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Invasive cordgrass (*Spartina* spp.) in south-eastern Australia induces island formation, salt marsh development, and carbon storage

Running Head: Cordgrass salt marsh

Abstract

Invasive vegetation species can lead to major changes in the geomorphology of coastal systems. Within temperate estuaries in the southern hemisphere, especially Australia and New Zealand, the cordgrass *Spartina* spp. has become established. These species are highly invasive and their prolific growth leads to the development of supratidal environments in formerly intertidal and subtidal environments. Here, we quantified the impact of *Spartina* invasion on the geomorphology and sequestration capacity of carbon in the sediments of Andersons Inlet, Victoria, Australia. *Spartina* was first introduced to the area in the 1930s to aid in land reclamation and control coastal erosion associated with coastal development. We found that *Spartina* now dominates the intertidal areas of the Inlet and promotes accretion (18 mm/yr) causing the formation of over 108 ha of supratidal islands over the past 100 years. These newly formed islands are calculated to potentially contain over 5.5 million tons of CO_2 equivalent carbon. Future management of the inlet and other *Spartina*-dominated environments within Australian presents a dilemma for resource managers; on the one hand *Spartina* is highly invasive and can outcompete native tidal marshes, thereby warranting its eradication, but on the other hand it is likely more resilient to rising sea levels and has the potential for carbon sequestration. Whether the potential advantages outweigh the significant habitat change, will likely require additional research into costs and benefits of all ecosystem services provided by *Spartina* including nutrient cycling, shoreline stabilisation, biodiversity as well as the longevity of carbon found within the sediments.

Key words: Ecosystem services, blue carbon, Spartina, salt marsh, sea level rise, invasive species

Introduction

Salt marshes are commonly found on the margins of estuaries and are characterised by halophytic vegetation that is inundated by the highest tides (Allen, 2000). Their evolution is closely related to sea level and tidal inundation; however the precise elevation of a salt marsh within the tidal prism is the product of a complex interaction of biophysical factors related to allochthonous and autochthonous sedimentation, vegetative communities and ground water (Rogers et al., 2014). Salt marshes are therefore not passive environments and they interact with wider estuarine environments through both vertical and lateral accretion. It is their ability to accrete which is most important for their continued presence under rising sea level, rather than simply their elevation in relation to sea level (Lovelock et al., 2014b; Reef et al., 2017).

The main external controls on salt marsh development are tidal regime as well as sediment supply (Allen, 2000). There must also be sufficient accommodation space for marshes to accrete with the highest tides being the principle boundary condition. Rates of accretion on the other hand are determined by the rates of sediment supply which can be derived from both organic and inorganic sources (Allen, 2000). Vegetation is a key element as it can both enhance deposition of suspended sediment as well as directly contribute biomass (Reed, 1995). In fact tidal marshes are among the most efficient ecological systems for the storage of organic carbon (Duarte et al., 2013; McLeod et al., 2011; Pidgeon, 2009), with salt marsh ecosystems ranking the highest in organic carbon storage potential amongst all coastal wetland and forested terrestrial ecosystems (Ouyang and Lee, 2014). The efficiency of carbon accumulation is related to the burial of organic material from accreting sediments and the anaerobic conditions which decrease rates of organic matter decomposition (Kristensen et al., 1995; Kristensen et al., 2008; Hedges and Keil, 1995).

As marsh evolution is dependent on their vegetative ecosystems, changes within these habitats can have major geomorphic implications. For example in Australia, Western Port, Victoria (Rogers et al., 2005) and Tweed River, New South Wales (Rogers et al., 2014), changes in tidal prism associated with sea level rise has led to mangrove colonisation of salt marsh habitat. At lower elevations within the tidal prism, the introduction of *Spartina* grass in the Tamar Estuary, Tasmania, Australia, led to accretion of a supratidal marsh over previously bare subtidal mud flats (Kriwoken and Hedge, 2000; Hedge and Kriwoken, 2000). In this study we explore the impact of invasive grass species (*Spartina*) within Venus Bay contained within a shallow barrier-estuary in Victoria, Australia. Through subsurface coring and aerial photo analysis we assess the positives and negative environmental impacts of invasive-species driven habitat change.

Regional Setting

Venus Bay has an approximate surface area of 3.4 km^2 located in the south eastern part of Anderson Inlet in West Gippsland, Victoria, Australia (Fig. 1). Andersons Inlet is predominantly submarine, with sediment movement associated with migrating tidal channels and movement of the tidal deltas at the estuary mouth. The estuary is 10 km long, being widest (2 – 3 km) in its central regions. It is separated from the open ocean by a beach-barrier system estimated to be 4500 years old (Li et al., 2000). The estuary is therefore classified as an partially-infilled barrier estuary according to the scheme of Roy (1984). The coastal plain surrounding the inlet is characterised by three terraces ranging up to 6 m elevation. The highest corresponds to the Last Interglacial period (c. 125ka) and the lower two, both <2 m elevation, relating to early – mid Holocene higher sea levels (Li et al., 2000).

The coast of Victoria is microtidal with a semidiurnal spring range of 1.1 m at Port Philip Heads (Port of Melbourne, 2013). The tidal prism with Andersons Inlet is 22.66 x 10^6 m^3 (McSweeney et al., 2017). The mean significant wave height for the Victorian coast is 2.4 m with a period of 8.4 seconds (Hughes and Heap, 2010). Modelling of open-ocean waves in Victoria indicates the mean annual wave height for Cape Paterson is 1.8 m (WaterTech, 2004). Wave data within Anderson Inlet is not recorded. Mean annual maximum and minimum air temperatures for Cape Paterson are 9.6 – 18.8 °C with a mean annual rainfall of 939 mm (BoM, 2012).

Spartina (cordgrass) is a genus of approximately 17 rhizomatous perennial grass species found in temperate estuarine and salt marsh environments. *Spartina* spp. are efficient colonisers of marine habitats renowned for their ability to stabilise estuarine surfaces, promote accretion, and the conversion of intertidal flats into supratidal monocultures. *Spartina* was widely planted for erosion control and reclamation through temperate regions because of these attributes (Hacker et al., 2001; An et al., 2007).

Two species of *Spartina*, *Spartina x townsendii* and *Spartina anglica* were introduced to coastal Victoria (Williamson, 1996). *S. x townsendii*, a sterile hybrid of American and English cordgrass species, was first introduced to the study site in the 1930s (Williamson, 1996). The second species, *S. anglica,* is the fertile product of chromozonal doubling of *S.townsendii* (Hacker et al., 2001). *S. anglica* was introduced to the study site in the 1960s (Williamson, 1996). *S. anglica* is probably the dominant species today, however, the two species are difficult to distinguish and there is little data available on the relative distributions of *S. anglica* and *S. x townsendii* within the study site.

Methods

The impact of *Spartina* was evaluated within a 280 ha section of Venus Bay (Fig. 1). Airborne Light Detection and Ranging (LiDAR) data were collected in 2007 by the Department of Environment and Primary Industries of the Victorian State Government. The surveying was conducted using a LADS Mk II system coupled with a GEC-Marconi FIN3110 inertial motion sensing system and a dual frequency kinematic global positioning system (kGPS). This dataset was processed to produce a seamless terrestrial-marine mosaic from elevations of +10 m to depths of -25 m with a final raster grid of 2.5 m resolution for the entire Victorian coast (Quadros and Rigby, 2010). Shoreline change on the islands was defined on the basis of the seaward boundary of the vegetation in aerial and satellite photographs from 1950, 1981, 2010 and 2015 (Table 1). The 1950s imagery was overexposed and comprised of three images that had been combined manually prior to digitisation. Ground truthing of the most recent aerial photograph indicated this boundary is either mangrove or *Spartina* grass. Images were georeferenced in ArcGIS 10.4.1 using control points obtained from the 2015 imagery. Images were transformed using a 1st order polynomial with RMS errors ranging between 0.42 and 12.2 m. Vegetation lines were digitised manually by a single operator. Positional uncertainty in defining the shoreline was calculated based on the pixel, rectification and digitization errors (Ford, 2013). Pixel and rectification errors are represented by the resolution of the original image and the Root Mean Square Error (RMSE) of the dereferencing process (Del Rio and Gracia, 2013). Digitization error was calculated as the standard deviation of the shoreline position from repeated digitisation of the largest mud island by a single operator (Ford, 2013). Total shoreline error is calculated as the root sum of all shoreline position errors and ranged between 4.4 and 28.3 m (Table 1). Island volume and height above MSL was calculated in ArcGIS from the 2007 LiDAR data. MSL was defined as the zero elevation contour line relative to Australian Height Datum (AHD).

A vibrocore core (76 mm diameter) was taken on the mud island closest to the boat ramp in Venus Bay (38.67056°S, 145.79892°E) in 2015 (Fig. 2). The location was selected as it represents an intertidal environment of the mud island region, the area where the impact of *Spartina* was most likely to be significant, and where the aerial photo analysis indicated the mud flats to be particularly dynamic.

In the laboratory, sediment grain size was analysed using a Beckman Coulter LP13320 laser particle sizer with grain texture classified according to the criteria of Leeder (1982) and size statistics calculated using the graphical procedures of Folk and Ward (1957). Total organic carbon and carbonate composition was undertaken using the loss on ignition method (Kennedy and Woods, 2013). Dating was undertaken at the Waikato Radiocarbon Dating Laboratory, New Zealand.

Pollen analysis, using standard procedures (including hot 10% KOH, 40% HF and acetolysis) as outlined in Faegri and Iversen (1989), was undertaken at 10 cm intervals in the uppermost part of the core with pre-treatment of 10% HCl prior to addition of HF. Organics were separated with KOH and acetolysis, with samples sieved through a 7 micron mesh. Slides were counted until at least 300 terrestrial pollen grains were identified based on species reference collections held by the School of Geography, The University of Melbourne. Pollen belonging to *Spartina* was not distinguishable from native *Poaceae* spp. Counts were processed and graphed using the computer programme Tilia 2.0.37 (Grimm, 1999).

Results

Islands

Islands in the aerial photos were defined as being vegetated communities, separated from the hinterland by channels, which have a proportion of their surface exposed at or above mean high water spring tide elevation. Three vegetated mud islands could be clearly identified in 1950 ranging in area from 0.14 – 20.14 ha with lengths and widths of up to 654 and 435 m respectively (Fig 2a). These islands grew in the 65 years between aerial images by progressive expansion of shorelines following vegetation colonisation of the intertidal mud flats, and through the formation and coalescence of new islands.

Two islands, identified in Fig 2, exemplify the processes of colonisation and island growth between 1950 and 2015. Island A was not present in 1950 but comprised in 1981 of small vegetation patches (<38 m^2) indicative of the recent establishment of plants on the previously unvegetated mudflats. By 2010 Island A had grown to comprise an island 1.4 ha in area with a close-to 100% vegetation cover. Island B was the smallest of the three islands present in 1950. By 1981 Island B had expanded in area by 97% to comprise an island 10.4 ha. By 2010 expansion of Island B and neighbouring mud islands had cumulated in the coalescence of at least three islands forming an island measuring 22 ha in area.

Sixteen islands were identified in the 1981 imagery, the three islands present in 1950 and an additional 13 islands that had formed where previously there had been bare tidal flats (Fig 2b). All three original islands had increased in area and the vegetation around the island margins comprised of scattered colonies indicative of ongoing island expansion. These sixteen islands expanded and merged to form eight large islands by 2010 and new islands continued to form (Fig 2c). The mud islands continued to expand in area between 2010 and 2015. By 2015 the study site comprised of ten islands with an average area of 10.8 ha and lengths and widths of up to 1100 and 750 m respectively (Fig 2d). No new islands formed between 2010 and 2015; however, extensive zones of scattered vegetation along the margins of several islands as well as isolated patches of new vegetation are clearly identifiable in the 2015 imagery indicating that island expansion and colonisation of the intertidal mud flats remains ongoing. Overall the total area of mud island within the study site has increased steadily from 34.4 ha in 1950 to 108.3 ha in 2015, a net increase of 214% (Table 2). While no elevation data is available for the study area prior to 2007 the extensive tidal flats evident in 1950 probably lay at close to mean sea level (MSL). Average island height in 2007 was 0.67 above MSL with a combined volume of about 688,711 m^3 above MSL.

The contemporary mud islands are colonised by a mix of *Spartina* and mangrove (*Avicennia marina var. australasica*) (Fig. 3). The initial increase in island area between 1950 and 1981 was largely due to the spread of *Spartina* since 1962 (Boston, 1981), and can be clearly distinguished from the indigenous mangrove/saltmarsh communities dominating the original mud islands in the 1981 aerial imagery. While we have no quantitative data on the floristic composition of the mud islands since 1981, examination of the aerial imagery suggest that the ongoing expansion of *Spartina* contributed to much of the increase in island area between 1981 and 2010. Since 2010 however island expansion appears to be the result of increasing mangrove densities not *Spartina*.

Stratigraphy

A vibrocore was collected in the centre of a small island which was a bare sediment flat in 1950 (Fig. 2d). A total depth of 3.41 m was reached through coring with a coarse shelly-sand layer at the base of the core preventing further penetration. A core length of 2.65 m was recovered and with no loss of sediment occurring resulting in a total compaction of 22%.

The basal unit of the core is dominated by medium – coarse sand and characterised by mud lenses and abundant shell material both in the form of whole valves of *Tellina deltoidalis* and broken shell hash layers (Fig. 4). Total organic carbon content is low (< 2%) while carbonate grains accounts for between 3 – 7% (Fig. 5). The whole shell valves are disarticulated and broken indicative of a relatively high energy environment of deposition. The mean and medium grain sizes are similar (1-2 ϕ, medium sand), reflecting the moderately – moderately well-sorted character of the sediments (Fig. 4). A single *T. deltoidalis* valve from the base of this unit was radiocarbon dated at 2747 – 2480 years CalBP (Table 3). This shell was disarticulated and allocthonous, therefore representing a maximum age for the base of the core.

Overlying the lower unit is a medium – fine, moderately – moderately-well sorted, sand with a minor (< 15%) component of mud. Small mud lenses (mm thick) were found throughout this unit, being particularly common from 1.8 – 2.2 m (2.31 – 2.83 compaction corrected) depth (Fig. 4). There was an absence of large visible shell material although peaks in carbonate content to over 12% suggest some shell material is present as sand-size grains (Fig. 5).

Overlying the sands to 0.8 m (1.2 m compaction corrected) depth is a muddy sand unit (mean grain size 2.5 and 4 ϕ (very fine to fine sand) which is very poorly sorted to poorly sorted. Carbonate content peaks at 9% and there is a marked increase in the total organic carbon content, rising to > 6% at the top of the unit. Live mangrove roots were found within this unit (Figs. 4 and 5).

The top of the core, from 0.8 m core depth to the surface is dominated by very poorly sorted, organic rich (>10% TOC, with a peak of 17%) fine mud, which contained large (c. 5 mm width) live mangrove roots but lacked visually observable shell material (Fig. 4). The mean grain size was between 5 and 6 ϕ (medium silt) in the upper 0.5 m and coarsened to 4 ϕ (coarse silt – very fine sand) in the lower parts of this uppermost unit (Fig. 3). This unit consistently has a low carbonate content (<3%) (Fig. 5).

Palynology

Well preserved pollen was found in the uppermost mud unit. The non-native tree *Pinus radiata* is particularly abundant at the surface accounting for 20% of pollen, with *Plantago lanceolata* present throughout the core with a peak at 0.65 m core depth (0.83 m compaction corrected) (Fig. 6). Specimens of *Rumex* spp. are found throughout the mud unit. These species are considered to be representative of the post-European period. Indigenous species *Eucalyptus* and *Myrtaceae* spp. are more abundant at the base of the mud unit (10%) compared to the top (< 5%). *Casuarina* sp. also are in greater abundance at the base (Fig. 6). During analysis soot particles, the byproduct of industrial activity, were found throughout the uppermost unit. Soot was classified on the basis of its round organic clast appearance which contrasts to angular charcoal particles.

Discussion

Spartina spp. was first introduced into Australia in the late 1920s and early 1930s and was recorded in Andersons Inlet by 1932 (Williamson, 1996). At the time of the earliest aerial photos 30 years later it had already established in the southern section of the estuary. This original population is likely to comprise the infertile *S. x townsendii*. A rapid expansion in the area occupied by *Spartina* spp. was recorded after the introduction of *S. anglica* in 1962 (Williamson, 1996)

Today Venus Bay is still dominated by supratidal islands which have increased their aerial coverage by 73.8 ha. At present these marshes are dominated by *Spartina* with a fringe of mangroves on their seaward edges. The surface sediments extend to over 1.0 m depth at the SW part of the island complex. These organic-rich sediments are characteristic of marsh environments, particularly those composed of *Spartina* as described in a global review of 143 sites by Ouyang and Lee (2014). Underlying this organic-rich layer are coarser fine sands, with low total organic content (TOC) more characteristic of the bare sediment flats surrounding the islands.

The presence of *P. radiata* pollen throughout the organic-rich salt marsh unit combined with an abundance of soot particles allows us to infer that the marsh has developed post European colonisation. Poor preservation of pollen grains below the salt marsh unit as well as possible contamination related to mangrove roots means inferences on the age of the non-marsh sediments are difficult. The inter-sub tidal flats on which the marsh grew, however, must be younger than 2747 – 2480 years CalBP, based on the radiocarbon age of a tidal channel unit at the base of the core (Fig. 7).

The marsh islands, therefore, have primarily grown vertically on top of subtidal muddy sand flats at rates of 18.5 mm/yr. Pre-existing channels on the bare sediment flats in the 1950's aerial photos appear to delineate the edge of the newly emergent marshes suggesting primarily vertical accretion. This is similar to the Beeftink-Rozema (1988) model of salt marsh development developed from the barrier and estuarine systems of The Netherlands. As the marshes vertically accrete, tidal channels tend to become more entrenched (Allen, 2000) and this can be observed on the older marsh surfaces in Andersons Inlet that were present over 50 years ago (Fig. 2). Channel dimensions are not, however, an accurate proxy of marsh age as their evolution can be affected by a range of conditions often independent of climate, tides or sedimentological conditions (Perillo and Iribarne, 2003). For example in Argentina (Rio de la Plata and Loyola Bay) channel development is related to hydrodynamic processes while in Bahia Blanca Estuary biology was critical in channel initiation (Perillo and Iribarne, 2003).

The marsh-dominated islands in Venus Bay are therefore likely the result of the introduction of *Spartina* due to the coincident of plant colonisation and island development, all of which occurred in the mid-20th century postdating catchment clearance by a century. The island formation has led to a major shift in the geomorphology of Venus Bay. In an Australian review, Macreadie et al. (2017) found that *Spartina*-dominated marshes had the highest levels of carbon accumulation rates among five halophyte genera (incl. *Disthichlis*, *Halimione*, *Juncus*, and *Phragmites*). In this study the total organic carbon within the *Spartina* portion of the marsh was > 10% of the dry sediment weight. Sampling of neighbouring salt marshes for organic carbon yields a carbon concentration of 2.16 +/- 1.05 g C_{org} cm^{-3} (Macreadie et al., 2017). Given the values of TOC are similar between the two marsh environments we can assume a similar degree of organic carbon storage beneath the mud islands. For the studied islands (688,711 m^3 above MSL based on the LiDAR data) this yields a total historical carbon store of at least 1.5 +/- 0.7 million tonnes, giving a total CO_2 equivalent of 5.5 million tonnes. Based on the data available this store is approximate, but does represent the potential of such systems for carbon storage. The longer term potential of the newly established marshes to sequester carbon will, however, depend on the dynamics of the marsh-biosedimentary system and the structural form of carbon present (labile etc).

The establishment of *Spartina* therefore poses a management dilemma. The species is highly invasive and has caused major geomorphic change within the estuary with the creation of intertidal mud islands. Island accretion has been linear since 1950 and therefore will most likely continue into the future especially as *Spartina* is widespread within Andersons Inlet. Major changes in the benthic habitats can therefore be expected with associated impacts on navigation and amenity use within Venus Bay. Actively accreting marsh environments on the other hand have greater potential to provide shoreline protection to sea level rise than bare sediment flats. In addition their high carbon content means there is potential for carbon storage, assuming that the carbon is primarily *in situ.*

An additional complication for managers is the impact of sea level rise on vegetative communities. In Victoria higher high tides are causing shifts in community compositions with mangroves colonising salt marsh environments in Western Port Bay (Saintilan et al., 2014; Rogers et al., 2005). This vegetative change, in turn, will have implications for the storage of below ground carbon as rates of sequestration are dependent on the wetland community structure (Lovelock et al., 2014a). A significant unknown is the ability of mangroves to displace *Spartina*-dominated marshes when compared to endemic communities. In Andersons Inlet the *Spartina*-dominated marshes are fringed by mangroves (*Avicennia marina var. australasica*). In Victoria and eastern Australia (specifically the Tweed River) the almost universal shift from saltmarsh to mangrove communities (Rogers et al., 2005; Saintilan et al., 2014; Rogers et al., 2014), may mean that the Venus Bay *Spartina* marshes could be replaced by mangrove in the future.

Conclusions

The colonisation of the invasive species *Spartina* has led to the development of supratidal marshes in Andersons Inlet, south eastern Australia. These marshes have developed in the past century on what were initially intertidal sediment flats. Based on aerial photograph analysis *Spartina* colonisation has been rapid and appears to continue to drive island evolution, with the islands doubling in size since 1950. The rapid expansion of the *Spartina* islands is most likely to continue into the next century.

The islands that have been created are very high in total organic carbon suggesting a high potential as a carbon sink. This potential will however be dependent on the type of carbon that is present as well as the long term stability of the newly accreted islands and their vegetative communities. Management of *Spartina*-dominated environment results in two major environmental trade-offs. *Spartina* is a highly invasive species which leads to major change in the habitats it colonises. This is because it forms supratidal surfaces in formerly sub-intertidal environments. On the other hand, *Spartina* marshes are high in organic content and can accrete at high rates and provide protection to the subaerial shoreline. The generation of supratidal habitats may provide opportunities for other colonisers such as mangrove. A critical unknown is the ability of mangroves to outcompete *Spartina* as sea level rises.

Figure Captions

Figure 1: Venus Bay is located within Anderson Inlet in southern Victoria. (a) Andersons Inlet is one of the most southernmost barrier estuaries on the Australian mainland occurring on the southern coast of Victoria. (b) Venus Bay (white box) is the area where *Spartina* grass has the most impact and is the focus of this study.

Figure 2: Aerial imagery of Venus Bay from 1950 to 2015 showing the growth of the islands in the past 65 years. Subsurface sediments were samples from the small island closest to shore which accreted during this period (arrowed yellow circle).

Figure 3: (a) the edge of the cored island looking towards the Venus Bay township. (b) *Spartina* and mangrove vegetation in the centre of the island where the coring was undertaken.

Figure 4: Sedimentology and stratigraphic log of the vibrocore. The uppermost parts of the core are fine grained dominated by silt. The sediment progressively coarsens with depth with a coarse sand with shell material found at the base of the core.

Figure 5: Total organic carbon (TOC) and carbonate composition through the core. There is a distinct difference between the upper 75 cm and lower parts of the core, with the surface sediment being high in TOC and low in carbonate.

Figure 6: Pollen composition of the surface fine organic unit. The abundance of exotic *Pinus* pollen indicates the post-European settlement age of this material.

Figure 7: Stratigraphic interpretation of the sedimentary history of the island from 3ka to present.

Table 1: Uncertainty in shoreline position on islands within Venus Bay

Table 2: Changes in island area in the past 65 years.

Table 3: Radiocarbon age from the tidal channel at the base of the core.

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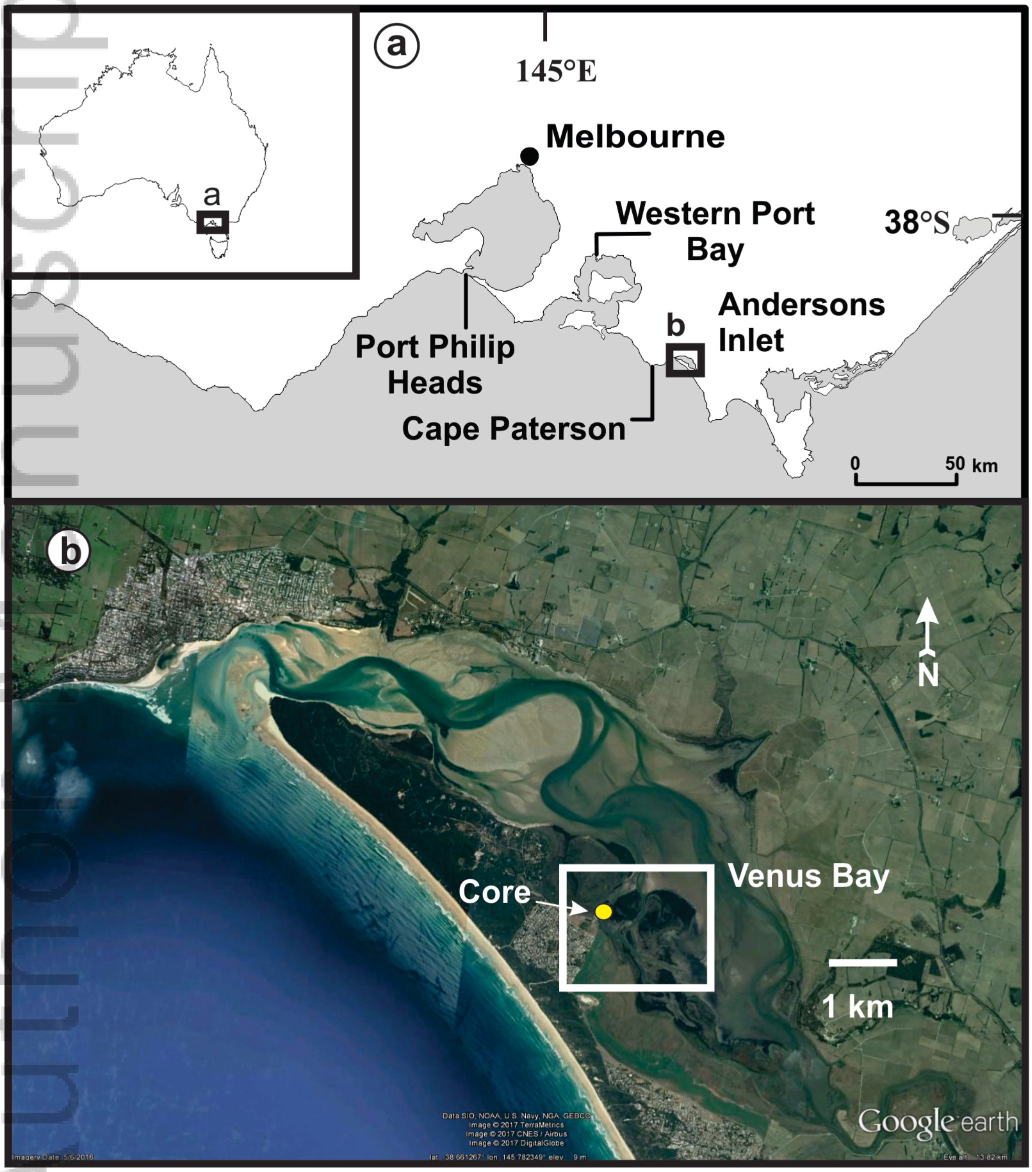

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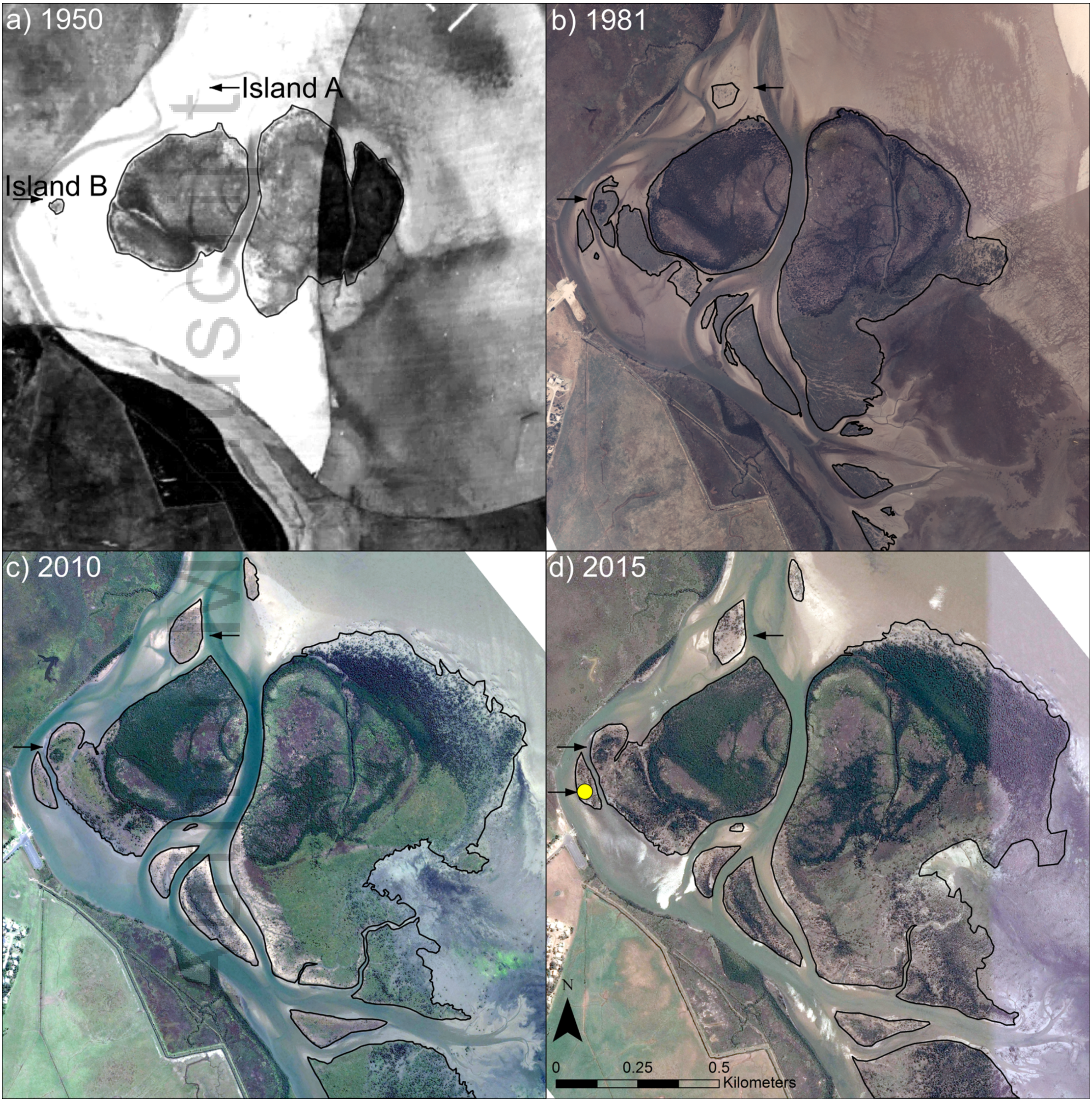

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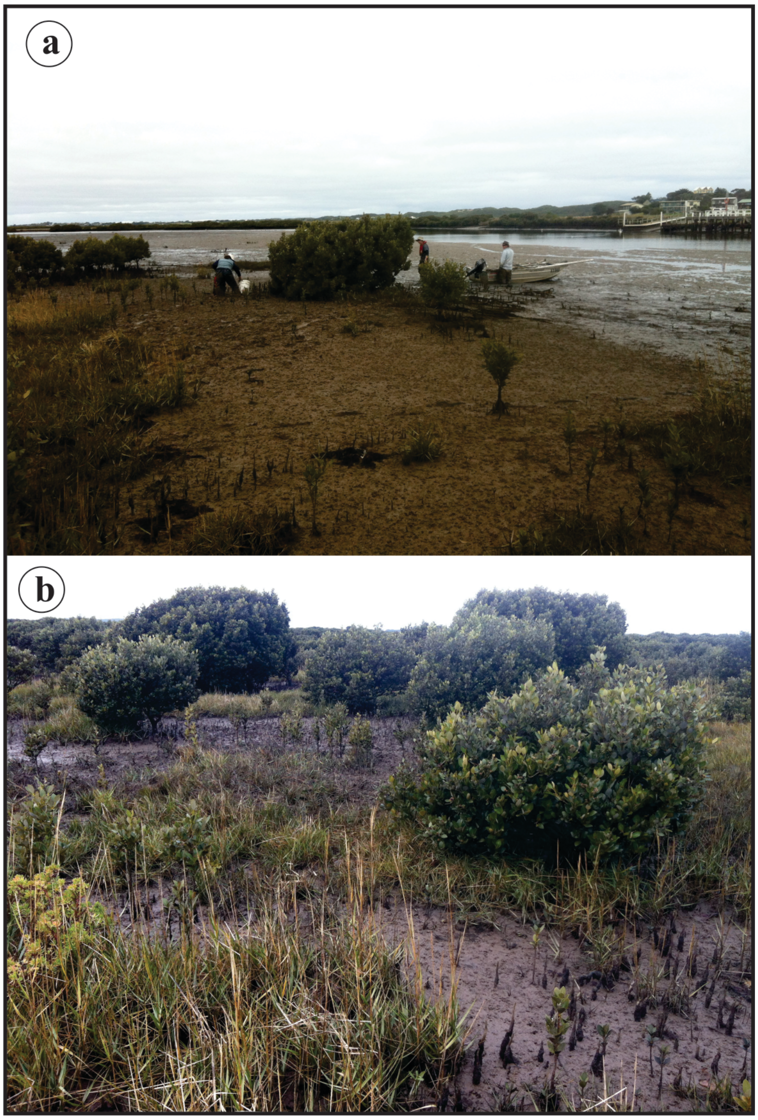

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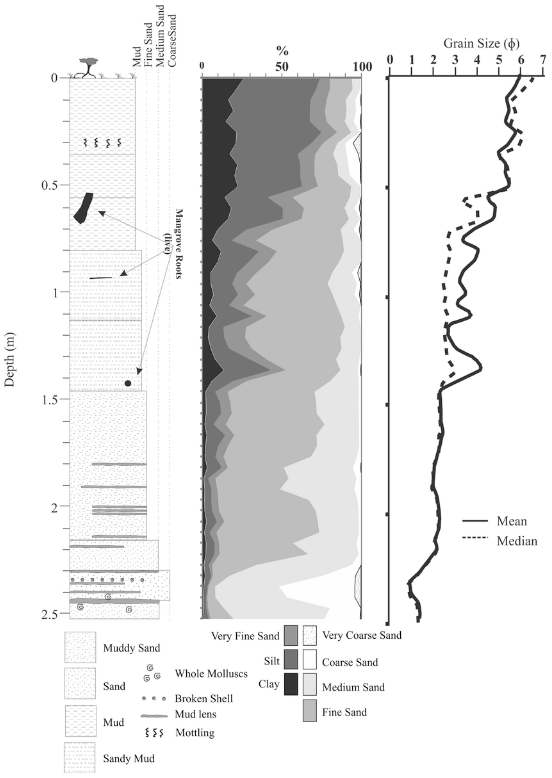

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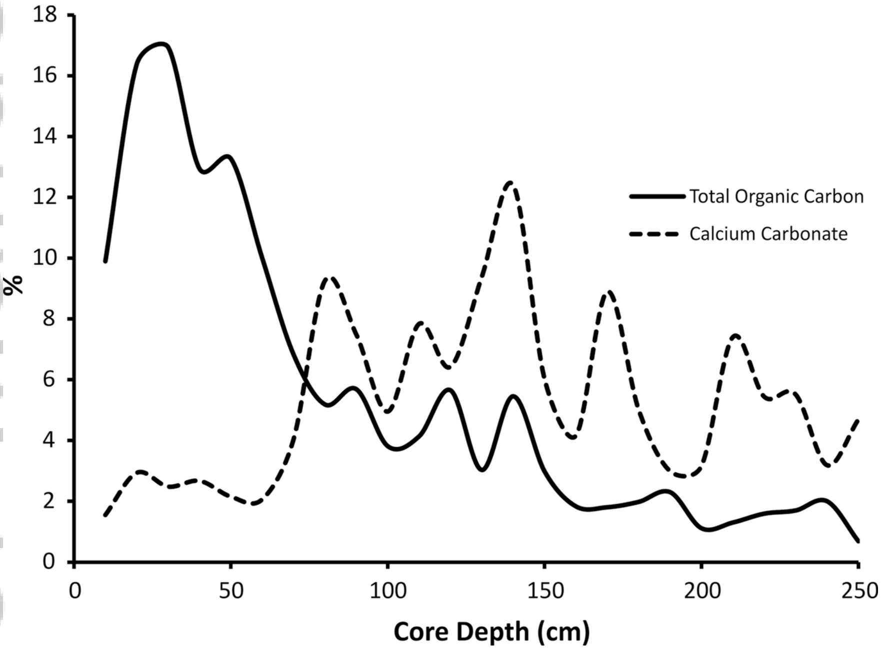

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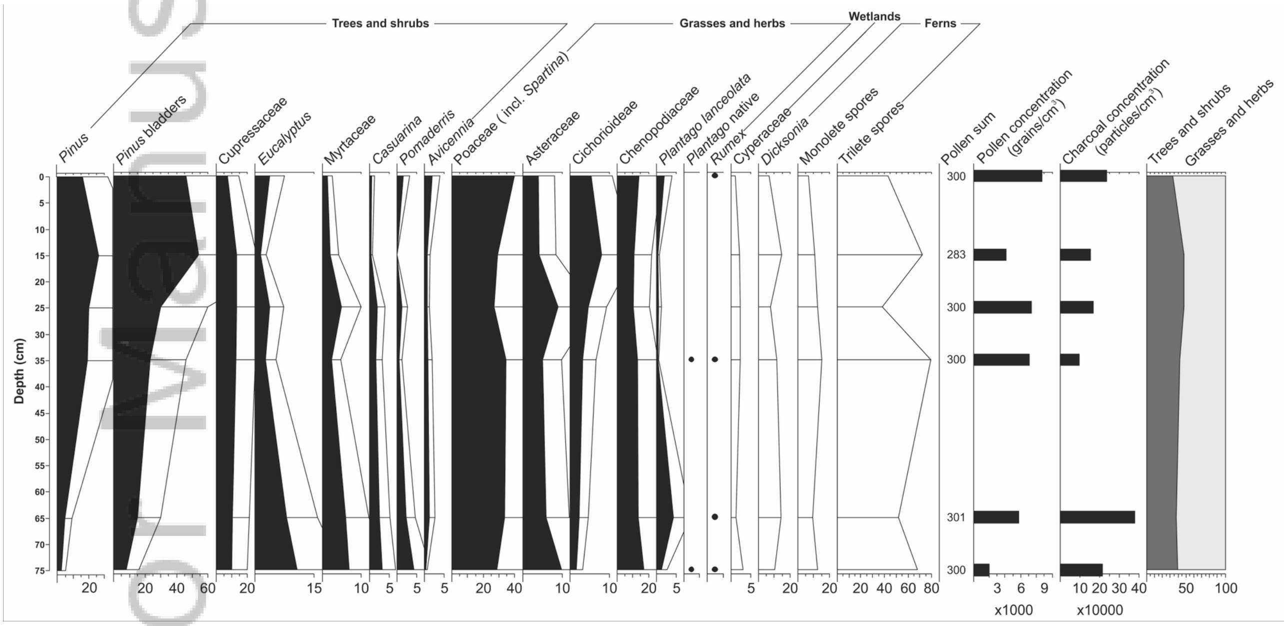

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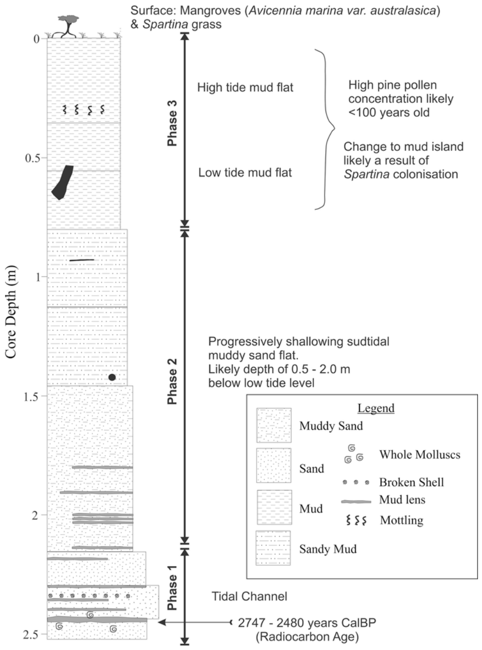

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