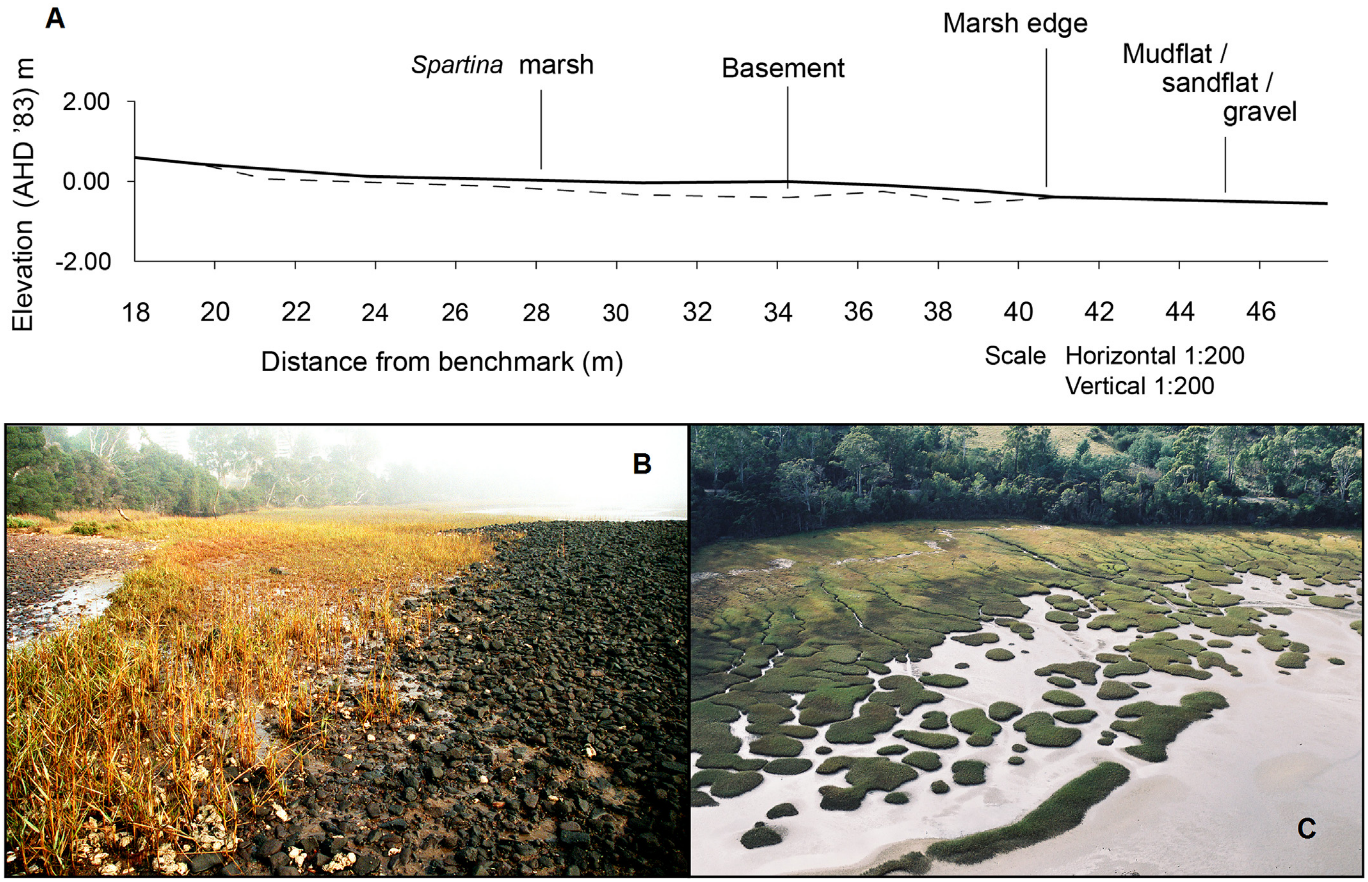

Fig. 3. A) Cross sectional profile from Deviot (W17) in the lower Tamar Estuary. B) Seaward margin having little elevational difference between the marsh and adjoining intertidal zone. C) Marshes prograding by coalescence of seaward pioneer clumps.

Windermere and is a well-developed marsh in a small embayment. The overall marsh surface was concave-up in the 1970's (Fig. 4B), becoming less pronounced over time to approach a flat surface by the late 1980's. The survey of 2006 was substantially more detailed than that of previous surveys, showing the channel networks that dissect the marsh and consistent convex-up marsh surface elements between tidal channels in the mid and lower marsh. As well as marsh surface topography change from flat to convex between 1989 and 2006, accretion occurred, resulting in an average increase in marsh elevation across the marsh of 155 mm, a net accretion rate of 9 mm a^{-1}. Between 1972 and 1989 the outer edge was a steep vegetated ramp, which remained stable and presumably graded into mudflat. However between 1989 and 2006 the outer edge retreated some 15 m to develop a micro-cliff of approximately 1.5 m in height.

The Windermere profile (Fig. 5) was near the original 1947 *S. anglica* introduction site. Temporal changes to surface topography, elevation and edge retreat along the profile are consistent with those observed at Rosevears (Fig. 4B). The 2006 seaward marsh elevation was generally 50 mm lower than that of 1989, suggesting a net erosion rate of 2.9 mm a^{-1}. There has however been accretion over this period in the centre of the current marsh extent (30–33 m from the survey benchmark), producing convex-up topography in this section, and *S. anglica* cover has extended to HWM in the past 17 years. Marsh retreat of approximately 10 m occurred between 1983 and 2006, with erosion of the lower marsh and mudflat, exposing the dolerite boulder beach and resulting in the 0.4 m micro-cliff at the seaward edge of the marsh. Erosion of the outer marsh is most likely explained by the proximity of the channel to the intertidal zone in this narrow and comparatively dynamic sector of the estuary. This could also have been exacerbated by boat wake from recreational and tour boats, the use of which is likely to have increased from 1983 onwards.

Swan Bay (Fig. 4A) is typical of shallower, flatter marshes described in Section 4.2 found in the lower estuary, and occurs on outcropping basalt flanked by extensive mudflats. An average marsh elevation increase of 94 mm occurred across this transect between 1983 and 1989 indicating a net accretion rate of 15.7 mm a^{-1}. There has been little elevation or morphologic change to the marsh since 1989, with the exception of the upper marsh within 50 m of HWM, where vertical increase of 56 mm occurred (3.7 mm a^{-1}). In the upper marsh, *Spartina* cover was estimated to be between 70 and 100%, decreasing to 20% in the lower marsh where *Spartina* growth was restricted to fractures and depressions in the outcropping dolerite where fine sediment had accumulated. There has been little sedimentation and negligible change to morphology or elevation in the lower marsh since 1989. From 1989 to 2006 there has however been landward migration of approximately 11 m of the seaward edge of *Spartina*, as well as landward expansion to the base of the sea wall.

Overall, marsh width remained relatively constant during the 17 year period between 1972 and 1989 at Rosevears (Fig. 4B), and in the 6 year period between 1983 and 1989 at Swan Bay and Windermere (Figs. 4A and 5). Marsh width and the extent of *Spartina* cover later decreased to a similar extent in each of the three profiles after 1989, with retreat of approximately 15 m, 10 m and 11 m at Rosevears, Windermere and Swan Bay respectively.

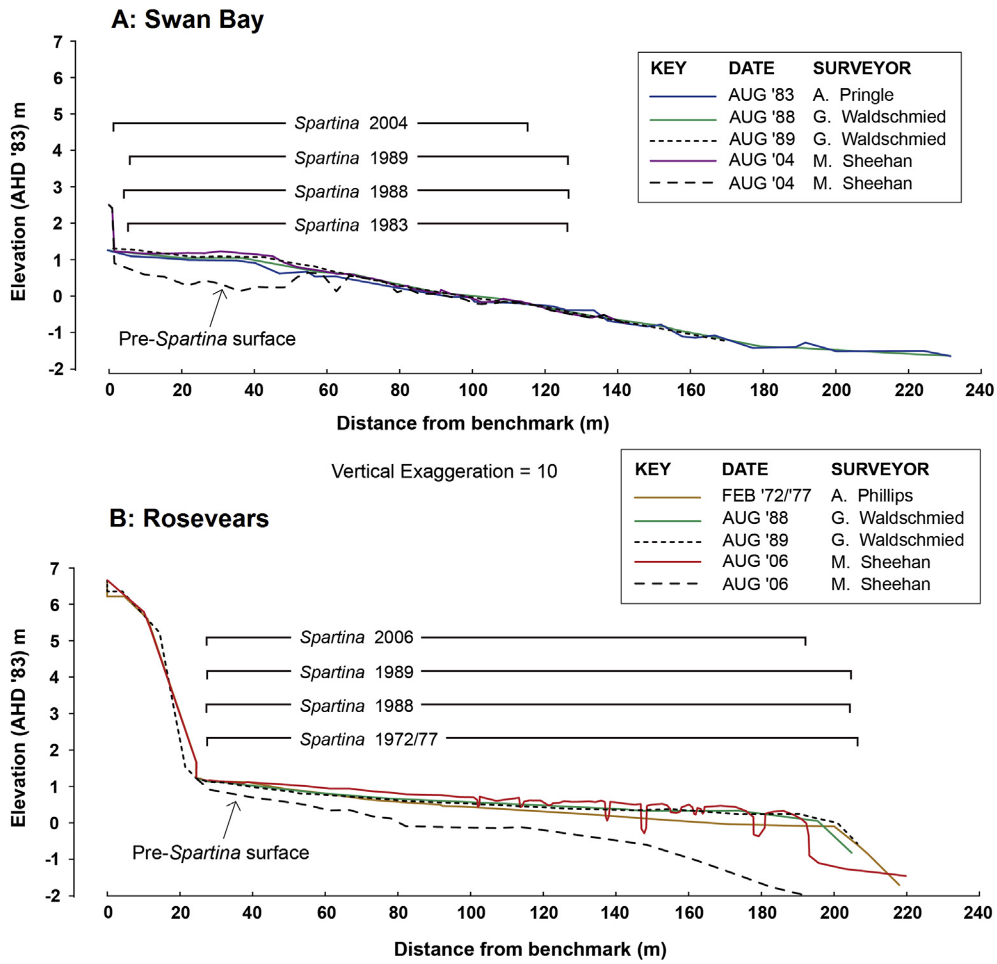

Fig. 4. Cross sectional historical profiles and the pre-*Spartina* surface of A) the Swan Bay marsh (E08) in the lower Tamar Estuary, and B) the Rosevears marsh (W06) in the upper estuary.

4.2.2. *Seaward margin of Spartina marshes*

The outer margin of upper estuary *Spartina* marshes were found to be strongly defined and all marked by erosional scarps and micro-cliffs of up to 2 m as shown by the profiles in Figs. 2 and 4B. The seaward margin overall shows severe undercutting and a tensional break developing behind the scarp, resulting in failure blocks apparent along much of the upper estuary marsh shore. Lower estuary marshes by contrast were found to have seaward edges that were laterally poorly defined, often with isolated clumps and little change in relief at the interface between the outer marsh surface and the lower intertidal zone, as shown by Figs. 3 and 4A.

In addition to the variation in edge morphology observed across the estuary, the relative elevation of the seaward margin of *Spartina* marshes was found to change down the estuary. Fig. 6 shows the elevation of ground level at the outer vegetated margin of the *Spartina* marshes at each transect relative to distance from the mouth of the estuary, showing a linear increase of some 0.54 m from the seaward estuarine limits of *S. anglica* towards the upper estuary ($R^2 = 0.7$).

4.3. *Sediment accumulated under Spartina marshes*

Results from determination of the pre-existing surface before rice grass introduction are shown in Fig. 7, which incorporates some earlier mapping by Pringle (1975). The pre-*Spartina* surface of the intertidal zone showed a high degree of variability throughout the estuary with regard to substrate type, width and gradient. Dolerite boulder beaches were more narrow and steeply graded, while the sands/gravels, basalts and dolerite platforms and tidal flats are much broader and gently grading.

Marsh profile diagrams indicate the level of the pre-existing surface along each profile (Figs. 2–5) up to 2 m below the current marsh surface, with this elevation tending to increase from the lower estuary to the upper estuary. Macrofossil identification showed that *S. anglica* rhyzomatous material accounts for most of the organic matter of the marsh. Results of organic content (LOI) analysis from cores obtained from each profile are given in Table 1. Outliers were excluded from means calculated for *Spartina* sediment, with low values interpreted that samples were below *Spartina*-trapped sediment, and large values likely to be a result of the sample containing a large root. *Spartina* marsh sediments are typically comprised of between 14 and 28% organic matter. Sharp declines in organic matter were observed in cores with soft substrate beneath the pre-*Spartina* boundary. This decline, combined with macrofossil identification was taken to be a suitable proxy for determining the pre-*Spartina* surface on tidal flat substrates.

4.4. *Sediment volume estimations*

Volume estimates calculated from GIS mapping and marsh depth averages indicate a total of 1,193,441 m^3 of material within

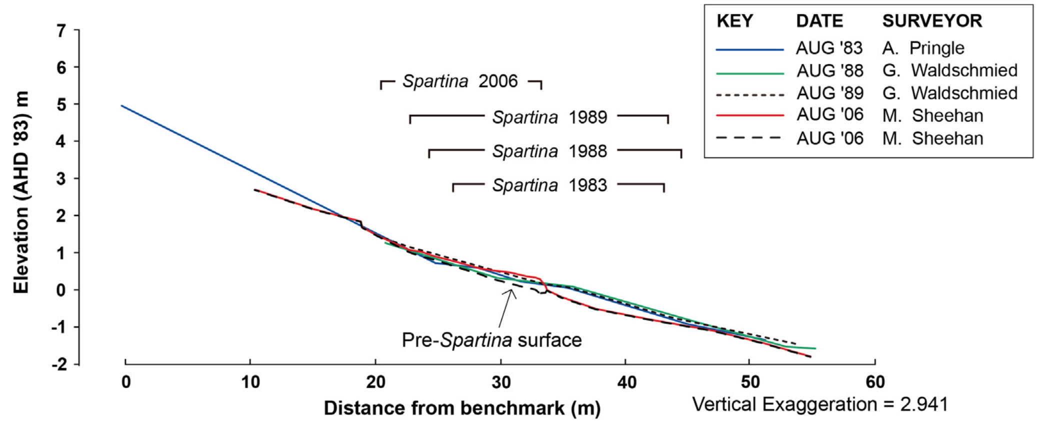

Fig. 5. Cross sectional profiles of the Windermere marsh (E05) showing surveys conducted in 1983, 1988, 1989 and 2006, and the pre-*Spartina* surface.

Spartina marshes. This does not include material beneath Nelson's Shoal, and swards seawards of Whirlpool Reach, as estimates of post- *Spartina* sediment depths were not able to be obtained from these locations. Table 2 shows results determined of both the lithic and organic components, and based on the estimated organic content (LOI) approximately 212,043 m^3 (17%) of the material within the marsh system is determined to be *Spartina*-derived organic matter.

5. Discussion

The colonisation by *Spartina* of an area that was previously largely clear of macrophytes has transformed the previous intertidal zones of gently grading mudflats, sandy beaches and boulder beaches into extensive *S. anglica* monocultures composed of fine grained sediments. The results from marsh morphology, topographic profile change over time, and nature and volume of sediment trapped allows assessment of the geomorphological change caused by *Spartina* introduction in this large Australian estuary, relative to findings from infestations mostly in more macrotidal settings elsewhere in the world (van der Wal et al., 2002; Balke et al., 2012; Xie et al., 2013).

5.1. Marsh surface morphology

All 16 profiles throughout the Tamar Estuary showed a low gradient cross sectional surface morphology under *Spartina*, creating a uniformly vegetated terrace between the landward break of slope and offshore lower shores. Average gradient of the *Spartina* marsh surface was observed to be between 0 and 5°.

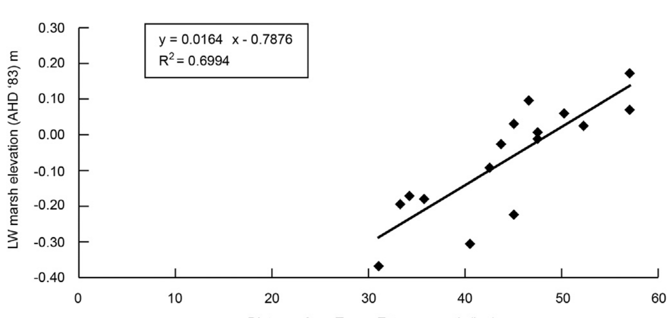

Fig. 6. Elevation of the marsh seaward edge of each of the 16 transects, plotted against distance from the mouth of the estuary. There is a positive linear trend in edge elevation increasing with distance from the mouth.

A morphology difference was found between marshes landwards of Gravelly Beach and those seawards based on the degree of vertical development, and the morphology of the marsh. Marshes landwards of Gravelly Beach (Figs. 2 and 4B) have increased vertically relative to the pre-*Spartina* surface to a greater extent than those of the lower estuary, such that surface topography and marsh development of these Type-1 marshes appear independent of the pre-*Spartina* surface morphology. Type-1 marsh profiles exhibited a flat to slightly concave-up upper marsh, a convex-up ridge in the outer mid marsh, and a relatively steeply graded convex-up lower marsh. A convex-upward profile is indicative of accretion (Kirby, 1992), and the Type-1 profile at Rosevears (Fig. 4B) showed such morphology 1972–2004.

Marshes seawards of Gravelly Beach (Figs. 3 and 4A) were found to be considerably thinner in marsh development and tending to have wider marsh expanses, these Type-2 marshes having topography generally dictated by the underlying pre-*Spartina* surface. They were flat in shape with the basement outcropping along the transect, with an upper marsh tendency towards slight concavity in transects W09, E06 and E07, and convexity on E10 and W16. The lower marsh section was in all cases flat to convex.

A conceptual model of evolution of Type-1 *Spartina* marshes in the Tamar from this study is shown in Fig. 8, for conditions in the upper estuary where sediment supply is in surplus. *Spartina* initially establishes as isolated shoots and clumps to a distance seaward that is controlled by inundation frequency and wave energy (Fig 8A). Sediment then accretes within the clumps of vegetation which, over time, coalesce to form a marsh (Fig 8B). The outer edge builds up to create a vegetated ramp (Fig 8C), until the equilibrium becomes changed to be followed by cliffing and undercutting of the seaward margin (Fig 8D). This brings beam failure and further marsh retreat (Fig 8E). Development over the last 50 years of Type-1 marshes are shown to follow European macrotidal models of salt marsh development (French and Stoddart, 1992; French, 1993; Allen, 2000) developing through a youthful phase with convex-up profiles of across seaward marshes, dissected by increasing creek density and depth. Mature marsh reaches higher tidal levels and becomes more concave-up (French, 1993), as found for landward sections of Type-1 marshes in the upper Tamar.

Differences between marsh profiles of the upper and lower estuary were attributed to marsh 'maturity' (Pringle, 1993), which implies an evolutionary or developmental process that would result in marshes throughout the estuary reaching the same end point. This study however showed that there has been little vertical elevation change over time at Swan Bay (Type-2 marsh) since the first survey in 1983 (Fig. 4A) compared to that of Type-1 marshes at

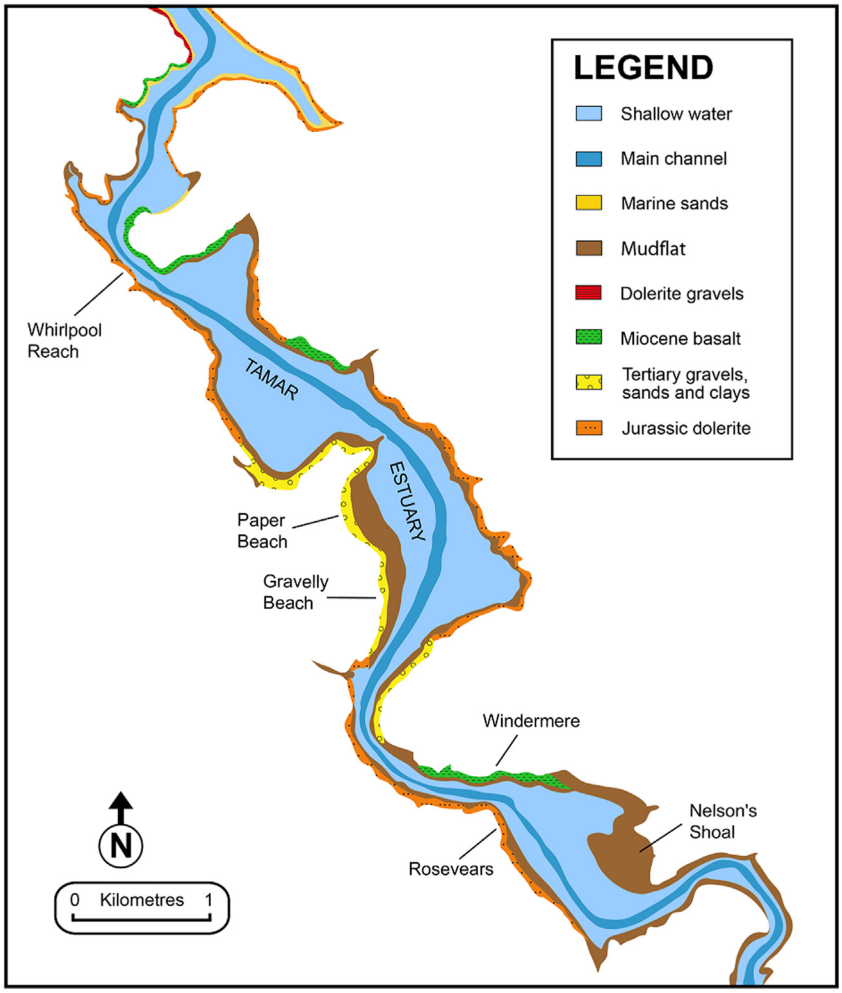

Fig. 7. Intertidal substratum of the Tamar Estuary, showing surfaces colonised by *Spartina* in the last 50 years.

Rosevears and Windermere (Figs. 4B and 5). While this observation was only quantified at one profile, the lack of Type-1 marshes in the lower estuary and consistently limited vertical development of lower estuary marshes support this finding.

Type-2 marshes are located in lower sections of the estuary where sediment supply is more limited as tributaries entering the lower estuary are minor, and have negligible sediment loads compared to major rivers entering the upper estuary (Foster et al., 1986). Furthermore, estuarine channel dimensions are larger and tidal currents stronger, leading to higher grain-size in estuarine sediments (Foster et al., 1986). The observed difference between Type-1 and Type-2 marshes likely results from variations in environmental conditions of sediment supply and estuarine physical conditions between the two sectors rather than it being an indication of maturity, Type-2 marshes are likely to remain as shallow swards without deterministically developing a mature marsh surface engineered by the *Spartina* cover, this limited by suitable sediment availability.

5.2. Seaward margin of *Spartina* marshes

A further difference in *Spartina* marshes throughout the estuary was apparent in marsh edge morphology. Type-1 marshes all showed micro-cliffs at the outer margin indicating that marshes do not continue to prograde seaward (Figs. 2 and 4B), and historical profiles showed that retreat occurred after 1989 (Figs. 4B and 5). The Rosevears and Windermere historical profiles both show retreat and cliffing at their seaward edges over time (Figs. 4B and 5), this more active at Rosevears relative to Windermere as shown by the amount of loss. Conversely, Type-2 marshes showed outer margins that are poorly defined, often with isolated clumps tending to coalesce, and little change in relief at the interface between the marsh and the lower intertidal zone (Fig. 3).

While all profiles displayed a stable and depositional marsh surface, erosional features were universally found at the outer margin of Type-1 marshes (Figs. 2, 4B and 5). Of marsh edge erosion types (Schwimmer, 2001), that in the Tamar resembles undercutting, root mat toppling and beam failure described from Delaware as occurring due to increased wave action. Historical profiles (Figs. 4B and 5) show both cliffing and marsh retreat to have occurred in the upper estuary since 1989, and all Type-1 profiles showed a seaward micro-cliff (Fig. 2). Lack of erosional features such as micro-cliffing and undercutting in the outer margins of Type-2 marshes is most likely due to insufficient vertical development of these marshes, combined with the attenuation of wave energy across the comparatively wider estuary and intertidal zones.

Large marsh scale retreat has been attributed to relative sea-level rise as shown from Louisiana (Ford et al., 1999; Wilson and Allison, 2008) and southern UK (Strong and Ayres, 2009). Relative sea-level rise in Tasmania during the latter half of the 20th century was 0.7 ± 0.6 mm a^{-1} (Gehrels et al., 2012). While the undercutting and retreat resembles the conceptual model of fringing marsh

Table 1
Organic content (LOI) of *Spartina* marshes. Values are expressed as percent, and those in italic were excluded from the mean calculated.

Depth (cm)	Legana (W01)	Dilston (E01)	(W03)	Rosevears 1 (W04)	Rosevears 2 (W06)	Windermere (E05)	Rosevears 3 (W07)	Native point (E06)	Blackwall (W08)	Blackwall 2 (W09)	(E07)	Swan bay (E08)	Hillwood (E10)	Supply river (W15)	(W16)	(W17)
0–10	21.5	22.3	19.0	18.8	21.2	25.9	28.7	22.6	27.2	25.1	24.0	24.2	20.3	16.9	20.6	8.8
10–20	16.4	22.6	19.8	21.5	15.1		24.1	22.89	26.7	48.2	21.5	n/a	21.4	16.2	16.4	
20–30	14.34	16.9	16.2	20.0	16.4		28.4	20.7	27.8	25.8	21.6	*82.1*	16.3	18.8	*45.3*	
30–40	13.7	15.7	16.12	17.5	14.4		21.3	28.6	21.0	21.5	20.7	20.0	*3.5*	17.0		
40–50	13.2	18.6	15.5	17.5	11.6		18.2	20.4	19.4	19.1	21.5	n/a	*1.9*	17.0		
50–60	12.4	14.3	15.2	16.0	11.1		15.1	21.3	15.3	*8.9*	18.9	18.2		17.1		
60–70	12.1	13.1	15.5	14.7	9.7		12.1	16.6	13.5		21.8	12.8				
70–80	11.5		19.8	15.2	9.3		*1.9*	17.5	*6.2*		24.8	19.1				
80–90	11.1		13.0	12.3	8.8			18.5			21.2	16.7				
90–100	*10.9*		12.2	10.7	*7.6*			16.3			*7.9*					
100–110	*10.8*				*5.8*			11.2			*8.7*					
110–120	*10.9*				*4.7*			*8.5*			*4.6*					
120–130	9.9				*5.0*						*20.3*					
130–140	*10.0*				*4.6*											
140–150	9.6				–											
150–160	9.6				*4.1*											
160–170	8.6				3.9											
Mean	14.03	17.6	16.2	16.4	14.97	25.9	21.1	19.4	21.6	28.0	21.8	18.5	19.9	17.2	18.5	8.8

response to relative sea level rise (Wilson and Allison, 2008) other factors contributing may include recent storm action combined with boat wake impacts on upper estuary marshes, which are closer to the boat channel than in the wider lower estuary (Fig. 1), and have shown increased marsh elevation over time (Figs. 4B and 5).

Retreat of *Spartina* marshes of the UK was first reported in 1919, with increasing losses observed subsequently (Allen, 2000). These losses have been attributed to horizontal erosion of the outer edges as the marshes built higher in the tidal frame, dieback of the plants, and colonisation by other salt marsh species once *Spartina* had sufficiently increased elevation of the marsh, allowing for their seaward expansion (Allen, 2000). As neither colonisation by other species nor loss of *Spartina* vigour has occurred in the Tamar, erosion of the outer margin as a response to increasing marsh elevation is therefore the most likely explanation for marsh retreat.

S. anglica is an ecosystem engineer in altering the environment in which it lives to better suit itself (Jones et al., 1994, 1997; Strong and Ayres, 2009), with stiff shoots enabling it to slow down flow velocities and accrete sediment. However, a disadvantage of this adaptation is that stem stiffness increases drag (Bouma et al., 2005b), which determines the lower limit of occurrence along the profile gradient. This study found that the lower seaward edge of *Spartina* increased in elevation up the estuary, from Type-2 to Type-1 marshes (Fig. 6). Since *Spartina* introduction, as sediment is accreted and the marsh develops, flow velocities encountered at the outer edge would increase as the marsh elevation increases, as the upper estuary channel becomes more confined. Such hydrological factors restrict further progradation, where despite sufficient sediment supply to facilitate accretion, the *Spartina* marsh excludes itself from further progradation where it develops a confined estuarine settings (Fig. 1). Erosion of the outer marsh is therefore likely due to marsh development confining the channel, then periods of more active currents, storm induced waves, boat wakes and relative sea-level rise disturb this equilibrium, resulting in the outer margin becoming undercut and retreating through beam failure.

5.3. Spartina extent and volume of sediment trapped

Of the overall *Spartina* cover found by GIS analysis to be 374 ha, Type-1 marshes covered 240 ha while Type-2 marshes covered 134 ha (Table 2). The total of 374 ha is a decrease of 46 ha since 1997 (Hedge, 1998), likely resulting from the Type-1 marsh retreat shown in this study and ongoing control efforts. Since 2002 DPIW, the community and NRM North have been successful in maintaining areas north of Middle Point as a 'Rice Grass Free Zone', with the aim to eradicate *Spartina* and control any further spread north (DPIW, 2006; Gunawardana and Locatelli, 2008). The *Spartina* management plan for the Tamar Estuary (DPIW, 2006) qualitatively estimated that the 2006 *Spartina* extent was >450 ha. Fig. 9 shows changes to *Spartina* extent since 1945, showing that the *Spartina* extent has been relatively stable since 1990, although spread north may be balanced by retreat of Type-1 marshes.

Table 2
Estimated volumes of lithic and organic material within Type-1 and Type-2 marshes of the Tamar estuary excluding Nelson's Shoal and swards downstream of Whirlpool Reach.

	Area (ha)	Total (m^3)	Lithic (m^3)	Organic (m^3)
Type 1 marshes	240.4	730,383	605,555	124,828
Type 2 marshes	134.4	463,058	375,843	87,215
Total	374.7	1,193,441	981,398	212,043

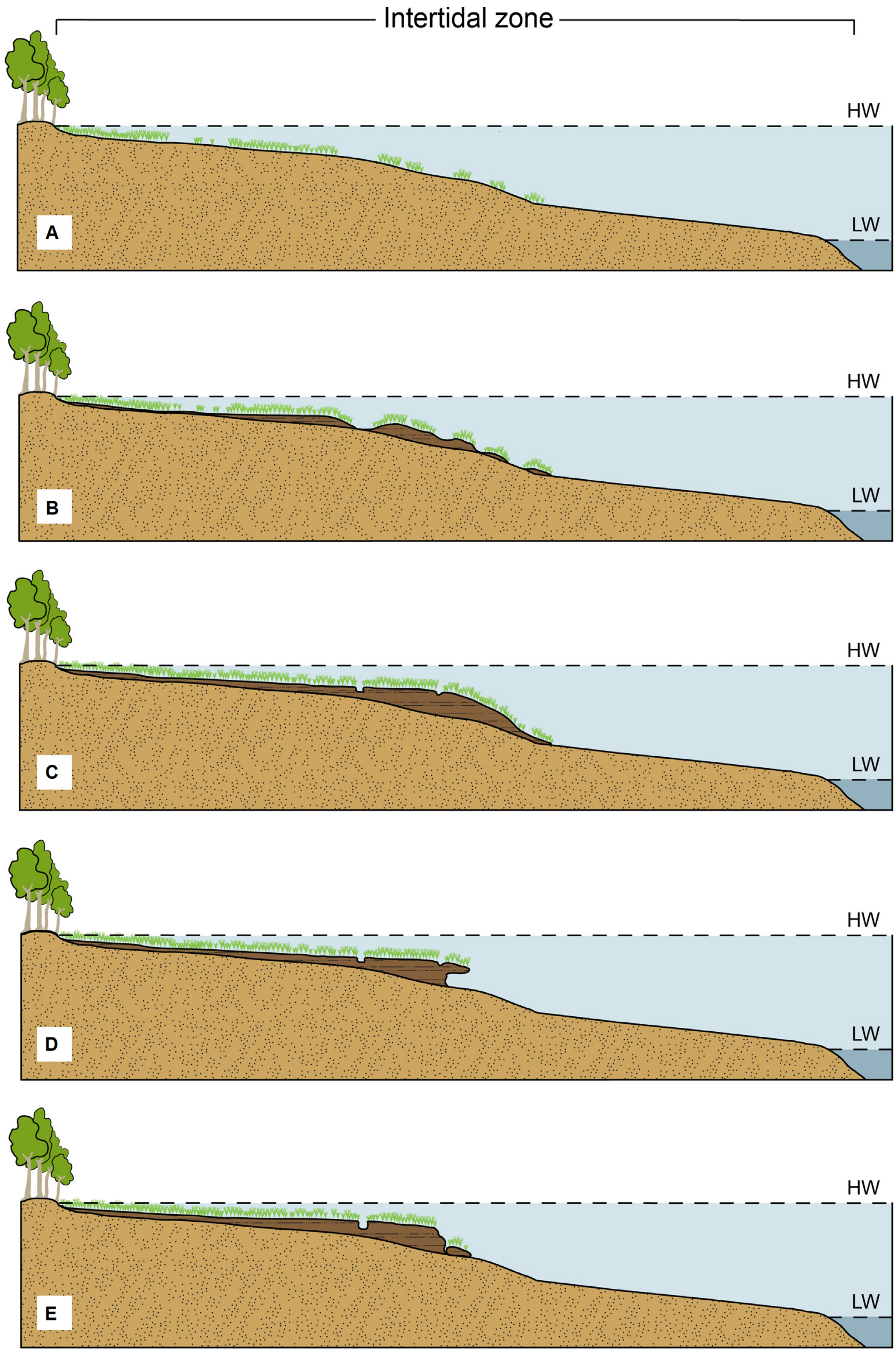

Fig. 8. A conceptual model of evolution of Type-1 *Spartina* marshes in the Tamar Estuary.

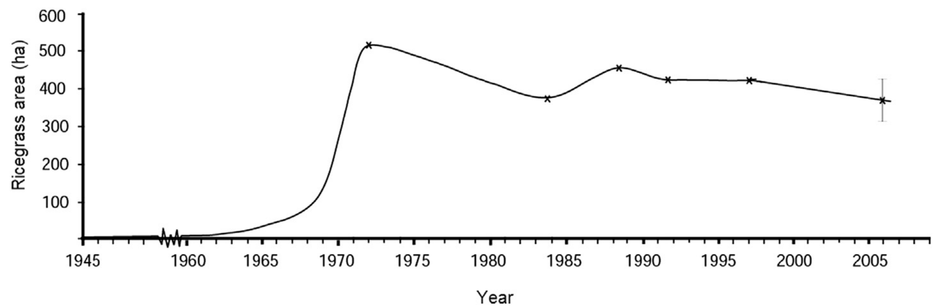

Fig. 9. Changes to the extent of *Spartina* in the Tamar Estuary between 1947 and 2006 (Sources. Pringle, 1993; DPIW, 2006; current study). The 2006 extent includes an error margin derived from the resolution of the ortho-photographs used for GIS analysis.

Since the introduction of *S. anglica* in the Tamar Estuary, this study shows that a total of 1,193,441 m^3 of material has been trapped, which is comprised of approximately 17% *Spartina*-derived organic matter and 83% inorganic matter that is predominantly silts and clays. Based on historical profiles, sedimentation rates since the introduction of *S. anglica* are between 8.7 and 52.4 mm a^{-1}, which is mid-range relative to *Spartina*-induced net sedimentation rates found in Europe, China and New Zealand (Oliver, 1920; Ranwell, 1964; Lee and Partridge, 1983; Chung, 1990; Long et al., 1999; Wang et al., 2008).

The accuracy of the volume estimate is based on the depth found on profiles of *Spartina*-trapped sediment, GIS mapping, grouping of like-sized swards and the assumption that the observed sediments depths along transects are representative of the adjacent intertidal zones. It is also dependent on the accuracy of the available imagery. The exclusion of Nelson's Shoal from volume estimates was necessary due to the logistical difficulties with site access and surveying. It is however the largest *Spartina* sward in the Tamar Estuary (Fig. 1) and could increase the volume estimations for the entire estuary by 5–10%.

Organic content results show that *Spartina*-derived organic matter typically accounts for between 15 and 28% of material within the marshes throughout the estuary (Table 1). The remaining 72–85% is therefore lithic material trapped by the *Spartina* sward since establishment. The total lithic component of approximately 981,397 m^3 is likely derived from the North and South Esk River catchment which have a high sediment discharge with landuse change over the last century, and historical dredging of the upper Tamar that released dredge material adjacent to growing *Spartina* banks (Foster et al., 1986).

6. Conclusions

This study demonstrates the extensive morphological change that has occurred in the intertidal zone of the Tamar Estuary since the introduction and establishment of *Spartina*. Previously unvegetated intertidal areas have been transformed into marsh terraces of sediment buildup that today dominate the estuary.

Two *Spartina* marsh morphologies have established within the Tamar Estuary over the last 50 years. Type-1 marshes are typically characterised by having accreted between 0.5 m and 2.0 m of sediment above the pre-*Spartina* surface. Surface topography of Type-1 marshes is independent of the pre-*Spartina* surface morphology, exhibiting a flat to slightly concave upper marsh, a convex ridge in the outer mid marsh, and a relatively steeply graded convex lower marsh. Type-2 marshes are found in the lower estuary and are considerably thinner than Type-1 marshes. Surface topography is generally dictated by the underlying pre-*Spartina* surface, often with the basement material outcropping within *Spartina* swards, but accretion towards Type-1 marsh morphology is limited fine grained sediment supply.

Assessment of temporal change in marshes through comparing recent profiles with historical baseline studies concludes that while marshes throughout the estuary continue to increase in vertical elevation, rates of vertical accretion have slowed, and *Spartina* marsh retreat has occurred of between 10 and 15 m since 1989. Furthermore, seaward edge micro-cliff morphology of upper estuary Type-1 marshes indicates that erosion of the seaward edge throughout the upper estuary has been significant.

This study demonstrates the potential for use of survey, coring and analysis of organic and macrofossil content in stratigraphy to allow volumetric determination of sediment accumulated. The *Spartina* extent within the Tamar Estuary of approximately 374 ha has in the last 50 years trapped sediment comprising of approximately 1,193,441 m^3 of material, 14–28% of which is *Spartina*-derived organic matter. *Spartina* infestation has therefore led to an increase in organic content within sediment deposits of the Tamar Estuary, combined with a fining of textures of coastal sediments, and a reduction of accommodation space within the estuary.

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References

Allen, J.R.L., 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and southern North Sea coasts of Europe. Quat. Sci. Rev. 19, 1155–1231.

An, S.Q., Gu, B.H., Zhou, C.F., Wang, Z.S., Deng, Z.F., Zhi, Y.B., Li, H.L., Chen, L., Yu, D.H., Liu, Y.H., 2007. *Spartina* invasion in China: implications for invasive species management and future research. Weed Res. 47, 183–191.

Attard, M., Thompson, M., Kelly, R., Locatelli, A., 2011. Tamar Estuary & Esk Rivers Ecosystem Health Assessment Program Monitoring Report 2011. NRM North, Launceston.

Balke, T., Klaassen, P., Garbutt, A., van der Wal, D., Herman, P.M.J., Bouma, T.J., 2012. Conditional outcome of ecosystem engineering: a case study on tussocks of the salt marsh pioneer *Spartina anglica*. Geomorphology 153–154, 232–238.

Baumel, A., Ainouche, M.L., Levasseur, J.E., 2001. Molecular investigations in populations of *Spartina anglica* C.E. Hubbard (Poaceae) invading coastal Brittany (France). Mol. Ecol. 10, 1689–1701.

Beasy, K.M., Ellison, J.C., 2013. Comparison of three methods for the quantification of sediment organic carbon in salt marshes of the Rubicon Estuary, Tasmania, Australia. Int. J. Biol. 5 (4), 1–13.
Beeftink, W.G., 1966. Vegetation and habitat of the salt marshes and beach plains in the south-western part of The Netherlands. Wentia 15, 83–108.
Beeftink, W.G., Rozema, J., 1988. The nature and functioning of salt marshes. In: Salomons, W., Bayne, B.L., Duursma, E.K., Forstner, U. (Eds.), Pollution of the North Sea: an Assessment. Springer, Berlin, pp. 59–87.
Bird, E., 2008. Coastal Geomorphology: an Introduction, second ed. John Wiley and Sons Ltd, Chichester.
Blott, S.J., Pye, K., 2004. Application of lidar digital terrain modelling to predict intertidal habitat development at a managed retreat site: Abbotts Hall, Essex, UK. Earth Surf. Process. Landforms 29, 893–905.
Boston, K.G., 1981. The Introduction of *Spartina townsendii (S.L)* to Australia. Melbourne State College Occasional Papers 6, pp. 1–57.
Bouma, T.J., De Vries, M.B., Low, E., Kusters, L., Herman, P.M.J., Tanczos, I.C., Temmerman, S., Hesselink, A., Meire, P., van Regenmortel, S., 2005a. Flow hydrodynamics on a mudflat and in salt marsh vegetation: identifying general relationships for habitat characterisations. Hydrobiologica 540, 259–274.
Bouma, T.J., De Vries, M.B., Low, E., Peralta, G., Tanczos, I.C., van de Koppel, J., Herman, P.M.J., 2005b. Trade-offs related to ecosystem engineering: a case study on stiffness of emerging macrophytes. Ecology 86, 2187–2199.
Bull, I.D., Van Bergen, P.F., Bol, R., Brown, S., Gledhill, A.R., Gray, A.J., Harkness, D.D., Woodbury, S.E., Evershed, R.P., 1999. Estimating the contribution of *Spartina anglica* biomass to salt-marsh sediments using compound specific stable carbon isotope measurements. Org. Geochem. 30, 477–483.
Callaway, J.C., Josselyn, M.N., 1992. The introduction and spread of smooth cordgrass (*Spartina alterniflora*) in South San Francisco Bay. Estuaries 15, 218–226.
Chung, C., 1990. Twenty-five years of introduced *Spartina anglica* in China. In: Gray, A.J., Benham, P.E.M. (Eds.), Spartina Anglica: a Research Review. Institute of Terrestrial Ecology, London, pp. 72–76.
Chung, C.H., 2006. Forty years of ecological engineering with *Spartina* plantations in China. Ecol. Eng. 27, 49–57.
Cipolletti, M.P., Delrieux, C.A., Perillo, G.M.E., Piccolo, M.C., 2012. Superresolution border segmentation and measurement in remote sensing images. Comput. Geosci. 40, 87–96.
Civille, J.C., Sayce, K., Smith, S.D., Strong, D.R., 2005. Reconstructing a century of *Spartina alterniflora* invasion with historical records and contemporary remote sensing. Ecoscience 12, 330–338.
Cui, B., He, Q., An, Y., 2011. *Spartina alterniflora* invasions and effects on crab communities in a western Pacific estuary. Ecol. Eng. 37, 1920–1924.
Daehler, C.C., Strong, D.R., 1996. Status, prediction and prevention of introduced cordgrass *Spartina* spp. invasions in Pacific estuaries, USA. Biol. Conserv. 78, 51–58.
DPIW (Department of Primary Industries and Water), 2006. Rice grass Area-based Management Plan: Tamar River/Beauty Point Region (2006–2008). Department of Primary Industries and Water, Hobart.
Ellison, J.C., 2008. Long-term retrospection on mangrove development using sediment cores and pollen analysis. Aquat. Bot. 89, 93–104.
Ellison, J.C., Sheehan, M.R., 2014. Past, present and futures of the Tamar Estuary. In: Wolanski, E. (Ed.), Estuaries of Australia in 2050 and beyond. Springer, Dordrecht, pp. 69–89.
Ford, M.A., Cahoon, D.R., Lynch, J.C., 1999. Restoring marsh elevation in a rapidly subsiding salt marsh by thin-layer deposition of dredged material. Ecol. Eng. 12, 189–205.
Foster, D.N., Nittim, R., Walker, J., 1986. Tamar River Siltation Study. Technical Report No. 85/07. University of NSW Water Research Laboratory.
French, J.R., 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, north Norfolk, U.K. Earth Surf. Process. Landforms 18, 63–81.
French, J.R., Stoddart, D.R., 1992. Hydrodynamics of salt marsh creek systems: Implications for marsh morphological development and material exchange. Earth Surf. Process. Landforms 17, 235–252.
Geoscience Australia, 2013. Earth Monitoring and Reference Systems. WWW Page. http://www.ga.gov.au/geodesy/ausgeoid/.
Gao, J., Bai, F., Yang, Y., Gao, S., Liu, Z., Li, L., 2012. Influence of *Spartina* colonization on the supply and accumulation of organic carbon in tidal Salt Marshes of Northern Jiangsu Province, China. J. Coast. Res. 28, 486–498.
Gehrels, W.R., Callard, S.L., Moss, P.T., Marshall, W.A., Blaauw, M., Hunter, J., Milton, J.A., Garnett, M.H., 2012. Nineteenth and twentieth century sea-level changes in Tasmania and New Zealand. Earth Planet. Sci. Lett. 315–316, 94–102.
Gleason, M.L., Elmer, D.A., Pien, N.C., Fisher, J.S., 1979. Effect of stem density upon sediment retention by salt marsh cordgrass, *Spartina alterniflora* Loisel. Estuaries 2, 271–273.
Gunawardana, D., Locatelli, A., 2008. Tamar Estuary Management Plan. SFM Environmental Solutions, Launceston.
Hedge, P., 1998. Strategy for the Management of Rice Grass *(Spartina anglica)* in Tasmania, Australia. Department of Primary Industries, Water and Environment, Tasmania.
Hedge, P., Kriwoken, L.K., 2000. Evidence for the effects of *Spartina anglica* invasion on benthic macrofauna in Little Swanport Estuary, Tasmania. Austral Ecol. 25, 150–159.
Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25, 101–110.
Hubbard, J.C.E., Stebbings, R.E., 1967. Distribution, date of origin and acreage of *Spartina townsendii* (s.l.) marshes in Great Britain. Proc. Bot. Soc. Br. Isles 7, 1–7.
Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69, 373–386.
Jones, C.G., Lawton, J.H., Shachak, M., 1997. Positive and negative effects of organisms as physical ecosystem engineers. Ecology 78, 1946–1957.
Keim, R.F., Skaugset, A.E., Bateman, D.S., 1999. Digital terrain modelling of small stream channels with a total-station theodolite. Adv. Water Resour. 23, 41–48.
Kirby, R., 1992. Effects of sea-level rise on muddy coastal margins. In: Prandle, D. (Ed.), Dynamics and Exchanges in Estuaries and the Coastal Zone. American Geophysical Union, Washington, pp. 313–334.
Kriwoken, L.K., Hedge, P., 2000. Exotic species and estuaries: managing *Spartina anglica* in Tasmania, Australia. Ocean. Coast. Manag. 43, 573–584.
Lee, W.G., Partridge, T.R., 1983. Rates of spread of *Spartina anglica* and sediment accretion in the New River Estuary, Invercargill, New Zealand. N. Z. J. Bot. 21, 231–236.
Leonard, L.A., Luther, M.E., 1995. Flow hydrodynamics in tidal marsh canopies. Limnol. Oceanogr. 40, 1474–1484.
Levin, L.A., Talley, T.S., Hewitt, J., 1998. Macrobenthos of *Spartina foliosa* (Pacific cordgrass) salt marshes in Southern California: community structure and composition to a Pacific mudflat and a *Spartina alterniflora* (Atlantic smooth cordgrass) marsh. Estuaries 21, 129–144.
Li, J., Gao, S., 2013. Estimating deposition rates using a morphologicalproxy of *Spartina alterniflora* plants. J. Coast. Res. 29 (6), 1452–1463.
Long, A.J., Scaife, R.G., Edwards, R.J., 1999. Pine Pollen in intertidal sediments from Poole Harbour, UK: Implications for late Holocene accretion rates and sea-level rise. Quat. Int. 55, 3–16.
McKeague, J.A., 1976. Manual on Soil Sampling and Methods of Analysis. Canadian Soil Survey Committee, Ottawa, Ontario.
Neira, C., Levin, L.A., Grosholz, E.D., 2005. Benthic macrofaunal communities of three sites in San Francisco Bay invaded by hybrid *Spartina*, with comparison to uninvaded habitats. Mar. Ecol. Prog. Ser. 292, 111–126.
Oliver, F.W., 1920. *Spartina* problems. Ann. Appl. Bot. 7, 25–39.
Paine, J.G., White, W.A., Smyth, R.C., Andrews, J.R., Gibeaut, J.C., 2004. Mapping coastal environments with lidar and EM on Mustang Island, Texas, U.S. The Lead. Edge 23, 894–898.
Partridge, T.R., 1987. *Spartina* in New Zealand. N. Z. J. Bot. 25, 567–575.
Phillips, A.W., 1975. The establishment of *Spartina* in the Tamar Estuary, Tasmania. Pap. Proc. Royal Soc. Tasman. 109, 65–75.
Pirzl, H., Coughanowr, C., 1997. State of the Tamar Estuary: a Review of Environmental Quality Data to 1997. Supervising Scientist Report 128. Supervising Scientist, Canberra.
Pringle, A., 1993. *Spartina anglica* colonisation and physical effects in the Tamar Estuary, Tasmania 1971-91. Pap. Proc. Royal Soc. Tasman. 127, 1–10.
Ranwell, S., 1964. *Spartina* salt marshes in southern England II. Rate and seasonal pattern of sediment accretion. J. Ecol. 52, 79–94.
Ranwell, S., 1967. World resources of *Spartina Townsenii* (sensu lato) and economic use of *Spartina* marshland. J. Appl. Ecol. 4, 239–256.
Rosso, P.H., Ustin, S.L., Hastings, A., 2006. Use of lidar to study changes associated with *Spartina* invasion in San Francisco Bay marshes. Remote Sens. Environ. 100, 295–306.
Schmid, K.A., Hadley, B.C., Wijekoon, N., 2011. Vertical accuracy and use of topographic LIDAR data in coastal marshes. J. Coast. Res. 27, 116–132.
Schwimmer, R.A., 2001. Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware, U.S.A. J. Coast. Res. 17, 672–683.
Schwimmer, R.A., Pizzuto, J.E., 2000. A model for the evolution of marsh shorelines. J. Sediment. Res. 70, 1026–1035.
Sheehan, M.R., Ellison, J.C., 2007. Baseline Survey of Tamar Estuary Shoreline Banks. NRM North, Launceston.
Shi, Z., Chen, J.Y., 1996. Morphodynamics and sediment dynamics on intertidal mudflats in China (1961–1994). Cont. Shelf Res. 16, 1909–1926.
Shi, Z., Hamilton, L.J., Wolanski, E., 2000. Near-bed currents and suspended sediment transport in salt marsh canopies. J. Coast. Res. 16, 909–914.
Smith, G.M., Thompson, A.G., Moller, I., Kromkamp, J.C., 2004. Using hyperspectral imaging for the assessment of mudflat surface stability. J. Coast. Res. 20, 1165–1175.
Steers, J.A., 1977. Physiography. In: Chapman, V.J. (Ed.), Wet Coastal Ecosystems. Elsevier, Amsterdam, pp. 31–60.
Strong, D.R., Ayres, D.A., 2013. Ecological and evolutionary misadventures of *Spartina*. Annu. Rev. Ecol. Evol. Syst. 44, 389–410.
Strong, D.R., Ayres, D.A., 2009. *Spartina* introductions and consequences in salt marshes. In: Silliman, B.R., Grosholz, E.D., Bertness, M.D. (Eds.), Human Impacts on Salt Marshes: a Global Perspective. University of California Press, Berkeley and Los Angeles, pp. 3–22.
Thompson, J.D., 1991. The biology of an invasive plant: what makes *Spartina anglica* so successful. Bioscience 41, 393–401.
van der Wal, D., Pye, K., Neal, A., 2002. Long-term morphological change in the Ribble Estuary, northwest England. Mar. Geol. 189, 249–266.
van Proosdij, D., Ollerhead, J., Davidson-Arnott, R.G.D., 2006. Seasonal and annual variations in the volumetric sediment balance of a macro-tidal salt marsh. Mar. Geol. 225, 103–127.
Wan, S., Qin, P., Liu, J., Zhou, H., 2009. The positive and negative effects of exotic *Spartina alterniflora* in China. Ecol. Eng. 35, 444–452.

Wang, A., Wang, Y., Chen, J., 2008. Role of *Spartina alterniflora* on sediment dynamics of coastal salt marshes — case study from central Jiangsu and middle Fujian coasts. Front. Earth Sci. China 2, 269–275.
Wilson, C.A., Allison, M.A., 2008. An equilibrium profile model for retreating marsh shorelines in southeast Louisiana. Estuar. Coast. Shelf Sci. 80, 483–494.
Xie, L., Zhang, Z., Zhang, Y., Wang, Y., Huang, X., 2013. Sedimentation and morphological changes at Yuantuojiao Point, estuary of the North Branch, Changjiang River. Acta Oceanol. Sin. 32, 24–34.
Zhou, H.X., Liu, J.E., Zhou, J., Qin, P., 2008. Effect of an alien species *Spartina alterniflora* Loisel on biogeochemical processes of intertidal ecosystem in the Jiangsu coastal region, China. Pedosphere 18, 77–85.