1-1-2019

Impacts of land reclamation on tidal marsh 'blue carbon' stocks

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Publication Details Citation

Ewers, C., Baldock, J., Hawke, B., Gadd, P. S., Zawadzki, A., Heijnis, H., Jacobsen, G., Rogers, K., & Macreadie, P. (2019). Impacts of land reclamation on tidal marsh 'blue carbon' stocks. Faculty of Science, Medicine and Health - Papers: Part B. Retrieved from https://ro.uow.edu.au/smhpapers1/669

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Abstract

Tidal marsh ecosystems are among earth's most efficient natural organic carbon (C) sinks and provide myriad ecosystem services. However, approximately half have been 'reclaimed' - i.e. converted to other land uses - potentially turning them into sources of greenhouse gas emissions. In this study, we applied C stock measurements and paleoanalytical techniques to sediments from reclaimed and intact tidal marshes in southeast Australia. We aimed to assess the impacts of reclamation on: 1) the magnitude of existing sediment C stocks; 2) ongoing C sequestration and storage; and 3) C quality. Differences in sediment horizon depths (indicated by Itrax-XRF scanning) and ages (indicated by lead-210 and radiocarbon dating) suggest a physical loss of sediments following reclamation, as well as slowing of sediment accumulation rates. Sediments at one meter depth were between ~2000 and ~5300 years older in reclaimed cores compared to intact marsh cores. We estimate a 70% loss of sediment C in reclaimed sites (equal to 73 Mg C ha -1), relative to stocks in intact tidal marshes during a comparable time period. Following reclamation, sediment C was characterized by coarse particulate organic matter with lower alkyl-o-alkyl ratios and higher amounts of aromatic C, suggesting a lower extent of decomposition and therefore lower likelihood of being incorporated into long-term C stocks compared to that of intact tidal marshes. We conclude that reclamation of tidal marshes can diminish C stocks that have accumulated over millennial time scales, and these losses may go undetected if additional analyses are not employed in conjunction with C stock estimates.

Publication Details

Ewers Lewis, C. J., Baldock, J. A., Hawke, B., Gadd, P. S., Zawadzki, A., Heijnis, H., Jacobsen, G. E., Rogers, K. & Macreadie, P. I. (2019). Impacts of land reclamation on tidal marsh 'blue carbon' stocks. Science of the Total Environment, 672 427-437.

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Impacts of land reclamation on tidal marsh 'blue carbon' stocks

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Running Head: Impacts of reclamation on blue carbon stocks

Key Words: blue carbon, land reclamation, carbon stocks, emissions, sediment carbon, tidal marsh, carbon sequestration, sediment carbon

Paper Type: Research article

Abstract

Tidal marsh ecosystems are among earth's most efficient natural organic carbon (C) sinks. However, approximately half have been 'reclaimed' – i.e. converted to other land uses – potentially turning them into sources of greenhouse gas emissions. In this study, we applied C stock measurements and paleoanalytical techniques to sediments from reclaimed and pristine tidal marshes in southeast Australia. We aimed to assess the impacts of reclamation on: 1) the magnitude of existing sediment C stocks; 2) ongoing C sequestration and storage; and 3) C quality. Differences in sediment horizon depths (indicated by Itrax-XRF scanning) and ages (indicated by lead-210 and radiocarbon dating) suggest a physical loss of sediments following reclamation, as well as slowing of sediment accumulation rates. Sediments at one meter depth were between ~2,000 and ~5,300 years older in reclaimed cores compared to pristine marsh cores. We estimate a 70% loss of sediment C in reclaimed sites (equal to 73 Mg C ha^{-1}), relative to stocks in pristine tidal marshes during a comparable time period. Following reclamation, sediment C was characterized by coarse particulate organic matter with lower alkyl-o-alkyl ratios and higher amounts of aromatic C, suggesting a lower extent of decomposition and therefore lower likelihood of being incorporated into long-term C stocks compared to that of pristine tidal marshes. We conclude that reclamation of tidal marshes can diminish C stocks that have accumulated over millennial time scales, and these losses may go undetected if sediment age dating is not employed in conjunction with C stock estimates.

Introduction

Land use change is one of the greatest sources of greenhouse gases to the atmosphere, contributing approximately 30% of global emissions and accelerating climate change (Houghton, 2003). Deforestation alone is the second greatest source of emissions, next to fossil fuel combustion (van der Werf et al., 2009). Recent research into coastal wetlands—tidal marshes, mangrove forests, and seagrass meadows—has identified these ecosystems as dense, rapidly accumulating organic carbon (C) sinks, earning them the term 'blue carbon' (Mcleod et al., 2011; Nellemann et al., 2009). Yet global inventories of blue C stocks, and impacts of their degradation on C storage, have only recently begun to emerge (e.g. Chmura, Anisfeld, Cahoon, & Lynch, 2003; Duarte, Losada, Hendriks, Mazarrasa, & Marbà, 2013; Pendleton et al., 2012).

Pools of organic C in blue C ecosystems include living above ground biomass, living belowground biomass, leaf litter and detritus, and that found in soils and sediments (hereafter referred to as sediments). The largest C pool resides in the sediments where it is stored due to a combination of potentially continuous accretion and conditions favorable for long-term organic C storage (Donato et al., 2011; Fourqurean et al., 2012). The sediment C pool is composed of both autochthonous C produced within the ecosystem itself (e.g. leaf litter) and allochthonous C that has been imported (e.g. from land via freshwater inputs, or the ocean; Mcleod et al., 2011).

Disturbance to any of these organic C pools may result in blue C sinks becoming sources of greenhouse gas emissions. In a review of global blue C emissions caused by disturbance, Pendleton *et al.* (2012) estimated an annual release of 0.15-1.02 Pg (billion tons) of CO_2 to the atmosphere, or 3-19% of that caused by deforestation. However, Pendleton *et al.* (2012) acknowledged that these estimates need refining through improvements to estimates of global distribution and land use conversion rates, as well as research on the fate of C stocks with disturbance. Lovelock *et al.* (2017) developed a qualitative framework to help assess the risk of emissions from blue C ecosystems, and emphasized a need for more direct evidence for the impacts of specific disturbance types on blue C stocks to turn it into a quantitative framework.

It is generally agreed that the greater the C stocks in a system, the greater the potential for emissions, as emissions are calculated as a proportion of the total stocks (e.g. Atwood et al., 2017; Donato et al., 2011; Ewers Lewis, Carnell, Sanderman, Baldock, & Macreadie, 2017). Although a lack of refined stock estimates is considered a limitation for calculating potential emissions from blue C ecosystems (e.g. Pendleton et al., 2012), more robust regional and global estimates of C stocks are becoming increasingly available (Atwood et al., 2017; Ewers Lewis et al., 2017; P. Macreadie et al., 2017; Sanderman et al., 2018).

The likelihood of remineralization of C stocks is a key component in determining the risk of blue C emissions, which is in turn dependent on the type of disturbance and the environmental conditions (Lovelock et al., 2017). The fate of organic C stocks after disturbance may include remineralization to inorganic forms that immediately or eventually result in emissions (e.g. dissolved inorganic C in the water column or CO_2 released to the atmosphere), export outside of the system, and/or reburial in the sediments; however, the proportion of C that ends up in each of these pools is generally unknown (Lane et al., 2016). Some forms of organic C ("C quality") are structurally more complex and therefore more resistant to remineralization (termed 'recalcitrant'), yet disturbance accelerates rates of decomposition of even these forms of C, meaning they are all vulnerable to some degree and should be considered potential sources of greenhouse gas emissions (Lovelock et al., 2017).

Loss of vegetation appears to have only mild impacts on sediment C if the sediments are not directly disturbed (P. I. Macreadie, Hughes, & Kimbro, 2013). In a 1.5-year assessment of the impact of herbicide use on C stocks and emissions, Lane *et al.* (2016)

found a 2.4-9.6% loss of C content in the top 50 cm of tidal marsh sediments, which is substantially lower than the percent stock losses of 25-100% proposed in reviews of disturbance to blue C ecosystems (Donato et al., 2011; Murray, Pendleton, Jenkins, & Sifleet, 2011; Pendleton et al., 2012; Siikamäki, Sanchirico, Jardine, McLaughlin, & Morris, 2013).

With direct disturbance to sediments there appear to be disproportionate impacts of the duration of disturbance on C stocks. Coverdale *et al.* (2014) and Serrano *et al.* (2016) found decades of disturbance resulted in the loss of approximately two centuries worth of C sequestration from sediments in marshes due to bioturbation and in seagrass meadows due to boat mooring activities, respectively. Similarly, disturbance to seagrass 50 years ago resulted in a shift to a bacterial community dominated by aerobic heterotrophs and a loss of 72% of sediment C stocks that required hundreds to thousands of years to accumulate (P. I. Macreadie et al., 2015).

Tidal marshes are particularly vulnerable to human disturbance in that they have been targeted for settlement, livestock grazing, and fishing as far back as the Neolithic Era (Gedan, Silliman, & Bertness, 2009). Land claim – or 'reclamation' – is one of the most prevalent causes of intertidal wetland decline globally. Estimates of coastal habitat loss due to reclamation include 88,820 ha from English estuaries since Roman times (Healy & Hickey, 2002), 6,500 ha from the Shannon estuary, Ireland, since the 19th century (Healy & Hickey, 2002). There are no direct measurements available for the area of tidal marsh reclaimed in Australia, but it is well-known as one of the, if not the greatest, cause of tidal marsh loss on the continent over the past two centuries (Laegdsgaard, 2006; P. Macreadie et al., 2017; Saintilan & Rogers, 2013).

In this study, we combined one-meter depth C stock measurements with paleoanalytical techniques to age and characterize sediments from tidal marshes reclaimed ~150 years ago and pristine tidal marshes in southeast Australia. The aim of the study was to assess the impacts of reclamation on: 1) sediment organic C stocks sequestered prior to reclamation; 2) ongoing C sequestration and storage after reclamation; and 3) C quality (i.e. the intrinsic chemical stability of the C).

Materials and Methods

Study Site

Koo Wee Rup (meaning "Great Swamp"), Victoria lies ~75 km southeast of Melbourne on the northern shore of Westernport Bay in southeast Australia. The Bay today is fringed with mangrove and tidal marsh ecosystems, but the region has a history of drainage and land-use conversion following European settlement that led to the destruction of freshwater and tidal wetlands. This included the conversion of the expansive Koo Wee Rup Swamp (around the year 1900) to agriculture that the region is known for today. This massive draining project resulted in flooding events in the region for decades to come. Meanwhile on the Bay, bund walls (levy banks) were built up to inhibit tidal exchange to existing tidal marshes and mangrove forests in an effort to facilitate conversion of the land (i.e. 'reclamation') to farm land for grazing and cropping or simply to prevent further migration of the tide (Boon et al., 2011). Many of these bund walls are still in place today, and many more have been built since the initial draining of the Koo Wee Rup Swamp.

To assess the impacts of reclamation on tidal marsh sediment C stocks, we chose the Koo Wee Rup region, where our three reclaimed sites (hereafter referred to as RECL1, RECL2, and RECL3) span historical property and are believed to have been reclaimed around the same time period (~1867; for a detailed site history see supporting information Text S1). Adjacent to these sites are intact tidal marsh (hereafter referred to as TM1, TM2, and TM3) to which the reclaimed sites were compared (Figure 1). In this region, it is estimated that a total of 110 ha of tidal marsh and 10 ha of mangrove have been lost since European settlement (Sinclair & Boon, 2012), so we can fairly accurately assume our sites were primarily saltmarsh before reclamation.

TM1 (S 38°13.112’ E 145°23.145’) and TM2 (S 38°13.479’ E 145°24.413’) lie furthest to the west and cover approximately 571,000 and 563,000 m^2, respectively. TM3 (S 38°12.890’ E 145°26.180’) lies further east between Cardinia Creek and Deep Creek, two of the main drainage channels for the area previously covered by the Great Swamp, and covers around 145,000 m^2. The tidal marsh communities are dominated by shrubby glasswort (*Tecticornia arbuscular*) and beaded glasswort (*Sarcocornia quinqueflora*) and fringed by a forest of *Avicennia marina* mangroves.

All three reclaimed sites are believed to have been tidal marsh prior to European settlement (pre-1750s; Boon et al., 2011), but now the areas are characterized by a mixed community of halo- and meso-phytes dominated by herbaceous pasture weeds and tussock grasses, such as *Poa labillardieri*, *Senecio sp*., *Lepidosperma lateral*, and *Carpobrotus glaucescens*. Each of the reclaimed sites is surrounded by bund walls and drainage channels on their southern, eastern, and western sides, with a fringing forest of *A. marina* mangroves on the seaward side of the walls, similar to those at the tidal marsh sites. RECL1 (S 38°12.890’ E 145°25.862’) lies between TM2 and TM3 and is flanked by Lyall’s Inlet and Cardinia Creek. The site lies south of the historical Harewood House and covers approximately 97,000 m^2. RECL2 (S 38°12.964’ E 145°26.571’) and RECL3 (S 38°13.024’ E 145°26.681) cover approximately 77,000 and 166,000 m^2, respectively, and are split by a fringing mangrove forest in the drainage channel between them. The two sites are surrounded by Deep Creek on the west and Bunyip River on the east. All three reclaimed sites fall within the boundaries of property bought by Lyall in 1856.

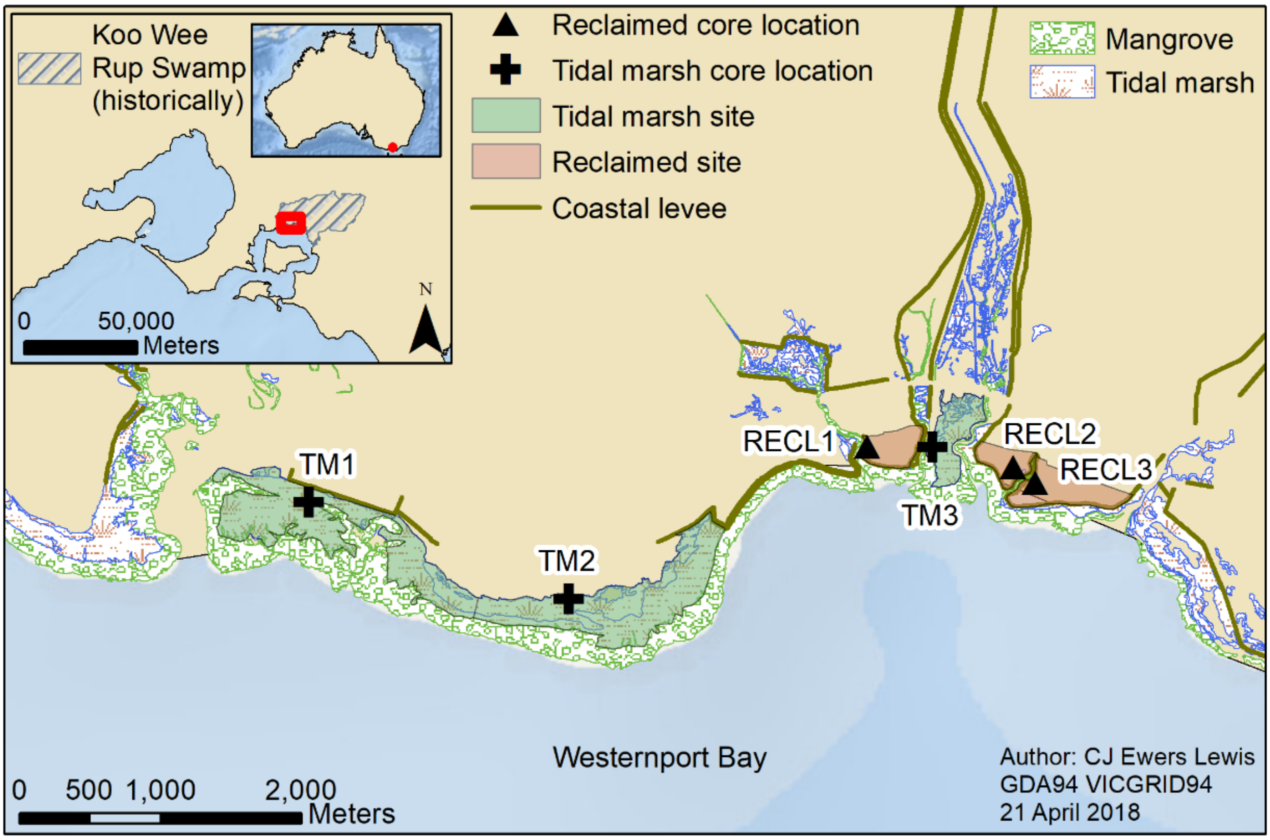

Figure 1. Sampling locations. Tidal marsh (green) and reclaimed (brown) sampling sites in northern Westernport Bay, Victoria, Australia. Coring locations within each site are indicated.

Sampling Method

Sediment cores were collected from tidal marsh and reclaimed sites between the 9th and 19th of November 2015. At each site, coring locations were selected based on a target elevation range of 1.5±0.25 m, and elevation for each core was measured with a real time kinematic global positioning system (RTK-GPS; TM1 1.39 m; TM2 1.74 m, TM3 1.63 m, RECL1 1.53 m, RECL2 1.38 m, RECL3 1.37 m). For each core, a 125-cm length, 5-cm inner-diameter polyvinyl chloride (PVC) pipe was manually hammered into the sediment as deep as possible. A rubber plug was inserted into the top of the core to create a vacuum seal and was pulled out of the sediment using a winch system attached to a small ladder. The top end of the core was plugged with foam then each end of the core was capped and taped for transport. Cores were stored in a 4°C cold room until processing. The six deepest cores (one from each site) were selected for further processing.

Itrax-XRF Core Scanning

Itrax-XRF core scanning was used as a fast, non-destructive method to assess elemental distribution (elements Al to Pb) and obtain high-resolution optical and x-radiograph (XRF) imagery (Rothwell & Croudace, 2015). Cores were transported to the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, NSW for Itrax-XRF core scanning, ^{210}Pb and ^{14}C dating. Cores were split lengthwise and analysed by Itrax using a molybdenum tube set to 55 mA and 30 kV with a dwell time of 10 s. A step size of 1 mm was chosen to capture variation down-core, resulting in run times of ~3.5 hours per 1 m of core. Elements and elemental ratios were chosen as proxies for their relevance of representing environmental change in coastal and marine sediments (Croudace & Rothwell, 2015), and peaks were used to align matching time points and events down-core across the six sites. Proxies were interpreted based on the compiled data in the Micro-XRF core scanning review chapter by Davies, Lamb, & Roberts, (2015).

Lead-210 (^{210}Pb) dating

One core from each site type (site TM3 to represent tidal marsh and site RECL1 to represent reclaimed areas) was used to generate surface sediment age profiles using lead-210 (^{210}Pb), which also allowed for calculation of sediment and C accumulation rates (Table S1;

Figures S1 and S2). Eight 1-cm interval samples were selected from each core. Based on the method described by Appleby and Oldfield (1978, 1992) and Appleby (2001), the activity of atmosphere-derived ^{210}Pb ($^{210}Pb_{unsupported}$) was measured in the sediment samples to estimate accumulation rates. Down-core changes in $^{210}Pb_{unsupported}$ activity were used to calculate sediment accumulation based on the half-life of ^{210}Pb of 22.26 years. For full details of the 210Pb dating analysis see supporting information Text S2.

Radiocarbon (^{14}C) dating

Samples for radiocarbon (^{14}C) dating were selected from further down the same cores used for ^{210}Pb dating (TM3 and RECL1) based on the Itrax-XRF scanning results. Areas containing what appeared to be organic rich sediment were targeted, and 1-cm sediment sections containing these materials were removed, totaling 3 samples from TM3 (36-37, 67-68, and 96-97 cm before compaction correction) and 5 samples from RECL1 (24-25, 34-35, 40-41, 46-47, and 67-68 cm before compaction correction; table S1). Radiocarbon (^{14}C) dates were determined for bulk sediment samples. Carbonates and humic acids were removed from these samples by treating the sample with 2M HCl (at 60^{o}C) for carbonate removal, a series of sodium hydroxide (NaOH) treatments (at 60^{0}C) for the removal of humics and a final treatment of 2M HCl (at room temperature). After drying, the samples were combusted to carbon dioxide (CO_2) and reduced to graphite using H_2/Fe at 600^{o}C, as outlined in Hua et al. (2001). The graphite targets were analysed by accelerator mass spectrometry (AMS) at the Centre for Accelerator Science (CAS) facility at ANSTO (Fink et al., 2004). The radiocarbon dates were calibrated with OxCal 4.2 (Ramsey, 2010) using the SHCal13 data set (Hogg et al., 2013). Radiocarbon dates are reported as the median calibrated age (cal BC/AD) with the calibrated age range (cal BC/AD; 95.4% probability).

Carbon content and quality analyses

Samples were sliced from the six half-cores by 1-cm increments systematically (every other cm in the top 20 cm, every 5 cm between 20-50 cm deep, and every 10 cm from 50 cm to the max depth of the core) and opportunistically (additional regions-of-interest, ROIs, based on Itrax and age dating results). Samples were dried at 60°C until a consistent weight was achieved (3-4 days). Samples were ground by gently breaking the sample by hand with a mortar and pestle, followed by 3 minutes in a Retsch Mortar Grinder RM 200. Gravimetric contents of total C and total nitrogen were determined by high temperature (1350°C) oxidative combustion on a LECO Trumac CN analyzer using lance oxygen flows and an extended purge to ensure complete combustion of carbonates. All samples were identified as non-calcareous and therefore the gravimetric organic C contents were equated to the measured total C values.

Diffuse reflectance Fourier transform mid-infrared spectroscopy (MIR; n=162) was used to select a subset of 30 samples for solid-state ^{13}C nuclear magnetic resonance spectroscopy (NMR). An MIR spectrum was acquired for all samples using the spectral acquisition and processing protocols described by Baldock *et al.* (2013), described in supporting information Text S3. Solid-state ^{13}C NMR analyses were completed on the 30 samples identified to cover the variability in the MIR spectra using a Bruker 200 MHz Avance spectrometer (Bruker Corporation, Billerica, MA, USA) with a 4.7 T, wide-bore superconducting magnet operating at a resonance frequency of 50.33 MHz. Further details of this procedure can be found in supporting information Text S4.

Calculations and Statistical Analysis

C density values (mg C cm^{-3}) were obtained by multiplying the gravimetric OC content by dry bulk density (DBD) for each sample measured. To estimate C stocks, C density values were interpolated for increments not directly analyzed using cubic splines (SRS1 Cubic Spline Software for Excel, version 2.5.1.0, SRS1 Software LLC), then converted to C stock (Mg C ha^{-1}) and all measured and interpolated C stock measurements were summed for the depth horizon of interest.

All depth measurements were corrected based on individual core compaction values. Compaction was calculated as the sediment core length divided by the depth sampled to in the field. Each sampling depth interval was divided by this proportion (e.g. compaction of 0.8 would mean a 1-2 cm sample represented 1.25-2.5 cm depth in the field).

For variables known to vary with depth (DBD, C density, alkyl:o-alkyl ratio, aromatics density), both GLMs and two-way ANOVAs were run to assess whether depth or time period, respectively, better explained the variability observed in the data.

Dry bulk density (DBD; g sediment cm^{-3}) measurements were square-root transformed to meet assumptions of normality and a general linear model (GLM) was run using depth (mid-depth of the sample) as a numerical factor and site type (tidal marsh or reclaimed) as a categorical factor, with an interaction term.

A multiple before-after control-impact (MBACI) design was used to compare response variables at each site type (tidal marsh and reclaimed) before and after reclamation. To measure comparable time periods between the site types, the deeper sections of the reclaimed cores that were older than the tidal marsh cores (older than 319 cal AD and based on Itrax alignment) were not included in the analyses when specifically referring to the time period before reclamation. Only samples that were directly measured for C (i.e. not interpolated) were included in the analyses of C density. C density was log transformed and

DBD was square root transformed to meet normality assumptions. A two-way ANOVA was run on each log(C density) and sqrt(DBD) with site type (tidal marsh, reclaimed) and time period ("before reclamation"= ~319 cal AD years ago to the time of reclamation (~1860), "after reclamation"= the time of reclamation (~1860) to present (2015)) as fixed factors. An interaction term was also included (site type*period). C stocks were calculated as the sum of each measured and interpolated C stock estimate. A two-way ANOVA was run on each sediment horizon width and C stock with site type (tidal marsh, reclaimed) and time period (before reclamation, after reclamation) as fixed factors, and site as random. An interaction term was also included for site type and period. Tukey's pairwise comparison was used to identify groupings for time periods and site types.

Two-sample t-tests were used for the following comparisons: 1) mean sediment horizon depth from the "before" period in tidal marsh vs reclaimed sites; 2) mean sediment horizon depth from the "after" reclamation period in tidal marsh vs reclaimed sites; 3) mean sediment C stock from the "before" period in tidal marsh vs reclaimed sites; 4) mean sediment C stock from the "after" reclamation period in tidal marsh vs reclaimed sites; 5) mean C stocks in the top 1 m of sediments for tidal marsh versus reclaimed sites.

Extent of decomposition of OC was assessed based on two proxies derived from the NMR data– alkyl:o-alkyl ratio and density of aromatics (sum of aryls and o-aryls; mg cm^{-3}) – as described by Baldock et al. (1997). Both proxies are expected to change with depth/age of sediments, so two sets of analyses were run for each proxy – a two-way ANOVA to assess the impact of time period (before or after reclamation), and a general linear model to test whether depth was a better predictor. Because of the correlation between depth and time period, the two factors were never included in a single statistical model. For each model, site type was also included as a categorical factor and an interaction term was added as appropriate (i.e. site type* time period or site type* depth). Tukey's pairwise comparison was used to determine groupings from the two-way ANOVAs.

All statistical analyses were run in Minitab statistical software (v. 17.2.1) or RStudio (v. 0.99.902).

Results

Radiometric Dating and Itrax-XRF Scans

Unsupported ^{210}Pb activities in the TM3 core exhibited a decay profile with depth, enabling ^{210}Pb dating calculations (Figure S1, Table S1). The ^{210}Pb dating shows the top 25 cm of sediment were accreted in the past 90±11 (CIC model) to 92±10 (CRS model) years at an average mass accumulation rate of 0.052±0.0045 g cm^{-2} yr^{-1}(CRS model only), equivalent to an average sediment accretion rate of 2.66 (CRS model) to 2.89 (CIC model) mm yr^{-1} (Figure 2).

Unsupported ^{210}Pb activities in the RECL1 core, on the other hand, did not exhibit a decay profile with depth, suggesting sediment mixing, particularly in the top 15 cm (Figure S2, Table S2). Between 16 and 28 cm the ^{210}Pb activity decreased with depth, suggesting the sediment below 15 cm has not been disturbed, and therefore was likely accreted before the site was reclaimed, as the original sediment stratigraphy has been maintained.

Radiocarbon dates suggest that the C in the reclaimed core is much older (4834 (4620-5067) years older) than that of the tidal marsh core, even though the two cores are only 10 cm different in depth, with the tidal marsh core being deeper (reclaimed core 4515 cal BC (4682-4372 cal BC) at ~105 cm deep, tidal marsh core 319 cal AD (248-385 cal AD) at ~115 cm deep; Table S3; Figures 2 and 3). Based on these age data, along with coordinating peaks in Itrax data, the sediments accreted down the entire length of the tidal marsh cores (to 115 cm) are equivalent to the age of the top 44, 25.5, and 33.5 cm of sediment in the reclaimed cores (RECL1, RECL2, and RECL3, respectively; Figures 2, 3, S3-S6).

In conjunction with age dating of the TM3 and RECL1 cores, patterns in Itrax-XRF data were used to determine matching time points down all tidal marsh and reclaimed cores (Figures 2, 3, S3-S6). The most relevant proxies for aligning cores were magnetic susceptibility, titanium (Ti), sulfur (S), chlorine (Cl), iron (Fe), bromine (Br), and incoherent/coherent scattering ratio. Coordinating peaks in these proxies were especially useful for matching peaks around the time of reclamation (based on the successful ^{210}Pb dating of RECL1), and further down in the reclaimed cores where sudden changes in these proxies suggest altered sedimentation dynamics driven by terrigenous inputs, which we have interpreted as the colonization of mangrove and/or tidal marsh community as the sediments accreted high enough in the tidal frame to support intertidal vegetation.

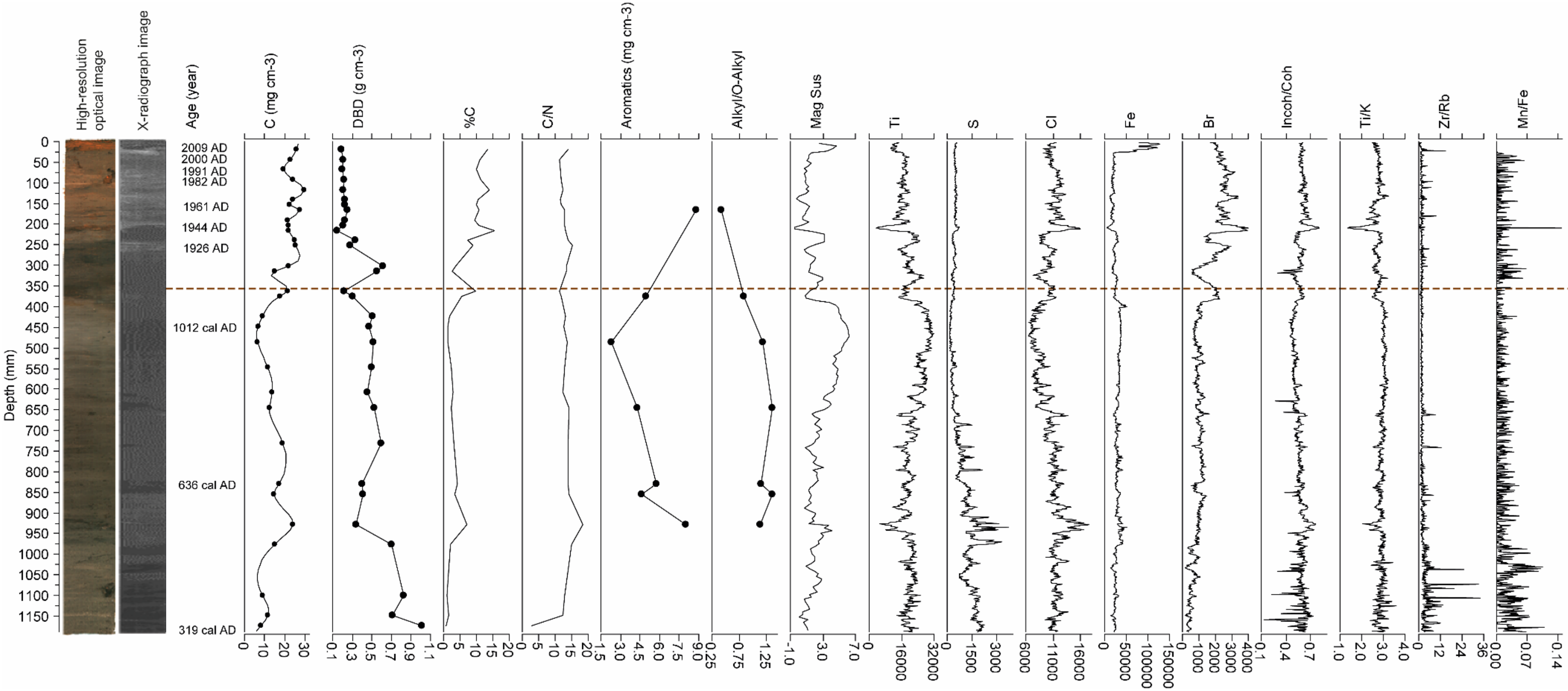

Figure 2. Tidal marsh (TM3) core profile. Age at each depth was determined from lead-210 profile (top 300 mm; Tables S1 and S2) and radiocarbon dating (depths > 300 mm; represented as median calibrated age; Table S3). C density (mg cm^{-3}), dry bulk density (DBD; g cm^{-3}), percent C, and C/N ratio are represented for each depth measured. A subset of samples was used to assess C quality, or extent of decomposition, with ^{13}C NMR, with decreasing aromatic C (sum of aryls and o-aryls; mg cm^{-3}) and increasing alkyl/o-alkyl ratios generally indicating an increased extent of decomposition (Baldock et al., 1997). Itrax-XRF elemental proxies (magnetic susceptibility, Ti, S, Cl, Fe, Br,

incoherent/coherent ratio, Ti/K, Zr/Rb, and Mn/Fe) were used to align cores across sites and identify key time points. The horizontal dashed brown line represents the approximate point in the sediment chronology when the reclaimed sites were reclaimed, and defines the cut-off between the ‘before’ versus ‘after’ comparisons in the tidal marsh cores.

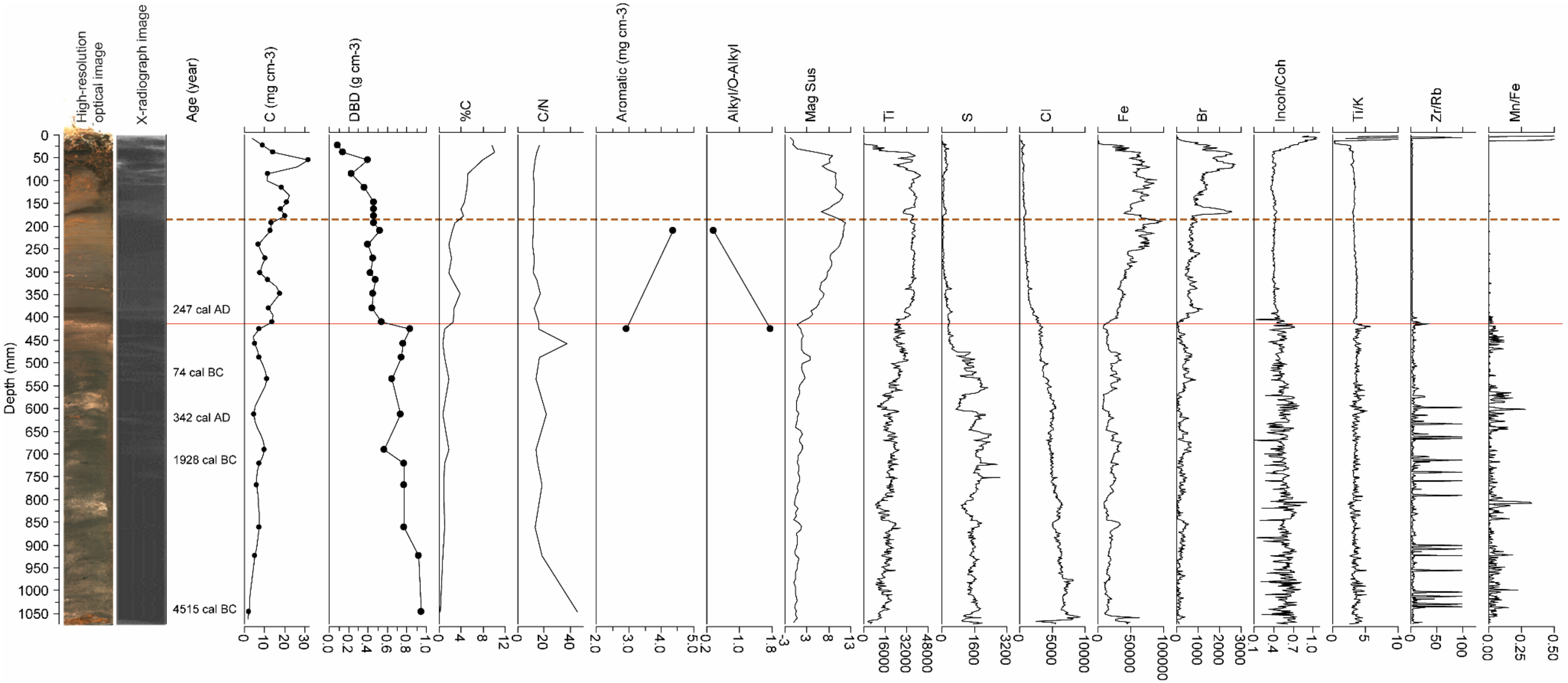

Figure 3. Reclaimed (RECL1) core profile. Age at each depth was determined from lead-210 profile (top 300 mm; unsuccessful in the reclaimed core; Tables S1 and S2) and radiocarbon dating (depths > 300 mm; represented as median calibrated age; Table S3). C density (mg cm^{-3}), dry

bulk density (DBD; g cm^{-3}), percent C, and C/N ratio are represented for each depth measured. A subset of samples was used to assess C quality, or extent of decomposition, with ^{13}C NMR, with decreasing aromatic C (sum of aryls and o-aryls; mg cm^{-3}) and increasing alkyl/o-alkyl ratios generally indicating an increased extent of decomposition (Baldock et al., 1997). Itrax-XRF elemental proxies (magnetic susceptibility, Ti, S, Cl, Fe, Br, incoherent/coherent ratio, Ti/K, Zr/Rb, and Mn/Fe) were used to align cores across sites and identify key time points. The horizontal dashed brown line represents the approximate point in the sediment chronology when the reclaimed sites were reclaimed, and defines the cut-off between the 'before' versus 'after' comparisons in the reclaimed cores; the horizontal solid orange line represents the time at which wetland vegetation colonized the area (likely mangrove followed by tidal marsh) and is the lower boundary of sediment included in the 'before' measurements for reclaimed cores.

Dry Bulk Density (DBD)

When assessing DBD simply by site type and depth (GLM), DBD differed significantly between site type ($F_{1,160}$=10.45; p=0.001), with higher mean DBD in reclaimed sites (0.5149±0.0247 g cm^{-3}; n=81) than pristine tidal marsh sites (0.3916±0.0249 g cm^{-3}; n=81). DBD also differed significantly by depth ($F_{1,160}$=60.58; p<0.001), and increased more steeply with depth in reclaimed sites than pristine tidal marshes, but not significantly (Figure S7; model R-sq=50.56%).

However, when time period was taken into account (2-way ANOVA), DBD did not differ by site type and there was no interaction between the two factors; average DBD was higher in before period sediments than after ($F_{1,119}$=67.20; p<0.001; R-sq=41.05%; Figure 4; Table 1).

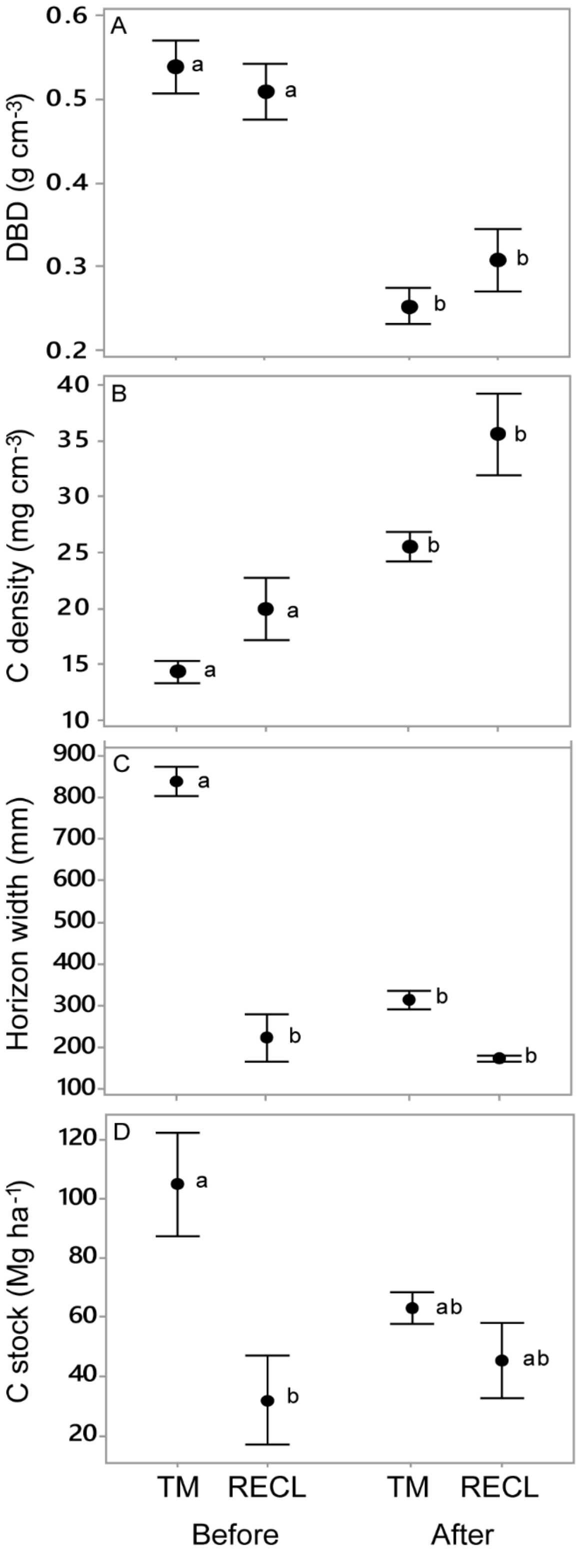
A
DBD (g cm-3)
0.6
0.5
0.4
0.3
0.2
a
a
b
b
B
C density (mg cm-3)
40
35
30
25
20
15
10
a
a
b
b
C
Horizon width (mm)
900
800
700
600
500
400
300
200
100
a
b
b
b
D
C stock (Mg ha-1)
120
100
80
60
40
20
a
b
ab
ab
TM
RECL
TM
RECL
Before
After

Figure 4. Mean dry bulk density (DBD; g cm^{-3}, A), mean carbon density (mg cm^{-3}, B), sediment horizon width (mm, C), and carbon stock (Mg ha^{-1}, D), ± SE by time period and site type. TM = pristine tidal marsh; RECL = reclaimed. Before = ~319 cal AD to time of reclamation ~150 years ago; After = time of reclamation ~150 years ago to present (2015). DBD was significantly higher in "before" than "after" sediments ($F_{1,119}$=67.20; p<0.001; R-sq=41.05%). C density was significantly different by site type ($F_{1,119}$=9.07; p=0.003) and period ($F_{1,119}$=46.56; p<0.001). Sediment horizon width was significantly different by site type ($F_{1,8}$=113.81; p<0.001) and period ($F_{1,8}$=65.94; p<0.001), with an interaction between the two factors ($F_{1,8}$=44.85; p<0.001; R-sq (adj)=95.27%). Carbon stocks differed significantly by site type ($F_{1,8}$=11.52; p=0.009), but did not differ by period and there was no interaction between factors (R-sq (adj)=55.81%).

Organic Carbon Density

MIR spectra showed no presence of inorganic C content in any of the samples. C density ranged from 3.87 to 70.42 mg C cm^{-3} across all measured samples, with a mean of 22.8 (± SE 1.19; n=123). Within cores, C density was generally higher towards the surface and lower towards the bottom, but there was no consistent pattern (e.g. exponential decay) in changes to C density with depth across the six cores (Figures S8).

Mean C density was significantly different by site type ($F_{1,119}$=9.07; p=0.003) and period ($F_{1,119}$=46.56; p<0.001), but there was no indication of an interaction between the two factors ($F_{1,119}$=0.04; p=0.839; R-sq=34.54; Figure 4; Table 1). Mean C density in tidal marshes was 14.34 mg C cm^{-3} (±1.02; n=40) before reclamation and 25.55 mg C cm^{-3} (±1.37; n=40) during the period after reclamation. In reclaimed sites, mean C density was 20.01 mg

C cm^{-3} (±2.77; n=20) before reclamation and 35.59 mg C cm^{-3} (±3.66; n=23) after reclamation.

Sediment Horizons

Sediment horizon width was significantly different by site type ($F_{1,8}$=113.81; p<0.001) and period ($F_{1,8}$=65.94; p<0.001), with an interaction between the two ($F_{1,8}$=44.85; p<0.001; R-sq (adj)=95.27%; Table 1; Figure 4).

When comparing horizon widths within a single time period, before period horizon width significantly differed between tidal marsh (841.0 +/- 35 mm; n=3) and reclaimed sites (223.0 +/- 57 mm; n=3; t-value = -9.17; p=0.003; df=3). After horizon width also differed significantly between tidal marsh (313.7 +/- 22 mm; n=3) and reclaimed sites (172.3 +/- 6.8 mm; n=3; t-value = -6.17; p=0.025; df=2; Figure S9).

Organic Carbon Stocks

C stocks differed significantly by site type ($F_{1,8}$=11.52; p=0.009), but did not differ by period and there was no interaction between factors (R-sq (adj)=55.81%; Figure 4; Table 1).

When comparing C stocks within a single time period (Figure S9), before C stocks varied marginally non-significantly (t-value=-3.19; p=0.05; df=3) between tidal marsh (104.8±17 Mg C ha^{-1}; n=3) and reclaimed sites (31.9±15 Mg C ha^{-1}; n=3). After C stocks were not significantly different between tidal marsh (63.17±5.3 Mg C ha^{-1}; n=3) and reclaimed sites (45.5±13 Mg C ha^{-1}; n=3; Figure S9).

Table 1. Response variables compared between site types across time periods.

	Tidal Marsh		**Reclaimed**		**R-sq (%)**	**Significance of Model Factors**
Response Variable	**Before**	**After**	**Before**	**After**		
DBD **(g cm^{-3})**	0.5377[a] (±0.0321) n=40	0.2512[b] (±0.0215) n=40	0.5086[a] (±0.0334) n=20	0.3072[b] (±0.0373) n=23	41.05	Site Type: n/a Period: $F_{1,119}$=67.20; p<0.001 Site Type*Period: n/a
C Density **(mg C cm^{-3})**	14.34[a] (±1.02) n=40	25.55[b] (±1.37) n=40	20.01[a] (±2.77) n=20	35.59[b] (±3.66) n=23	34.54	Site Type: $F_{1,119}$=9.07; p=0.003 Period: $F_{1,119}$=46.56; p<0.001 Site Type*Period: n/a
Sediment Horizon (mm)	841.0[a] (±35.3) n=3	313.7[b] (±21.9) n=3	223.0[b] (±57.4) n=3	172.3[b] (±6.84) n=3	(adj) 95.27	Site Type: $F_{1,8}$=113.81; p<0.001 Period: $F_{1,8}$=65.94; p<0.001 Site Type*Period: $F_{1,8}$=44.85; p<0.001
Carbon Stocks (Mg C ha^{-1})	104.8[a] (±17.3) n=3	63.17[ab] (±5.33) n=3	31.9[b] (±14.9) n=3	45.5[ab] (±12.7) n=3	(adj) 55.81	Site Type: $F_{1,8}$=11.52; p=0.009 Period: n/a Site Type*Period: n/a

Alkyl: O-Alkyl ratio	1.3045[a] (±0.0881) n=9	0.746[b] (±0.151) n=8	1.077[ab] (±0.141) n=10	0.424[ab] (n/a) n=1	(adj) 23.60	Site Type: n/a Period: $F_{1,24}$=7.27; p=0.013 Site Type*Period: n/a
Aromatics (mg cm^{-3})	4.640[b] (±0.676) n=9	7.98[ab] (±1.07) n=8	5.07[b] (±1.10) n=10	14.345[a] (n/a) n=1	(adj) 30.19	Site Type: n/a Period: ($F_{1,24}$=13.87; p=0.001) Site Type*Period: n/a

Mean (+/- SE)

[a] and [b] represent groupings from Tukey's pairwise comparisons

For small n, R-sq adjusted (adj) is reported

Mean C stocks measured to 100 cm deep were not different between tidal marsh and reclaimed sites (t-value=-0.01; p=0.994; df=2; Figure 5), though there was much greater variability among reclaimed sites (mean=149.60±43.70 Mg C ha^{-1}; min 63.80; max 206.80) than among tidal marsh sites (mean =149.19±1.95 Mg C ha^{-1}; min 145.29; max 151.20). This variability was driven by the large difference in C stocks between RECL1 (63.77 Mg C ha^{-1}), which had a lower C stock than the tidal marsh sites, and the other reclaimed sites, which had higher stocks than the tidal marsh sites (RECL2 = 206.84 Mg C ha^{-1}; RECL3 = 178.07 Mg C ha^{-1}). Based on radiocarbon dating, sediments at 100 cm deep were approximately 2,025 to 5,343 years older in reclaimed sites (where the 100 cm mark falls between two sections of sediment dated as 1928 cal BC (2030-1777 cal BC) and 4515 cal BC (4682-4372 cal BC)) than in tidal marsh sites (where the 100-cm mark lies between two sections of sediments dated as 636 cal AD (593-661 cal AD) and 319 cal AD (248-385 cal AD).

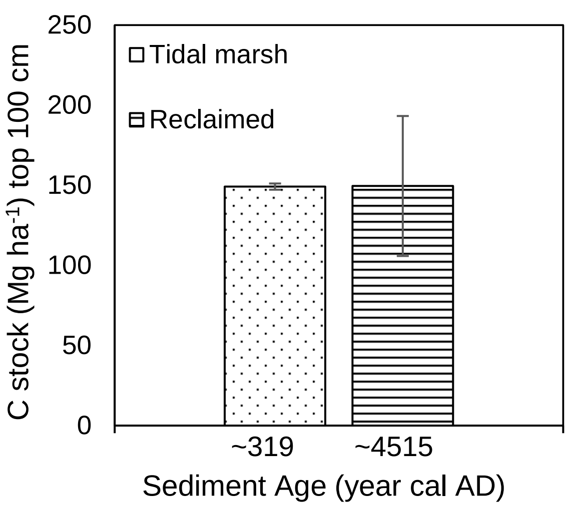

Figure 5. Mean C stocks (Mg C ha^{-1}; ±SE) to 100 cm deep were no different between tidal marsh and reclaimed sites. Radiocarbon dates are represented as median calibrated age (cal AD) for the deepest aged section of each core. According to the radiocarbon dates, sediments around 100 cm

deep could be as much as 5300 years older in reclaimed sites (4682-4372 cal BC) than in tidal marsh sites (248-385 cal AD).

Organic Carbon Quality (NMR Analysis)

Full NMR spectra are presented in Figure S10. Statistical analyses of alkyl:o-alkyl ratios suggest that although means differed by time period ($F_{1,24}$=7.27; p=0.013; R-sq(adj)=23.60%; Figure 6), the variability in alkyl:o-alkyl ratios was better explained by depth ($F_{1,25}$=23.55; p<0.001; R-sq(adj)=44.43%; Figure S11). Site type, and the interaction with site type, were not significant in either model.

Although density of aromatics varied significantly with depth ($F_{1,24}$=5.51; p=0.028; R-sq(adj)=16.19%; Figure S12), time period better explained the variability observed ($F_{1,24}$=13.87; p=0.001; R-sq(adj)=30.19%; Figure 7). Aromatics did not differ significantly by site type in either model.

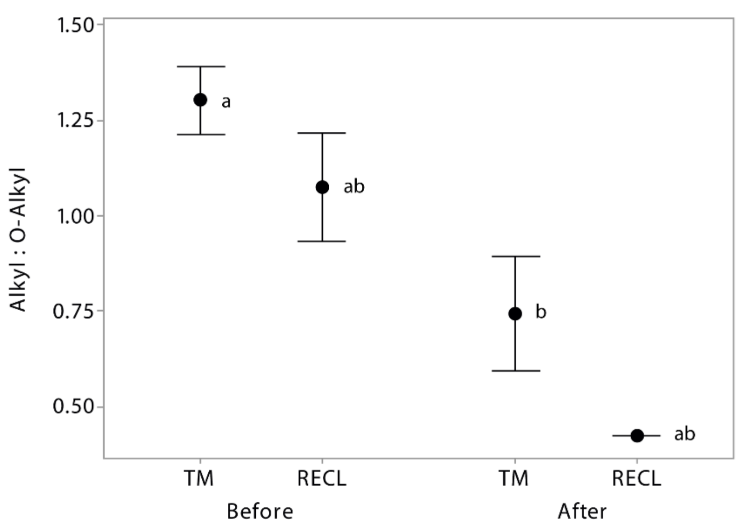

Figure 6. Alkyl:o-alkyl by time period and site type. Alkyl:o-alkyl ratios differed by time period ($F_{1,24}$=7.27; p=0.013; R-sq(adj)=23.60%), but not site type.

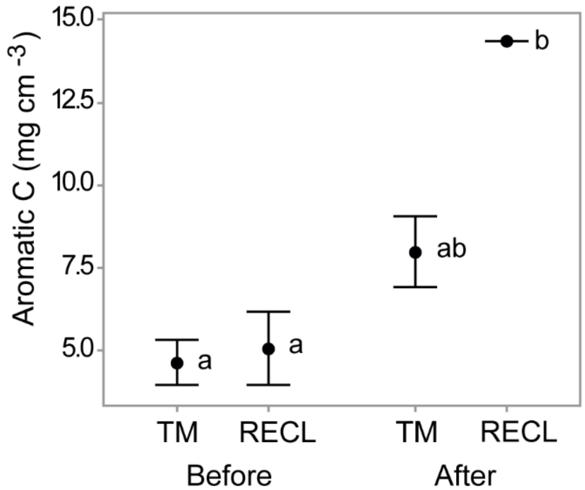

Figure 7. Density of aromatic C (mg cm^{-3}) by time period and site type. Aromatics differed significantly by time period ($F_{1,24}$=13.87; p=0.001; R-sq(adj)=30.19%), but not site type.

Discussion

Identification of historical time points using Itrax and radiometric dating

Based on the radiometric dating and Itrax patterns in our cores, we have identified two major ecologically important time periods in the tidal marsh cores and three in the reclaimed cores (Figures 2-3, S3-S6).

The base of the reclaimed core dates to around the time of the last interglacial period (5-6,000 years ago) when the shoreline of Westernport Bay was further inland and about 1-2 m higher than present day (Marsden & Mallett, 1975). From about 5,000 years ago to the 1800s, sea level was falling (though now it has been rising since 1800s due to climate change), and the current shoreline has been in place <2,000 years (Marsden & Mallett, 1975). Following this period, we see a shift in Itrax parameters at just over the 247 cal AD mark (415 mm in RECL1; 280 mm in RECL2; 475 mm in RECL3). A drop in Cl and S, along with an increase in terrigenous elements (Ti, K, Al, mag sus), suggest a shift from mostly marine inputs to sediment accumulation coming from the catchment. Concurrently, an increase in Br and levelling off of incoh/coh ratio show an increase and more consistent input of organic matter, suggesting higher productivity. The concurrent peaks in Ti, mag sus, and Fe suggest catchment input of allochthonous silt and fine sand. Levelling off of Ti/K and Zr/Rb ratios suggest a shift from sporadic to consistent grain size of sediment inputs, while the levelling off of the Mn/Fe ratio suggests a shift to less oxygenation in the water column, which may reflect more rapid sedimentation rates. We interpret the sudden shift in Itrax parameters (at >247 cal AD) to represent a shift from a subtidal marine environment (the “before tidal marsh colonization” period) to progradation of an intertidal marine environment as sea level was dropping, allowing for this area that was once underwater to support intertidal communities – mangroves then tidal marsh (referred to here as the “before” reclamation period).

Based on the radiometric dating in the TM3 and RECL1 cores and the alignment of Itrax patterns across cores, we have identified the shift from tidal marsh to reclaimed ecosystems in the core profiles. In the RECL1 core, a ^{210}Pb decay profile was observed between 28 and 16 cm, but then appeared mixed above 15 cm. At 15 cm a signal is also observed in the Itrax data, with decreases in magnetic susceptibility, Ti, and Fe with a concurrent Br peak, which we interpret as an episode of increased incorporation of autochthonous plant materials to the sediments from leaf litter and plant materials as tidal marsh plants died off. In the tidal marsh core we observed a shift from a terrestrial to more marine signature in the margin between the ^{14}C and ^{210}Pb dates (36 and 25 cm, respectively), which we interpret as the time of reclamation (~1867). Cl input remained relatively steady or increased, reflecting the decrease in freshwater runoff caused by diversion into creeks via man-made channels built around the time of reclamation and draining. Prior to reclamation, from <636 cal AD, levels of magnetic susceptibility and inputs of terrigenous elements (Ti, K, Al) were increasing in tidal marshes, reflecting greater inputs from the catchment. After reclamation, these inputs became less consistent, suggesting less freshwater flow over the tidal marsh due to the channeling of drainage water. This shift is not seen in reclaimed sites and there is still a strong terrestrial signature after reclamation, as the catchment became the primary source of new sediments due to the lack of tidal inundation.

Impacts of reclamation on past and present tidal marsh sediment carbon stocks

Our hypothesis that C stocks accreted before reclamation (~319 cal AD to ~1867 AD) would be similar in the two site types (when all sites were tidal marshes) was not supported. On average, previously sequestered C stocks in reclaimed sites were 30% of those in tidal marsh sites. Concurrently, narrower sediment horizons were observed for this period in reclaimed sites, and across entire ~1m deep cores much greater time spans were represented in reclaimed sites (up to 5300 years older) compared to tidal marshes (Figure 2 and 3; Table S3).

The substantially larger time span represented, associated with a narrower sediment horizon and reduced C stocks, in the reclaimed cores may be attributed to a combination of factors. Here, we discuss the evidence in our data that the observed differences in sediment horizons and C stocks are likely due to erosion and reduced accretion rates in the reclaimed sites, but not compaction or preferential remineralization of organic C.

Compaction of sediments and soils with age and depth is common in blue C and terrestrial ecosystems (Skilbeck, Trevathan-Tackett, Apichanangkool, & Macreadie, 2017). Changes to the sediment environment, such as reclamation, can accelerate compaction, as was observed by Spencer et al. (2017). In a study assessing the impacts of prior land use on restored tidal marsh sediment quality, reclaimed sediments (embanked to block tidal flooding) had lower microporosity and higher DBD than tidal marsh sediments, attributed to a change in sediment volume (Spencer et al., 2017). This reduction in volume is attributed to collapse of pore networks once pore water was absent, and shrinkage of clay minerals, which normally swell with water in a process known as "dilation storage" in tidal marsh sediments. Reduction in pore space and increase in dry bulk density are associated with compaction caused by natural processes as well (stress due to mass of sediment column above, time; Brain, 2016). Though DBD in our study was higher in reclaimed sites overall (due to the presence of much older sediments), there was no significant difference in DBD between site types when period was taken into account, meaning compaction cannot explain the difference in sediment horizon observed.

Preferential remineralization of organic C from the sediment can also result in what appears to be compaction, but with little change in DBD. Previously, Lane *et al.* (2016) observed a ~1.5 cm elevation loss, attributed to a mass loss of 207 g C_{org} m^{-2}, from tidal marshes sprayed with herbicides over a 1.5 year period. Losses of organic material in surface sediments in the form of death and oxidation of root materials, which add structural complexity and strength to the soil matrix, can lead to collapse and compaction of peaty sediments (Delaune, Nyman, & Patrick, 1994). However, if diagenesis of organic matter was driving the reduction in C stocks and sediment horizons in our reclaimed sites we would expect to see lower C densities in reclaimed “before” sediments than tidal marsh. In fact, C density was higher on average in reclaimed sites than tidal marsh during the before period (though not significantly; Figure 5, Table 1). It therefore appears that the narrower sediment horizons of the reclaimed sites are most likely due to a physical loss of both the organic and inorganic components of the sediment. There are two mechanisms that could be responsible for the narrower sediment horizons in the reclaimed sites.

First, erosion following reclamation could have altered previously accreted sediments and associated C stocks. The process of reclamation at our sites involved blocking off tidal flooding and digging drainage channels, which would have led to the eventual death of the tidal marsh vegetation. After reclamation, there would have likely been a lag period before succession of the terrestrial community began, during which time the sediments may have been destabilized from above- and below-ground plant decomposition. This episode of tidal marsh plant deterioration is supported by the peak in Br observed in RECL1, as discussed previously. Without healthy vegetation structure stabilizing the sediments, these areas would have been vulnerable to erosion. The primary cause of erosion at these sites, once vulnerable, was likely the result of freshwater flooding, which the region was notorious for for decades following the draining of the Koo Wee Rup Swamp (Roberts, 1985). Eroded sediment C may be re-buried elsewhere, dissolved into the water column as DOC or DIC, or remineralized into inorganic forms (CO_2 or CH_4) and released into the atmosphere (Lane et al., 2016; Pendleton et al., 2012). If eroded, the exposure of these C stocks to surface bacteria and oxygen make them more vulnerable to remineralization than those buried in pristine tidal marshes (Trevathan-Tackett et al., 2017).

Second, sediment accretion may have slowed down considerably following reclamation. Our hypothesis that sediment C stocks accumulated since reclamation would not be as large in reclaimed ecosystems as in tidal marshes was not supported. Although the sediment horizon width after reclamation was narrower in reclaimed ecosystems (Figure 7, Table 1), there was no difference in the magnitude of C stocks after reclamation (Figure 9, Table 1), due to the generally higher C density in reclaimed sites compared to tidal marshes during the after period, though the difference was not significant.

However, without specific dates for the shallow sediments of the reclaimed core profile, we cannot estimate a sediment accumulation rate or definitively determine which section (age range) of the sediment horizon that is missing. We also cannot rule out the possibility that the time point associated with reclamation occurred higher in the core. Our estimate of the point of reclamation in our core profiles was conservative. Similarities in the Itrax data were used to identify ages across cores that were not dated. The contribution of different elements to the sediment is driven by differences in the contribution of marine and terrestrial processes to sedimentation, and although our sites are directly adjacent to one another, there still may be variation in these processes across sites, leading to inconsistencies in the Itrax patterns observed. The intact ^{210}Pb profile below 16 cm in our reclaimed core suggests sediments from this point and lower were not physically disturbed during reclamation; however, it is possible that reclamation occurred higher in the core profile, with mixing effects reaching down (e.g. via root growth) deeper than what was the surface layer during reclamation, to 16 cm deep. A shallower depth of the reclamation time point would suggest that sedimentation slowed down considerably after reclamation, in which case the narrower horizon and lower C stock could be partly attributed to slower accretion.

Reduced rates of accretion may have implications for resilience of these ecosystem against sea level rise, with tidal marshes in the region more likely to gain elevation quickly enough to keep pace with sea level rise than reclaimed sites, though there are myriad other physical and biological factors that may influence elevation changes and water dynamics related to sea level rise in any particular ecosystem (Kirwan & Megonigal, 2013). Faster sediment burial in tidal marshes may also reduce conditions favorable to decomposition and organic C remineralization, such as oxygen availability and resuspension (Mcleod et al., 2011).

Because our ^{210}Pb dating of surface sediments in the reclaimed core was unsuccessful, we are not able to definitively determine whether the rate of sediment accretion or loss of particular layers of the sediment are driving differences between reclaimed and pristine tidal marsh profiles. We can, however, roughly estimate C stocks of reclaimed sites, had they accreted and stored sediment equivalent to that of the pristine tidal marshes during this period (i.e. if they hadn’t been disturbed; Table 1). With an additional 618 mm of sediment (the difference between the mean horizon widths of the two site types) the total C stock in the reclaimed sites for the before period (~120 Mg C ha^{-1}) based on their actual measured C density would have been similar to that observed for tidal marshes (104.8 ±17.3 Mg C ha^{-1}). This is a conservative estimate, and does not take into consideration that sediment C density may have also been higher in the reclaimed sites prior to disturbance.

The loss of C stocks in reclaimed tidal marshes in our study suggest the impact of this type of disturbance at a global scale could be substantial. A 70% loss of previously sequestered stocks was equivalent to a reduction of 72.9 Mg C ha^{-1} (104.8 minus 31.9 Mg C ha^{-1}; Table 1).

As an example of this magnitude, if the main cause of ongoing tidal marsh loss in Australia is reclamation, annual conversion of 16,105 ha of tidal marsh (1,376,500 ha x loss rate of 1.17%; Lawrence, Baker, & Lovelock, 2012) results in 4.31 million Mg CO_2 eq every year (72.9 Mg C ha^{-1} x 3.67 CO_2 eq/C). This is equivalent to emissions from an additional 250,000 Australians per year (based on the 2014 per capita CO2 emissions of 17.3 Mg CO2 per person; Olivier, Muntean, & Peters, 2015).

C quality following reclamation

Our analysis of C quality suggests conditions in tidal marshes are more favorable for long-term C storage than reclaimed sites. Generally, a decrease in aromatic C content and an increase in alkyl:o-alkyl ratio are each associated with an increasing extent of decomposition (Baldock et al., 1997; i.e. these are the changes associated with increased depth). Trends in the NMR data, though not significant due to our small sample size, are supported by visual inspection of our sediments. As expected, alkyl:o-alkyl ratios were the same during the time before reclamation at both sites, when they were both tidal marshes. After reclamation, alkyl:o-alkyl ratio was lower than the range observed in tidal marshes, suggesting more labile sediments in the surface of the reclaimed sites (Figures 6). A similar trend was observed for aromatic C, which was significantly higher in sediments after reclamation in both site types, and was twice as high in reclaimed sites compared to tidal marshes (Figure 7). Upon visual inspection, though higher in C density, the top ~15 cm of surface sediments in the reclaimed cores were composed of a thick layer of highly organic, low density, large particle size plant matter. Generally, decreasing particle size is associated with preferential loss of labile organic C and a reduction in decomposability (Baldock, Sanderman, et al., 2013). These observations support the results of the NMR analyses in that surface sediments of reclaimed sites were composed of fresh, easily decomposable organic materials. These data support the apparent difference in accumulation rate suggesting that although they have higher C density, the fresh (less decomposed) surface materials in reclaimed cores are less likely than the finer particles observed in the surface of tidal marsh cores to be incorporated into long-term C stocks.

Implications for measuring blue carbon standing stocks

Our analysis of C stocks in the top meter of sediments revealed no difference between standing stocks in pristine and reclaimed tidal marsh sites. Coring of the top 30 to 100 cm is often used to assess the value of terrestrial soil C sinks and blue C sinks (Ewers Lewis et al., 2017; Howard, Hoyt, Isensee, Pidgeon, & Telszewski, 2014; Liddicoat et al., 2015) and can be useful for determining total C vulnerable to remineralization with disturbance (Lovelock et al., 2017; Pendleton et al., 2012). This method, however, does not give an indication of the net C gains or losses, of the impacts of historical disturbance on C stocks, or ongoing sequestration and storage. In our study, though C stocks measured in the top meter of sediments in tidal marsh and reclaimed sites were equal, they were the result of a difference in time span of between 2000 to 5300 years and a loss of 70% of the C stock in reclaimed sites before the time of reclamation, equal to 73 Mg C ha^{-1}. Additionally, the potential for C to be incorporated into long-term storage cannot be assessed based on stocks alone, without knowledge of C quality, nor can sequestration rates. Therefore, we conclude that the measurements of top meter C stocks can be useful for understanding the magnitude of stocks, but should be combined with other methods when assessing fluctuations in C stocks over time in the form of gains or losses.

Implications for the global impacts of disturbance to blue carbon stocks

Quantification of emissions caused by disturbance to blue C ecosystems is a critical next step for improving our understanding of global C cycling. In this study, we assessed the impact of historical disturbance, in the form of reclamation, to previous tidal marsh sediment C stocks and ongoing storage. Disturbances that directly impact vegetation are considered mild in comparison to those that involve direct perturbation of sediments, in terms of potential C losses from sediments (Coverdale et al., 2014; P. I. Macreadie et al., 2013; Serrano et al., 2016). Reclamation may be among the least invasive forms of disturbance to blue C ecosystems, as it often involves simply blocking off tidal inundation and allowing natural succession to a terrestrial ecosystem, or involves infilling with soil, burying C stocks beneath. However, results of this study suggest hydrological modifications to tidal marshes that result in reclamation can cause substantial reductions in sediment C storage (70%). Further, changes to the plant community and inundation regimes appear to alter the rate (via changes to sedimentation) and permanence (via changes to C quality) of ongoing C storage. Assessment of stocks based on magnitude to a specified depth may be useful for quantifying stocks present in the top, most vulnerable portion of the sediment, but should be used in conjunction with other methods to assess gains and losses of C from sediments through time. We conclude that reclamation of tidal marshes may substantially reduce long-term sediment C stocks and be virtually undetectable post hoc. We suggest further research into the mechanisms of sediment and C loss resulting from reclamation to better understand and quantify the impacts of land use change on blue C sinks.

Acknowledgments

We thank the Australian Institute of Nuclear Science and Engineering (AINSE) for grant ALNGRA 15530 that funded the Itrax, ^{210}Pb, and ^{14}C dating. We acknowledge financial support from the Australian Government for the Centre for Accelerator Science at the Australian Nuclear Science and Technology Organisation (ANSTO) through the National Collaborative Research Infrastructure Strategy (NCRIS). JB, JS, and PM thank the support of the CSIRO Carbon Cluster. PM thanks the support of an Australian Research Council Linkage Grant LP160100242. PM and CEL received funding from Deakin's Centre for Integrative Ecology. CEL also thanks the University of Technology Sydney for scholarship support.

Conflict of Interest Statement

We state there were no financial or other conflicts of interest for any author. Supporting data for this study can be found in the supplementary materials associated with this article.

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