Carbon sequestration by Victorian inland wetlands

Blue Carbon Lab
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Blue Carbon Lab, Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University.

List of Definitions

Carbon sequestration rate**:** The rate at which carbon dioxide and other forms of carbon is being captured and stored within the soil. Expressed as mass of carbon per unit area per year (e.g. Mg C ha^{-1} yr^{-1}).

CO_2 eq.**:** Stands for carbon dioxide equivalents. This is a standard unit for converting the amount of carbon and methane into the equivalent amount of CO_2.

CH_4: Chemical symbol for methane.

Ha: Hectare (10,000 m^2)

Mg: Mega-gram or metric tonne (1,000,000 grams).

Soil Accretion rate: The rate of increase in soil height due to sedimentation within a system, usually expressed as millimetres per year (mm yr^{-1}).

Soil Accumulation rate: The rate at which soil (both organic and mineral) is accumulating within a system, generally expressed on a mass per unit area (e.g. Mg ha^{-1} yr^{-1}) basis.

Soil: The upper layer of the earth, made up of a complex matrix of mineral and organic sediments of different sizes (ranging from clay to boulders) from different sources (Mitsch and Gosselink 2007).

Soil carbon content: Amount of carbon (specified as either total, organic or inorganic) within a given soil sample, also known as a carbon pool. Usually expressed as mass per unit area (e.g. g C cm^{-2}). Combining carbon content for all samples from a given soil core will give carbon stock of that core.

Soil carbon concentration: The concentration of carbon (specified as either total, organic or inorganic) within the soil sample, generally expressed as grams per kilogram of soil (e.g. g C kg^{-1}), or as a percentage.

Soil inorganic carbon: Fraction of carbon within the soil which is mineral-based with the most common form being calcium carbonate.

Soil organic carbon: Fraction of carbon within the soil which is derived from organic matter such a plants.

Soil carbon stock: The amount of carbon stored within a system's soils. Summation of the carbon content values from a given core. Generally reported as either soil carbon stock (includes both inorganic and organic fractions) or soil organic carbon (SOC) stock (only the organic fraction). Usually presented either on a unit mass per area basis to a certain depth (e.g. Mg C_{org} ha^{-1} to 1 m soil depth) or on just mass basis when estimating over large areal extents.

TC: Total Carbon. Includes both inorganic carbon (IC) and organic carbon (OC).

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Executive Summary

Wetlands are areas of permanent, periodic, or intermittent inundation that hold still or very slow moving water. Wetlands can be natural or human-made, and in Victoria include billabongs, lakes, swamps, marshes, peatlands, floodplains, mangroves, mudflats, and seagrass areas. According to the most recent (2013) inventory, the state's 23,739 natural wetlands cover an area of 614,259 hectares, and most (69%) occur on private land. Victoria also has a further 11,060 artificial wetlands spanning 170,613 hectares, plus 321 wetlands (2,702 ha) that have not been classified.

Victoria's wetlands supply a range of values for ecosystem function and human well-being. Traditional Owners of the land have long regarded wetlands as key areas for food and other resources, making them an important part of the region's cultural heritage. Within an agricultural context, wetlands are used for stock grazing, water supply, and amenity. Wetlands also help trap sediments, pollutants, and cycle nutrients: a particularly important function in coastal areas, in which wetlands provide flood protection and help reduce the impacts of runoff. Victoria's wetlands are also important for supporting biodiversity (e.g. birds, fish, flora) and sustaining threatened species (24% of threatened native species depend on wetlands for their survival).

Yet as the impacts of climate change are increasingly realised, wetlands are drawing more and more attention for a different reason: they have vast potential for capturing atmospheric carbon. So far, investigations of the carbon sequestration capacity of wetlands have concentrated on coastal or 'blue carbon' wetlands (i.e. seagrasses, saltmarshes, and mangroves). But in fact, estimates identify inland wetlands as the earth's largest store of terrestrial carbon: they contain 33% of the soil carbon pool, yet occupy a mere 6–8% of the land surface. Despite this potentially extreme worth, wetlands have historically been underappreciated; since European settlement, Victoria has seen widespread losses of wetlands through agricultural development, urban development, and water extraction. Crucially, wetland loss and degradation has two major consequences: the loss of carbon sequestration capacity; and the potential release of ancient carbon back into the atmosphere – an impact that effectively transforms wetlands from carbon *sinks* into carbon *sources*.

The purpose of this study was to survey Victoria's inland wetlands (n = 103, sampled between August 2015 and February 2016) for their carbon sequestration capacity. Wetlands were chosen from a list of priority wetlands identified by each of the ten Victorian Catchment Management Authorities (CMAs), and consisted of the following wetland categories: freshwater meadow, shallow freshwater marsh, deep freshwater marsh, permanent open freshwater, semi-permanent saline wetland, permanent saline wetland, and high country peatland. Sampling involved taking soil cores (to 1 m; n = 3 cores per wetland) and analysing the total carbon content (via MIR and a CHN analyser) at different depths (up to 6 samples) in each core. In total, we analysed 1,674 samples. To determine carbon sequestration rates, we collated published data on soil accretion rates and utilised the carbon stock information, to calculate soil carbon sequestration rates.

Carbon densities ranged from 0.0 to 260.87 mg C_{org} cm^{-3}, with a mean $\pm$ SEM (standard error of the mean) of 31.45± 0.82 mg C_{org} cm^{-3}. Carbon densities were generally highest in surface soils (0–2 cm), dropping by approximately 50% by 48–50 cm. High country peatlands had the highest carbon stocks (292.54 ± 177.60 Mg C_{org} ha^{-1}); saline wetlands and permanent open freshwater had the lowest carbon stocks (64.28 ± 47.60 and 113.02 ± 119.94 Mg C_{org} ha^{-1} respectively). Soil accretion rates ranged from 1.02 to 30.00 mm yr^{-1}, with a mean ± standard error of 6.66 ± 1.33 mm y^{-1}. Mean carbon sequestration rate for Victorian inland wetlands was estimated at 6.93 ± 1.37 Mg CO_2 eq. ha^{-1} yr^{-1}, with a total estimated carbon stock of 68 million Mg C_{org}.

The value of the carbon stock to depth of refusal of Victorian inland wetlands equates to $AUD 6 billion, and an annual carbon sequestration value of $AUD 76.74 million per year. The latter value is based on annual sequestration of 3,117,682 tonnes of CO_2 equivalents per year – equivalent to the CO_2 emissions of 176,538 Australians. Disturbance and loss of wetlands also has the potential to release significant quantities of CO_2 back into the environment. Here, we estimated that since European settlement, such losses have released 22.5–74.2 million Mg CO_2 equivalents (based on 27.25 to 90% of soil carbon lost). Loss of permanent open freshwater wetlands accounts for the largest proportion (43%) of the estimated emissions, while deep freshwater marshes and shallow freshwater marshes account for 22.7% and 22.5% respectively.

In summary, we recommend the following actions be taken to maximize wetland carbon stocks in Victoria:

1) Prioritize wetland carbon hotspots for conservation and protection from disturbance.
2) Focus revegetation projects in areas with higher sediment accretion rates, such as deep or shallow freshwater marshes and riverine wetlands.
3) Restore natural hydrology (e.g. via bund wall/drain removals or through environmental water delivery) to enhance how wetlands sequester carbon.

Overall, via the most comprehensive investigation of inland wetland carbon stocks in Australia, this study confirms that Victoria's inland wetlands represent significant carbon sinks. As Australia seeks to capitalise on new biosequestration opportunities, there is great interest in restoring such habitats for carbon offset purposes; indeed, the federal government announced that it will be among the first countries to include wetlands in its National Greenhouse Gas Inventory.

However, to facilitate this move, research must also now examine how inland wetlands might *contribute* greenhouse gases, because as well as capturing CO_2, these systems are also the world's largest source of methane – a potent greenhouse gas. In Australia, there are currently too few data to develop fully-constrained carbon budgets that balance the carbon sequestration capacity of inland wetlands with their release of greenhouse gases. Therefore, we recommend future studies that:

1) measure greenhouse gas fluxes (particularly methane) from inland wetlands;

2) determine the opportunity for carbon offsetting in wetlands in Victoria;

3) determine how carbon stocks and greenhouse gas release is affected by environmental and land-use change (e.g. grazing, wet-dry cycles); and

4) examine whether it is possible to restore wetlands in ways that minimise methane release and maximise carbon sequestration.

Introduction

Wetlands are some of the most productive habitats in the world. They support a unique biodiversity (Strayer and Dudgeon, 2010), and provide important ecosystem services, such as nutrient cycling, erosion control, and flood mitigation (Mitra et al. 2005, Mitsch and Gosselink 2007, de Groot et al. 2012, Costanza et al. 2014, Russi et al. 2013). But rising carbon dioxide levels in the atmosphere have brought attention to another important service of wetland systems: the capacity for wetlands to store carbon. By taking up carbon during photosynthesis and growth and burying undecomposed plant litter in anaerobic soils, wetlands store an average of 34 to 44 times more carbon than do terrestrial forests (McCleod et al. 2011, Bernal and Mitsch 2012). Global estimates suggest that freshwater wetlands contain 33% of the soil carbon pool: a disproportionately high contribution given that they occupy a mere 6–8% of the land surface (Mitra et al. 2005, Lal 2007, Mitsch and Gosselink 2007).

Despite their importance, wetlands have been historically underappreciated, and an estimated 87% of global wetland area has been lost since 1700 (Davidson 2014). They are threatened by pollution, transformation, water extraction, and modification (MEA 2005, Moser et al. 1996, van Asselen et al. 2013, Vörösmarty et al. 2010). Such disturbance can undermine a wetland's ability to capture carbon, but critically, damage to wetlands can also release significant amounts of carbon that have *already* been stored (Lal et al. 2007, Page and Dalal 2011, Pendleton et al. 2012). Conversion to agricultural land for cropping and grazing, in particular, has negative consequences on wetland soil carbon storage and sequestration. For example, Sigua et al. 2009 measured a 96% reduction in soil organic carbon (%) when a wetland was converted to beef cattle pasture, while Meyer et al. (2008), estimated an 80% loss of soil carbon after roughly 40 years of soybean and corn cultivation. Quantifying the contribution of wetland ecosystems to carbon capture and storage is vital not only to ensuring these valuable systems are managed to maximise storage, but to providing extra justification for protection of areas valuable for a multitude of other services.

While research suggests that inland freshwater wetlands may provide significant carbon storage, there is high variability across this diverse range of systems making generalisation across hydrogeomorphic types difficult. For example, in Ohio, USA, depressional wetlands sequester 2.25 times more carbon than riverine communities (317 ± 93 gC m^{-2} yr^{-1} compared to 140 ± 16 gC m^{-2} yr^{-1}; Bernal and Mitsch 2012). Within these broader hydrogeomorphic categories, different plant communities (Mitsch et al 2013, Villa and Mitsch 2015) also impact carbon sequestration rates.

There are few studies that attempt to systematically compare carbon stocks and sequestration rates between wetland types and across catchments within a single region. Specifically, this project aims to: **1)** undertake the first broad-scale assessment of carbon stocks of inland Victorian wetlands; **2)** identify carbon hotspots based on these data; and **3)** assess the potential impact of historical wetland loss on carbon stocks.

Methods

This study was conducted across the state of Victoria in southeastern Australia (Figure 1). The inland catchments of Victoria contain 530,413 hectares of wetlands, but an estimated 201,175 ha (or roughly 26%) have been lost since European settlement (Papas and Moloney 2012). The wetlands that still exist in Victoria are also vary in condition. In a recent state-wide assessment of close to 600 wetlands in Victoria, almost two thirds of wetlands on public land were in good or excellent condition, compared to 39% on private land (DSE 2012). Moderate to very poor hydrology was found in 46% of wetlands, and 19% showed a moderate, poor or very poor assessment for disturbance to soils (DSE 2012). Given the broadscale nature of the survey, our study sampled mostly wetlands in good condition across both public and private land to produce a best case scenario estimate of the carbon value of our remaining wetland resources.

1. Site selection

To evenly spread the sampling effort across the state, we sampled at least 10 wetlands in each Catchment Management Authority (CMA) region, totalling 103 wetlands (Figure 1). Wetlands were chosen from a list of priority wetlands identified by each CMA, but also across six key wetland categories defined by Corrick and Norman (1980): freshwater meadow, shallow freshwater marsh, deep freshwater marsh, permanent open freshwater, permanent saline wetland, and high country peatland.

2. Field sampling

Between August 2015 and February 2016 we collected five soil cores at each of 103 wetlands across the ten participating CMA regions. At each site we selected a single dominant vegetation stratum to sample within, to ensure soil was collected from areas with the same overlying litter material as well as similar inundation level. Cores were taken 50 m apart from one another in an attempt to sample more widely across the sites.

At each of the five sampling points, a 5 cm (inner-diameter) PVC pipe (the core) was hammered into the soil until 1 m was reached, or until core refusal (no further penetration). Soil compaction was calculated based on the depth of soil contained in the core compared to the depth of the core in the ground. These values are then later used to correct the depth of the sample taken (eg. with compaction of 0.75, a 15 cm sample becomes 18.75 cm). To ensure the soil remained stable during removal, a rubber plug was inserted into the top of the core to create a vacuum seal. After removal, a foam plug was inserted down the top of the pipe to maintain the sediment stratigraphy during transport. Both ends of the core were capped and duct taped to prevent moisture loss. All cores were brought back to the laboratory at Deakin University in Burwood, Victoria, for subsequent processing.

At each sampling point, a 1 m^2 quadrat centred on the collection site of each core was used to aid in visual estimation of species cover and height. These data were collated to verify wetland type and dominant vegetation classifications obtained from online spatial databases (DELWP Biodiversity Interactive Map at www.depi.vic.gov.au/environment-and-wildlife/biodiversity/biodiversity-interactive-map and the Wetland Current spatial layer at www.data.vic.gov.au).

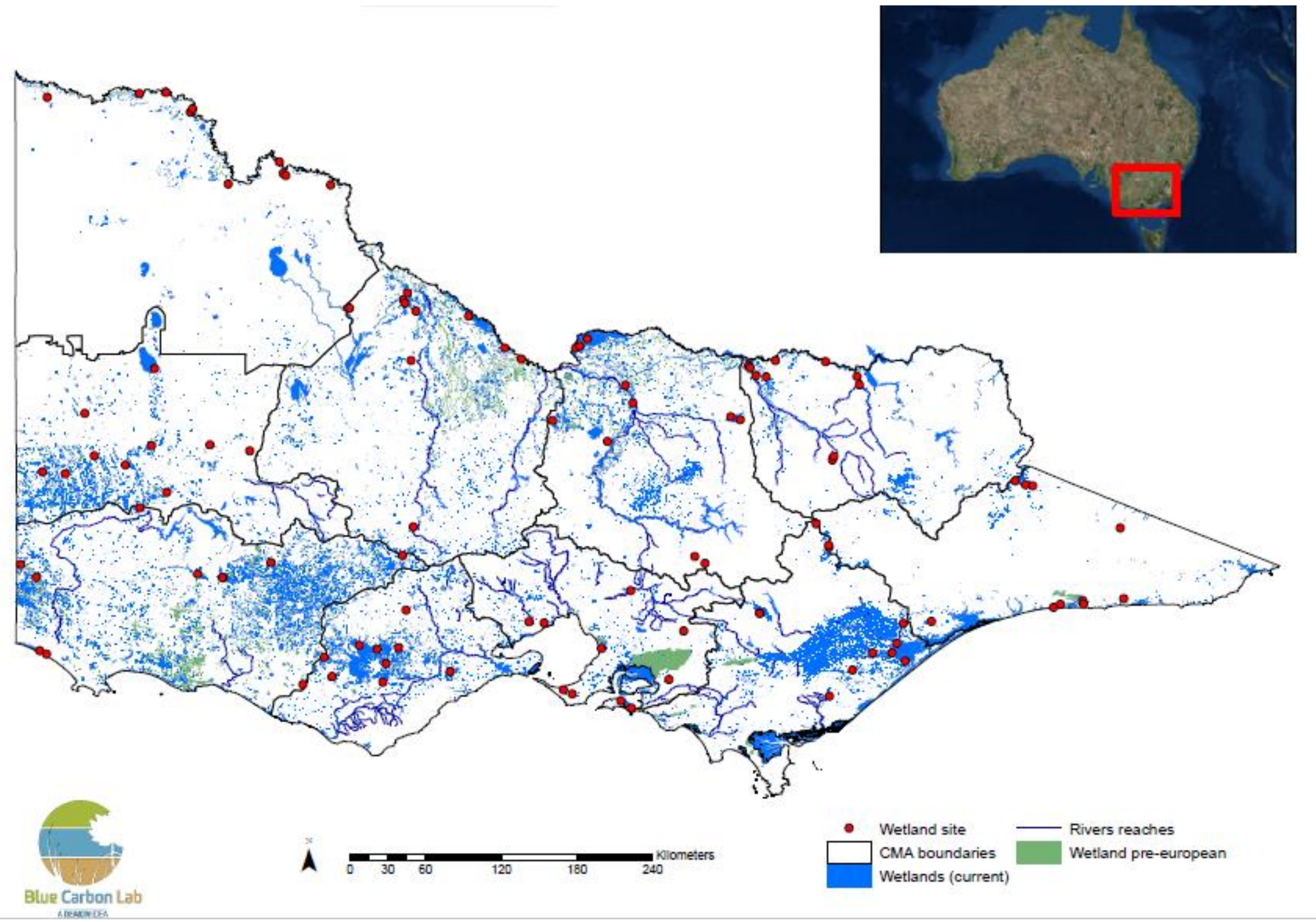


Figure 1. Extant wetlands and waterbodies in Victoria and the location of the 103 wetlands sampled in this study.

3. Laboratory Processing

In the laboratory, soil from three of the five replicate cores from each site were extruded and sectioned at 0–2 cm, 12–14 cm, 28–30 cm, 48—50 cm, 74—76 cm, and 98—100 cm for carbon stock calculations (Figure 2). Any dead plant material was left in the sections and the sections were then dried until consistent weight at 50°C for 48-72 hours. Dry weight was used to calculate sediment bulk density (weight (g) / volume (cm^3)) and then homogenized with a stainless steel mortar and pestle (Retch RM200).

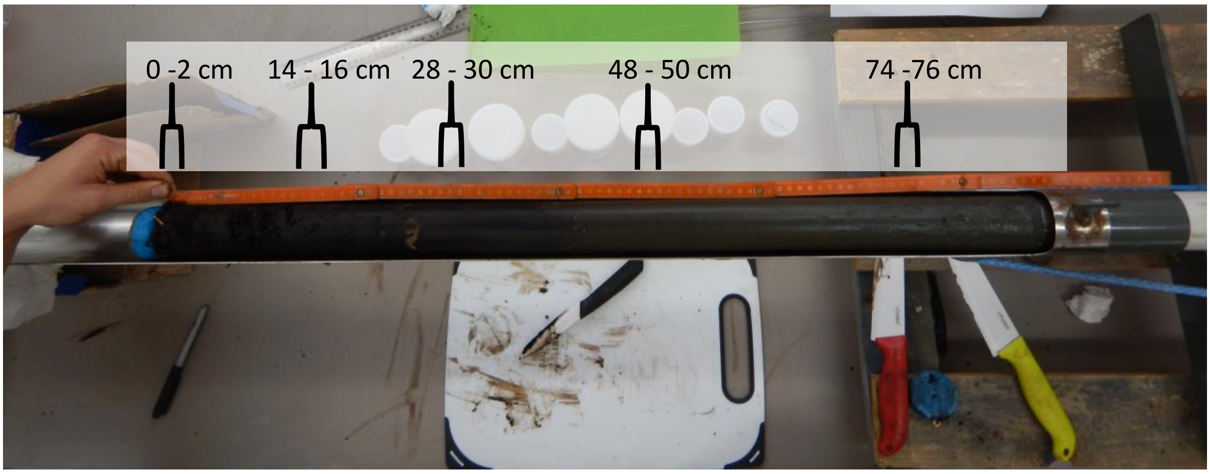


Figure 2. Example sediment core illustrating the depth sections sampled in this study (core taken from Seaford Wetland in Port Phillip and Western Port CMA).

At 11 of the 103 sites, the fourth core was processed for carbon analysis and ^{210}Pb age dating, and was sectioned every centimetre from 0–20 cm. The sections for ^{210}Pb dating were split in half, with one half to be age dated, and the other reserved for carbon analysis, so that carbon sequestration values could be calculated.

As some of the samples were collected from declared Phylloxera Infested Zones (areas infected with an aphid-like insect pest of grapevines (*Daktulosphaira vitifoliae*), all cores were gamma irradiated at 50kGray for 60 hours (by Steritech, Dandenong, Victoria), before being sent to the soil carbon lab at CSIRO, South Australia, for analysis. This irradiation process has been demonstrated to have no major influence on carbon measurements in soil samples (Balldock et al. unpublished data).

Based on the protocols of Baldock et al. (2013), a Thermo Nicolet 6700 FTIR spectrometer equipped with a Pike AutoDiff automated diffuse reflectance accessory was used to obtain diffuse reflectance Fourier-transform MIR spectra for all samples across a spectral range of 8700-400 cm^{-1} at 8 cm^{-1}. Using Unscrambler X ver 10.1 software, a principle component analysis (PCA) was used to visualize spectra variability and the Kennard-Stone Algorithm (Kennard & Stone 1969) was used to pick the most representative 286 samples from the total dataset. The resultant model was then used to predict C_{org} values for the remaining 1386 samples.

For the 198 samples, total carbon (TC) and total nitrogen (TN) were determined in the laboratory. High temperature (1350°C) oxidative combustion on a LECO Trumac CN analyser was used to estimate TC and TN, using lance oxygen flows and an extended purge to ensure complete combustion of carbonates. Non-calcareous samples identified based on MIR spectra (absence of reflectance peak at 2500cm^{-1}) had no further analysis (TC = TOC). Here we present the C_{org} results.

4. Carbon stock calculations

The depth of refusal at each site varied (some as shallow as 16 cm), but most cores reached at least 50 cm. We followed the approach for calculating total sedimentary carbon stock as outlined by Howard et al. (2014). We calculated soil carbon density by multiplying the dry bulk density by the percent carbon (Step 1). To obtain carbon stocks for the full 2 cm section of sediment, we multiplied the C_{org} density (mg C_{org} cm^{-3}) calculated for each depth interval by two (Step 2). For each carbon stock core with more than three depth data points, cubic splines were used to calculate the C_{org} values for intermediate depth ranges that were not analysed (Step 3). Although cubic splines are commonly preferred for soil carbon analysis (e.g. Minasny et al. 2006), linear splines are more appropriate for cores where there were only two or three data points per core. Carbon stock values for all depth intervals (both measured and estimated) were summed to calculate carbon stocks (per cm^2) to the depth sampled for each core (Step 4). This value was used to upscale C_{org} stocks to Mg C_{org} ha^{-1} using the following unit conversion factors: 1,000,000 g = 1 Mg (megagram), and 100,000,000 cm^2 = 1 hectare.

Step 1.

Soil carbon density (g/cm^3) = dry bulk density (g/cm^3) * (% C_{org} /100)

Step 2.

Carbon content in core sections (g/cm^3) = Soil carbon density (g/cm^3) * Thickness of core section (2 cm)

Step 3.

Create cubic equations (splines) for each core, using the depth samples measured, to estimate carbon density in each 2 cm section throughout the entire core.

Step 4.

Sum the carbon density values for each 2 cm section, to get a total carbon stock for the entire core.

Step 5.

Total sedimentary carbon (MgC ha^{-1}) = Averaged core carbon (g/cm^3) * (1 Mg/1,000,000 g) *(100,000,000 cm^2/1 hectare)

5. Carbon sequestration rate measurements

The profiles of ^{210}Pb concentrations were determined for one sediment core at each 11 of the 103 wetlands. Analysis of its decay product ^{210}Po, in equilibrium with ^{210}Pb was used to determine concentrations of ^{210}Pb (Sanchez-Cabeza, Masque & Ani-Ragolta 1998). Soil samples were spiked with known amounts of ^{209}Po, acid digested, plated and their emissions were measured by alpha spectrometry using Passivated Implanted Planar Silicon (PIPS) detectors (CANBERRA, Mod. PD-450.18 A.M). The concentrations of ^{210}Pb were calculated by applying an appropriate decay–ingrowth correction and accounting for blank (one per 10 samples) and detector background, which were both almost negligible (awaiting final results). Analyses of samples and reference materials were carried out in parallel.

Concentrations of ^{226}Ra (Radium isotope) were determined by gamma spectrometry using a high-purity Germanium (Ge) well-type detector (CANBERRA, mod. GCW3523) through the 295 and 351 keV emission lines of ^{214}Pb. Samples were stored in sealed containers for 3 weeks prior to counting to attain equilibrium between ^{226}Ra and its short-lived decay products. Concentrations of $^{210}Pbex$ were obtained by subtracting the $^{210}Pb_{sup}$ from the total ^{210}Pb at each section. The concentrations of ^{226}Ra were in agreement with those of ^{210}Pb in the deepest sections of the cores, where no excess ^{210}Pb ($^{210}Pb_{ex}$) was present. All sediment cores had similar concentrations of supported ^{210}Pb (i.e. in equilibrium with ^{226}Ra; $^{210}Pb_{sup}$ = awaiting final results). The model of constant rate of supply (CRS; Appleby & Oldfield 1978), which assumes a constant flux of $^{210}Pb_{ex}$ to the sediment surface, was used to date the sediment based on $^{210}Pb_{ex}$ inventories and estimate sediment accretion rates in the cores. The CRS model was adapted for those sites with missing inventories of $210Pb_{ex}$, following Appleby (2001).

Beyond carbon sequestration measurements taken in this study, there have also been a number of other studies that have calculated sediment accretion rates in wetlands in Victoria (Gell et al. 2009, Gell et al. 2014). We compiled these data sets, and combined the sediment accretion rate (mm yr^{-1}) with carbon density estimates from up to three wetlands from the current stock assessment (Table 2). Carbon density values from stock assessment sites allowed estimation of the average carbon sequestration rate at the literature sites.

6. Estimated emissions from wetland losses since European settlement

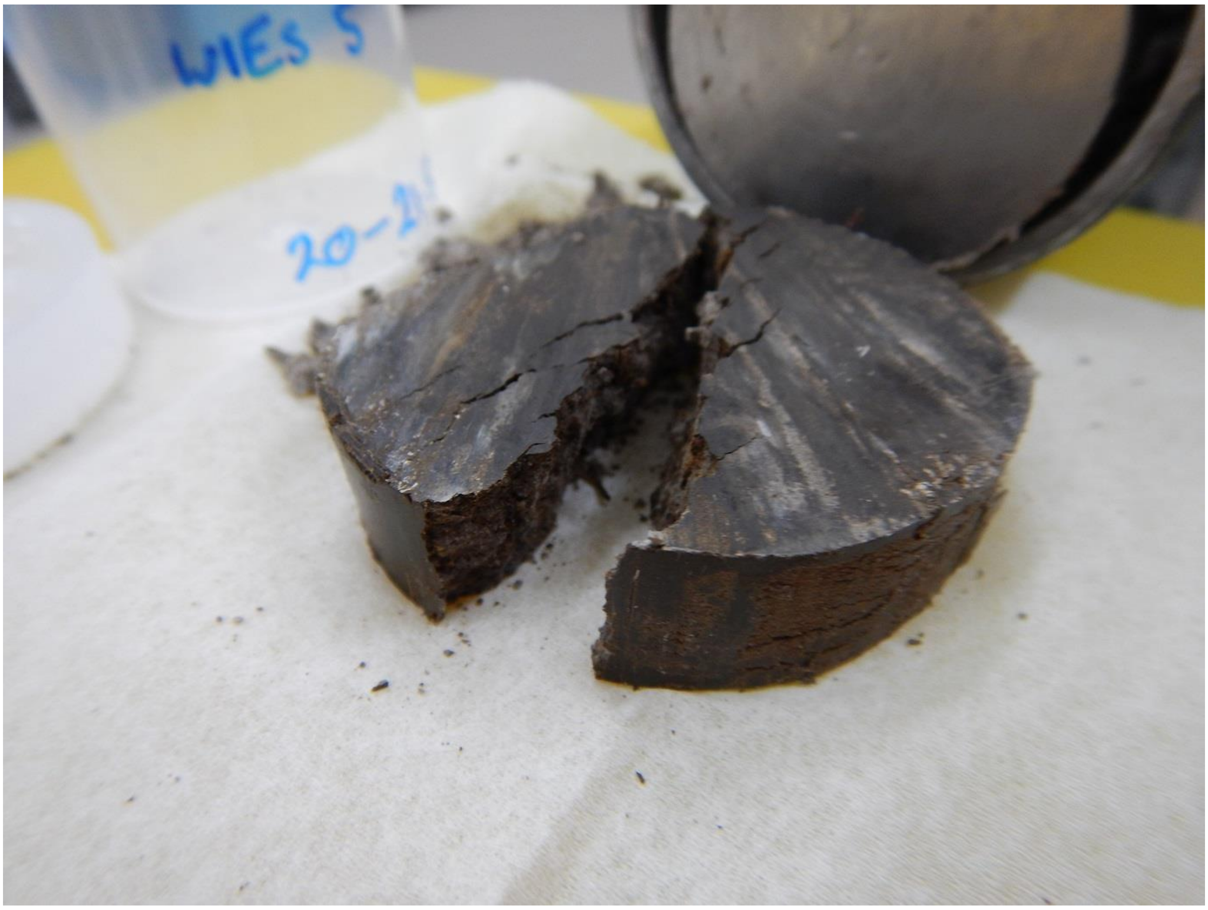
Carbon emissions from wetland loss were calculated based on carbon stock estimates from this study in combination with data on pre-European (pre-1778s) and present-day distribution. Area of ecosystem loss from each CMA was calculated by comparing pre-European wetland extent layer with current wetland extent. Next, average carbon density of CMA, calculated by averaging measurements from 1-5 wetlands that occurred within each sector, were multiplied by the area of loss to estimate total sediment carbon stocks that were previously present. Where sediment cores had not been collected within the CMA, the average carbon stock value for the CMA was based on the average of that wetland type in all of Victoria.

The upper, lower, and intermediate estimates of carbon remineralization were calculated based on values used in previous studies. Murray et al. (2011) estimated that 90% of the OC in the top meter of sediment is released as CO_2 emissions, while Donato et al. (2011) estimated that 50% of the top 30 cm would be converted and 25% from the remainder of the top meter of sediment. Siikamaki et al. (2013) combined these estimates to calculate a high (90%), low (27.25%) and intermediate

(58.625%) estimate of the carbon stock lost as CO_2 equivalents (eq.). The emissions estimates are presented here as 90, 58.625, and 27.25% remineralization of C_{org} from to the depth that was sampled in this study, converted from C_{org} to CO_2 eq. by multiplying by 3.67 (Pendleton et al. 2012).

7. Data analysis

Carbon stock values to refusal were transformed ($\log_{10}$(Mg C_{org} ha^{-1})) prior to statistical analysis to meet assumptions of normality and equal variances. Carbon stock was compared across ecosystems using a one-way ANOVA, with carbon stock as the response and wetland type as the factor. A post-hoc Tukey Pairwise Comparison was performed to distinguish differences in population means. A fully nested ANOVA was performed to compare carbon stock in each ecosystem across the six CMA regions where they co-occurred, using carbon stock as the response and wetland type and CMA as factors.



Sediment sample extruded in the lab.

Results

We have set up the results section to reflect information relating to the aims and objectives of this project. Section **1)** undertakes the first broad-scale assessment of carbon stocks of inland Victorian wetlands, **2)** identifies carbon hotspots based on these data, and **3)** assesses the potential impact of historical wetland loss on carbon stocks.

Aim 1. Carbon stocks and sequestration rates across Victoria

1.1. Carbon density, dry bulk density and % carbon values

The organic carbon density of all samples collected from wetlands across Victoria, ranged from 0.0 to 260.87 mg C_{org} cm^{-3}, with a mean $\pm$ SEM (standard error of the mean) of 31.45± 0.82 mg C_{org} cm^{-3}. Supplementary Table 1 provides information on how carbon density varied with depth. Carbon density was generally highest at the surface (0—2 cm) and at 14—16 cm, with a 25% decline by 28—30 cm and 50% by 48—50 cm. However, there were a number of sites that did not follow this trend.

The Dry Bulk Density of all samples ranged from 0.03 to 2.35 g cm^{-3}, with an average of 1.01 ± 0.02 g cm^{-3} (Figure 3a). This is a relatively high dry bulk density value compared to other wetland studies (Meyer et al. 2008, Whitacker et al. 2015). The percentage C_{org} values across all samples ranged from 0.0 to 55.85 %, with an average of 7.72 ± 0.31% (Figure 3b).

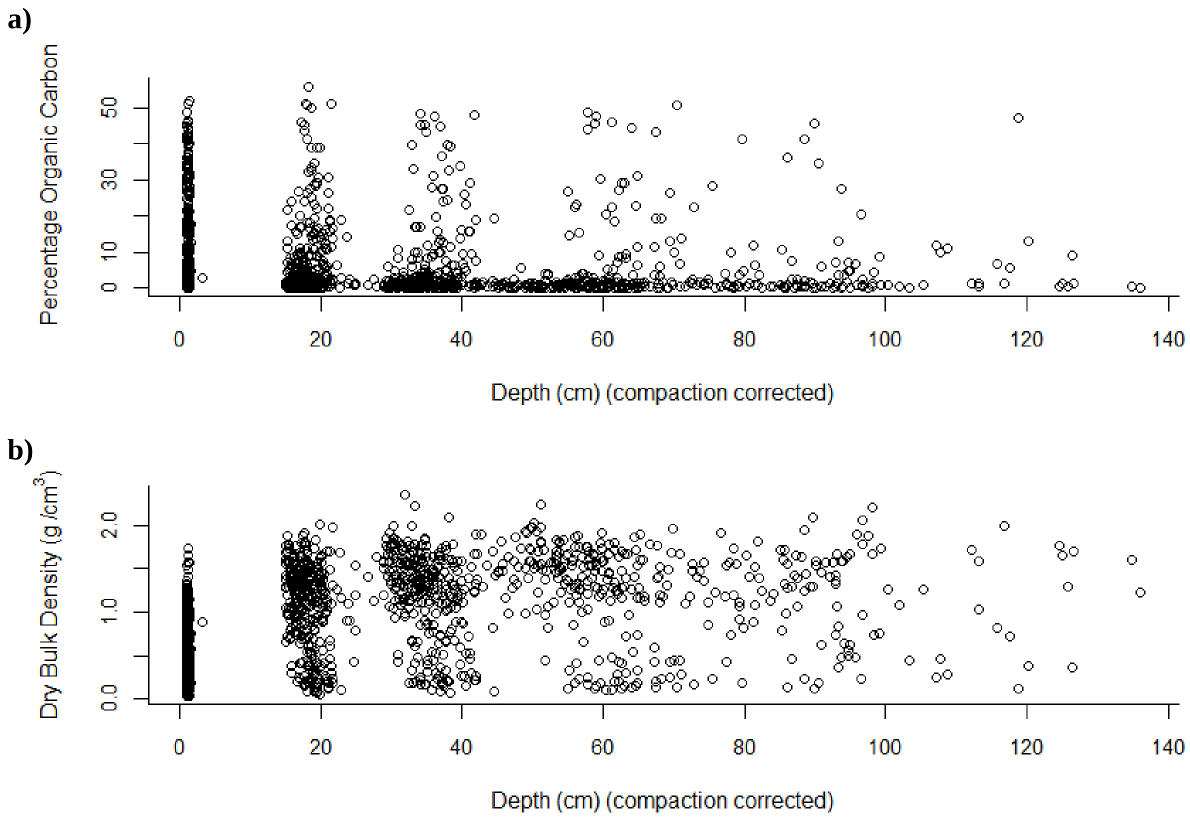


Figure 3. (a) Organic carbon content (% carbon, n=1251) and **(b)** dry bulk density (DBD, g, cm^{-3}, n=1251) samples across the 103 wetland sampled, plotted by depth sampled corrected for sediment compaction.

1.2. Wetland comparisons

Average surface (0 – 2 cm) soil total carbon (C_{org}) density varied greatly between wetland types, 24.03 ± 20.86 (permanent open freshwater), 35.07 ± 21.04 (freshwater meadow), 41.15 ± 25.68 (shallow freshwater marsh) and 46.68 ± 35.11 (deep freshwater marsh), 50.94 ± 24.35 (alpine peatlands) and 22.76 ± 14.32 (saline wetlands) mg C_{org} cm^{-3} (Table 3). When comparing soil carbon stocks across the five wetland types most sampled, permanent open freshwater wetlands had significantly lower carbon stocks compared to shallow freshwater marsh, deep freshwater marsh and alpine peatlands ((ANOVA, $F_{2, 857}$=140.20, p <0.001; Figure 3, Supplementary table 1). This equated to average sediment carbon stocks of 113.02 ± 119.94 Mg C_{org} ha^{-1} for permanent open freshwater, 201.26 ± 196.49 Mg C_{org} ha^{-1} for shallow freshwater marsh, 233.31 ± 192.20 Mg C_{org} ha^{-1} for deep freshwater marsh, and 292.54 ± 177.60 Mg C_{org} ha^{-1} for high country peatlands. Alpine peatlands also had higher carbon stocks when compared to freshwater meadows 126.41 ± 104.19 Mg C_{org} ha^{-1} (Supplementary Table 1).

Carbon stocks varied significantly between CMA regions, but these differences also depended on the wetland type. For deep freshwater marshes, Glenelg Hopkins had the highest carbon stocks with an average of 376.03 ± 269.42 Mg C_{org} ha^{-1} (Table 1, Supplementary Table 1). Port Phillip and Western Port had the highest average carbon stocks for shallow freshwater marsh, with an average of 426.63 ± 194.21Mg C_{org} ha^{-1} (Table 1, Supplementary Table 1). In comparison, for alpine peatlands, there was no significant difference between CMAs.

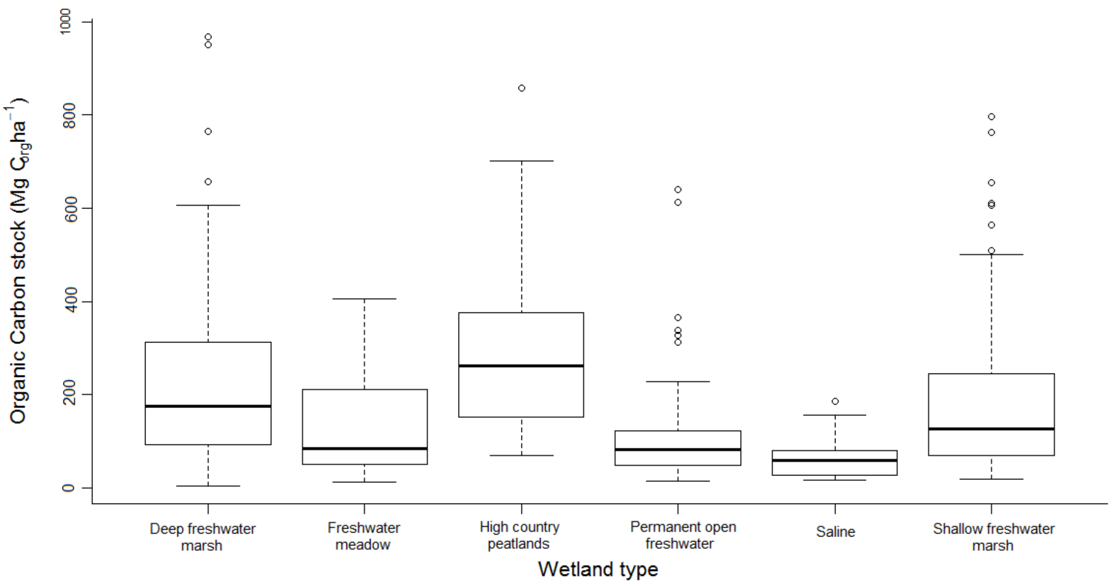


Figure 4. Average organic carbon stocks to refusal (n= 317 cores) for the various wetland types, according to the Corrick and Norman (1980) classification.

Table 1. Overview of the wetland types sampled within each CMA region and the average (± SD) organic carbon stock (Mg C_{org} ha^{-1})

	Saline	Permanent open freshwater	Freshwater meadow	Shallow freshwater marsh	Deep freshwater marsh	High country peatlands
Corangamite	73.52 ± 51.87	314.40 ± 247.99			250.21 ±147.09	
East Gippsland		177.94 ± 0.52	234.32 ± 42.69		287.34 ± 54.11	263.13 ± 177.91
Glenelg Hopkins		127.04 ± 88.53	18.64 ± 6.24	175.24 ± 53.48	491.30 ± 279.31	
Goulburn Broken		75.01 ± 41.92		112.97 ± 25.24	132.32 ± 53.10	386.94 ± 281.42
Mallee		78.08 ± 28.05	115.66 ± 20.59	58.48 ± 13.56	7.97 ± 3.78	
North Central	20.79 ± 3.59	88.99 ± 65.55		25.66 ± 7.08	122.36 ± 97.35	
North East		130.45 ± 19.14		86.85 ± 32.99	123.10 ± 48.78	367.34± 105.64
Port Phillip & Western Port			179.03 ± 108.57	418.41 ± 174.18	508.98 ± 55.92	
West Gippsland				319.54 ± 287.82	275.13 ± 138.59	232.32 ± 116.24
Wimmera	61.57 ± 17.83	37.14 ± 25.18	42.23 ± 17.12	66.11 ± 35.77	94.42 ± 57.58	
State Average	**64.28** ± **47.60**	**113.02** ± **119.94**	**126.41** ± **104.19**	**201.26** ± **196.49**	**233.31** ± **192.20**	**292.54** ± **177.60**

1.3. Carbon sequestration rates

Sediment accretion rates were compiled from a number of published studies in southeast Australian wetlands (Table 2). Soil accretion rate can be translated into carbon sequestration rate by multiplying by carbon density. Soil accretion rates ranged from 1.02 to 30.00 mm yr^{-1}, with a mean ± standard error of 6.66 ± 1.33 mm y^{-1}. Using carbon density data from our carbon measurements, average carbon sequestration rates were 6.93 ± 1.37 Mg CO_2 eq. ha^{-1} yr^{-1}.

Previous syntheses of sediment accretion rates by Gell et al. (2009) indicate a substantial increase in sediment accretion rate since European settlement. This is evident in the high values of sites located along the River Murray, including King's Billabong, Pikes creek, Barmah, Hogans 1, and Callemondah 1. This increase in sediment accretion has presumably also resulted in increased carbon sequestration in these wetlands.

a)

b)

Figure 5. **a)** Barmah Lake in Barmah National Park: one of the sites with the highest carbon sequestration rates in Victoria. **b)** Lake Colac, the site with the lowest carbon sequestration rate.

Table 2. Estimated carbon sequestration rates in wetlands, utilising other age dating studies in southeastern Australia. Using this information on sediment accretion rate (SAR), we then choose the closest wetlands of a similar type, and averaged these to estimate the C_{org} density of the surface sediment (0—2 cm), and used this to calculate the carbon sequestration rate in CO_2 equivalents, per hectare, per year.

Site	CMA	Reference	Latitude (S)	Longitude (E)	SAR (mm yr^{-1})	Estimated C_{org} density 0-2cm (mg C_{org} cm^{-3})	Estimated C_{org} sequestration rate (Mg CO_2 eq. ha^{-1} yr^{-1})	Estimated carbon sequestration value (\$$ha^{-1}$ yr^{-1})
Kings Billabong	Mallee	Kattell et al 2015	-34.239	142.226	14.29	28.31	14.84	358.5
Junction Park Billabong	NSW	Gell et al 2009	-34.772	143.301	3.80	27.41	3.82	92.3
Hopcrofts Billabong	Mallee	Gell et al 2009	-34.715	143.151	5.00	27.41	5.03	121.5
Lake Cullulleraine	Mallee	Gell et al 2009	-34.273	141.597	5.00	17.15	3.15	76.0
Tareena Billabong	NSW	Gell et al 2005b	-34.061	141.234	3.50	27.41	3.52	85.0
Ral Ral Creek	SA	Gell et al 2009	-34.045	140.744	9.50	27.41	9.56	230.8
Pikes Creek	SA	Gell et al 2009	-34.295	140.656	30.00	27.41	30.18	728.9
Willsmere Billabong	PPW	Lintern et al 2016	-37.783	145.056	9.40	32.79	11.31	273.2
Bolin Billabong	PPW	Lintern et al 2016	-37.769	145.078	4.00	32.79	4.81	116.2
Delegate River	EG	Gell Stuart Smith 1993	-37.229	148.839	3.47	36.44	4.64	112.1
Barmah Forest	GB	Thoms et al 1999	-35.862	145.322	21.80	27.48	21.99	531.0
Hogans 1	NSW	Reid et al 2007	-36.025	146.715	10.00	19.69	7.23	174.5
no. 9	NSW	Thoms et al 1999	-35.927	147.713	7.37	19.69	5.33	128.6
no. 11	NE	Thoms et al 1999	-36.129	146.953	2.53	24.39	2.26	54.7
no. 19	NSW	Thoms et al 1999	-36.025	146.227	4.10	19.69	2.96	71.6
no. 23	NE	Thoms et al 1999	-36.133	146.210	3.85	23.70	3.35	80.9
no. 32	GB	Thoms et al 1999	-36.008	145.809	5.30	19.69	3.83	92.5
no. 38	GB	Thoms et al 1999	-35.870	145.372	10.00	27.48	10.09	243.6
Callemondah 1	GB	Thoms et al 1999	-36.695	145.160	1.70	23.00	1.44	34.7
Callemondah 2	GB	Thoms et al 1999	-36.689	145.164	3.20	23.00	2.70	65.2
Lake Curlip	EG	Ladd 1978	-37.750	148.565	1.40	20.40	1.05	25.3
Lake Surprise	GH	Barr et al 2014	-38.061	141.923	4.24	52.33	8.14	196.7
Lake Elingamite	GH	Barr et al 2014	-38.356	143.004	5.93	37.12	8.08	195.1
Lake Colac	C	Gell et al 2012	-38.309	143.589	1.02	5.91	0.22	5.3
Lake Purrumbete	C	Tibby et al 2012	-38.284	143.230	2.46	41.09	3.71	89.6
Wetland average $\underline{+}$ SEM					**6.66 ± 1.33**	**29.68 ± 2.58**	**6.93 ± 1.37**	**167.35 $\underline{+}$ 32.97**

1.4. Victoria wetland carbon stock and sequestration rate estimates

Using the carbon stock data from the sites sampled, Victoria's total wetland soil organic carbon stocks are estimated to be over 68 million Mg C_{org} (Table 3). Given that not all sites could be sampled to the full 1 m depth, this stock value is likely to be an underestimate as the soil in most cases would have extended beyond the depth that we could sample using this technique. Permanent open freshwater wetlands are responsible for 18% of Victoria's wetland carbon stock, mostly due to their extensive area in Victoria (about 30% of the wetland area). Freshwater meadows store 16% of Victoria's inland wetland soil carbon stocks, while saline wetlands only account for 9% of soil carbon stocks despite accounting for almost 25% of the state's wetlands by area. Conversely, despite their high soil carbon stocks, due to their limited distribution (0.73% of total inland wetland area), alpine peatlands store 1.14 % of inland wetland soil carbon stocks in Victoria.

By converting the estimated carbon stocks for Victoria to CO_2 equivalents and using a 2013-14 carbon price of $AUD 24.15/tonne, Victoria's carbon stocks are valued at $AUD 6 billion. Similarly, by using the average carbon sequestration rate from the wetlands listed in Table 2 (6.93 ± 1.37 Mg CO_2 eq. ha^{-1} yr^{-1}), to the total area of freshwater wetlands in Victoria (458,540 ha), the estimated carbon sequestration of Victoria's freshwater wetlands is 3,177,682 tonnes of CO_2 equivalents per year. This has a potential value of $AUD 76.74 million per year, or is equivalent to the CO_2 emissions of 176,538 Australians.

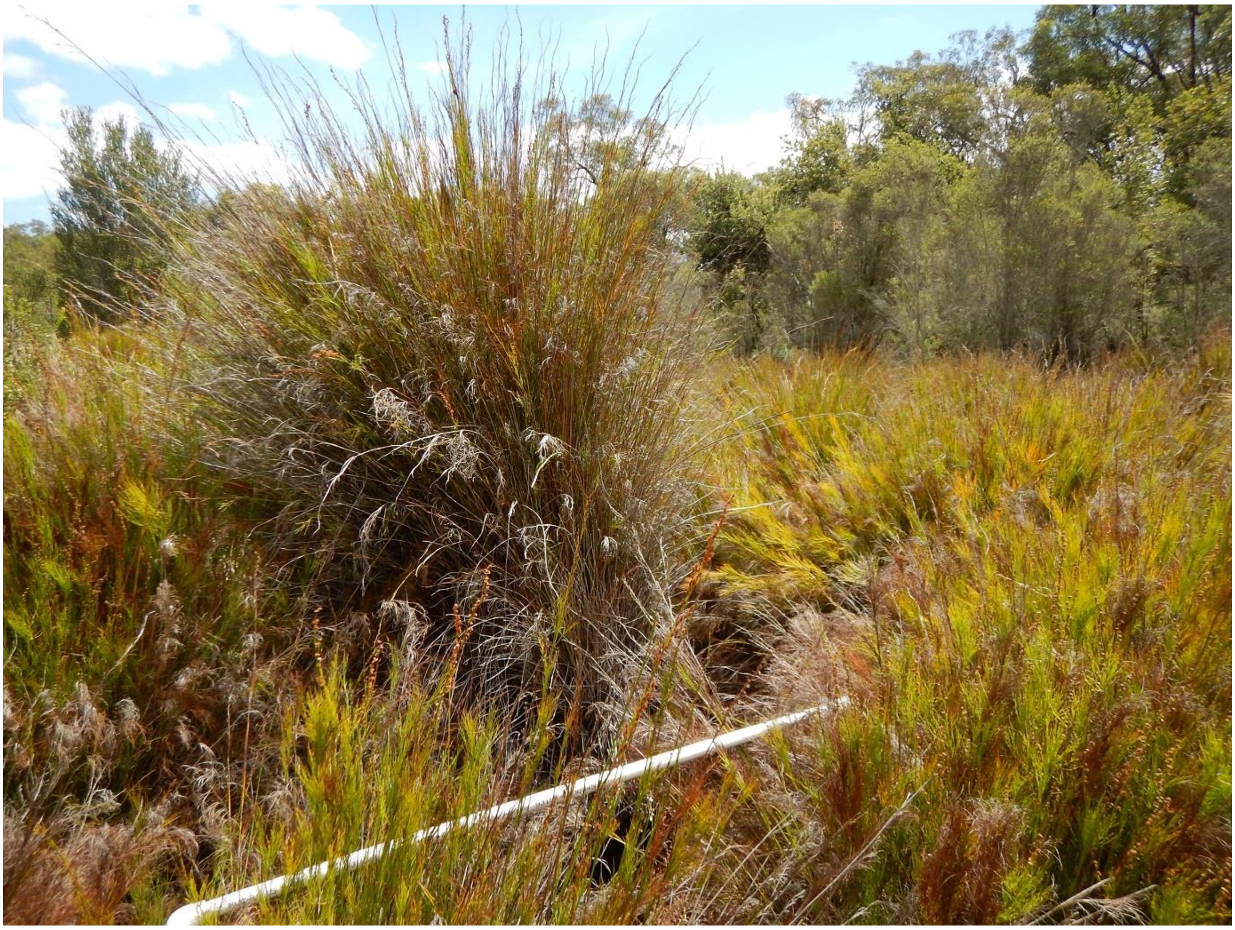
Table 3. Wetland sediment carbon density, average total organic carbon stock, total wetland area in Victoria and our estimated organic carbon stocks for Victoria by wetland type (Corrick and Norman 1980). These values are not extrapolated to a standard measure; cores are sampled in the field to refusal and are therefore site specific. These values are combined with the total area of each wetland type, to produce an estimate of organic carbon stock by wetland type.

Wetland type	Number of cores	Average of 0 – 2 cm mg C_{org} cm^{-3} ± SD	Average of Mg C_{org} ha^{-1} ± SD	Total Victorian Area (Hectares)	Total stocks (Mg C_{org})
Deep freshwater marsh	100	46.68 ± 35.11	233.31 ± 192.20	55,790.10	15,004,315.98
Freshwater meadow	32	35.07 ± 21.04	126.41 ± 104.19	144,179.50	14,199,789.49
High country peatlands	36	50.94 ± 24.35	292.54 ± 177.60	4,475.70	190,355.78
Permanent open freshwater	67	24.03 ± 20.86	113.02 ± 119.94	185,034.90	19,825,164.75
Saline	21	22.76 ± 14.32	64.28 ± 47.60	155,718.50	10,005,798.46
Shallow freshwater marsh	57	41.15 ± 25.68	201.26 ± 196.49	69,060.70	8,891,555.50
Grand Total	**316**	**38.50 ± 28.65**	**185.74 ± 175.90**	**614,259.40**	**68,116,979.96**

Aim 2. Carbon stock and sequestration hotspots

The wetlands with the highest carbon stock values are listed in Table 4. Here, McKenzie's Rd bog in West Gippsland CMA has the highest average carbon stock, followed by Long swamp in Glenelg Hopkins CMA and Highland peatland site 4 in Goulburn Broken CMA. While these wetlands have the highest carbon stock values per hectare, the wetlands with the largest estimated carbon stocks are Lake Corangamite, Lake Coleman, Heart Morass, Long Swamp and Ewings Morass, due to their large area.

Carbon Hotspot mapping (Figure 6) visually overlays the average soil organic carbon content from the wetland types sampled and within each CMA region (Table 1).Where we did not have data for a wetland type in a CMA, we used the state average value. It provides a method for identifying high value habitat patches using spatial information. The current analysis highlights that the wetlands along the Murray River, southwestern Victoria and in the Gippsland Lakes region are some of the highest value blue carbon locations (Figure 7; a and b).



Mckenzie's Rd Bog, West Gippsland CMA.

Table 4. The top twenty wetlands, listed in order of highest average Organic carbon stock. The estimated wetland organic carbon stock is calculated from the average organic carbon stock to refusal multiplied by the current wetland area. The estimated organic carbon stock value of this wetland is then calculated from the estimated wetland organic carbon stock, by converting to CO_2 equivalents and using the 2014 carbon price of $24.15 per Mg of CO_2 equivalents.

Site	CMA	Wetland type	Area (Ha)	Average organic carbon stock (Mg C_{org} ha^{-1})	Estimated wetland organic carbon stock (Mg C_{org})	Estimated Organic Carbon stock value ($)
McKenzie's Rd Bog	WG	Shallow freshwater marsh	2	780.31 ± 24.38	1,560.63	138,319
Long Swamp	GH	Deep freshwater marsh	726.2	631.68 ± 382.31	458,725.17	40,657,041
Highlands Peatlands 4	GB	High country peatlands	4.6	585.43 ± 262.77	2,692.96	238,678
Lang Lang Swamp	PPW	Shallow freshwater marsh	5.6	575.75 ± 99.38	3,224.20	285,762
Bryans Swamp	GH	Deep freshwater marsh	666.3	550.53 ± 114.78	366,815.71	32,511,060
Rhyll Swamp	GH	Deep freshwater marsh	43.1	508.98 ± 55.92	21,936.85	1,944,274
Delegate River Bog	EG	High country peatlands	176	507.97 ± 168.42	89,402.38	7,923,778
Lake Purrumbete	C	Permanent open	527.8	489.56 ± 159.04	258,388.94	22,901,141
Boneo Swamp	PPW	Shallow freshwater marsh	320.2	473.32 ± 107.83	151,557.67	13,432,632
Heart Morass	WG	Deep freshwater marsh	1560.3	402.13 ± 102.67	627,440.76	55,610,388
Nunziata Bog	NE	High country peatlands	4	397.10 ± 86.11	1,588.39	140,779
Seaford Wetlands	GH	Shallow freshwater marsh	93.2	391.00 ± 104.07	36,441.25	3,229,807
Dereel Lagoon	C	Deep freshwater marsh	33.6	352.03 ± 51.04	11,828.17	1,048,337
Cooper's Bog	M	High country peatlands	3.8	337.58 ± 133.52	1,282.80	113,696
Cabbage Tree Lagoon	EG	Deep freshwater marsh	442.9	332.19 ± 51.27	147,125.99	13,039,850
Bunyip Reserve	PPW	Freshwater meadow	39.1	331.20 ± 64.06	12,949.85	1,147,752
Dam Valley Bog	WG	High country peatlands	1.3	315.26 ± 136.10	409.83	36,324
Lake Curlip	EG	Deep freshwater marsh	944.5	301.54 ± 72.02	284,808.71	25,242,739
Lake Elingamite	GH	Permanent open	278.9	289.58 ± 53.24	80,763.18	7,158,081
Lara Swamp	WG	Deep freshwater marsh	6	284.47 ± 247.61	1,706.80	151,274

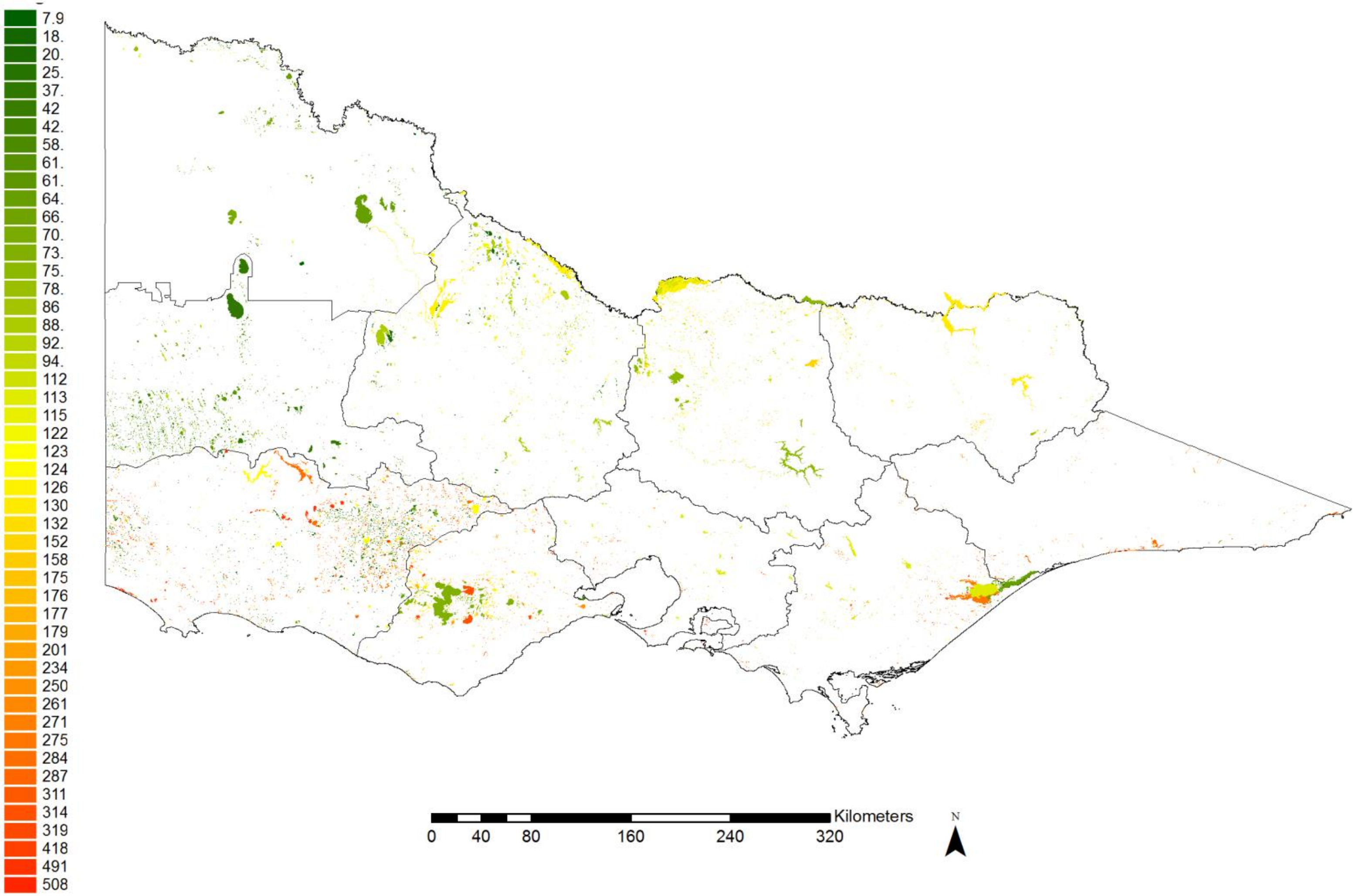


Figure 6. Wetland carbon hotspots in Victoria. Higher carbon stock values (to depth of refusal) are represented by red, and lower values by green

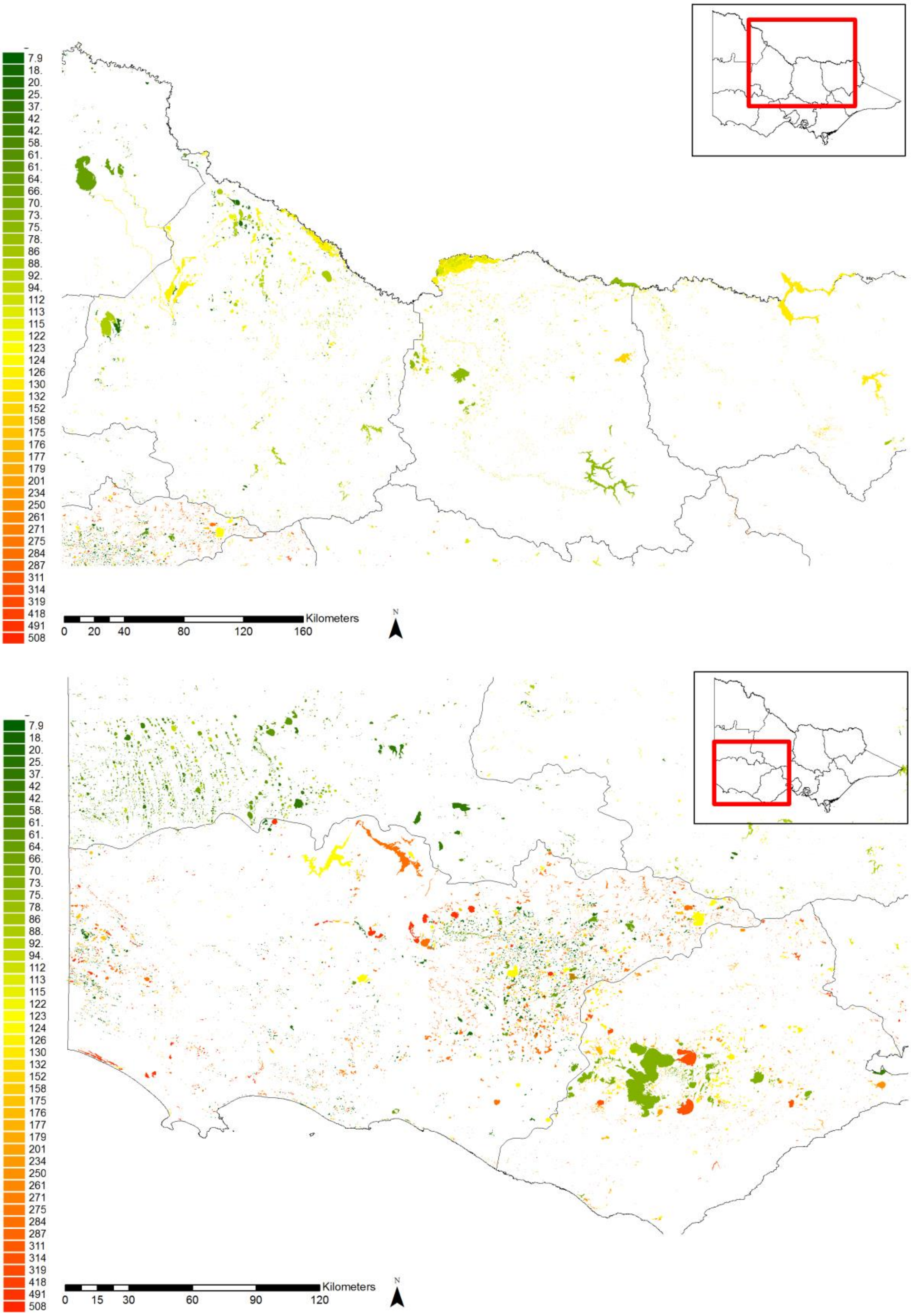
a)
b)


Figure 7. Wetland carbon hotspots in Victoria. Higher carbon stock values (to depth of refusal) are represented by red, and lower values by green **a)** The central Murray River region, which includes Goulburn Broken CMA and North Central CMA. **b)** Southwestern Victoria with Glenelg Hopkins CMA and Corangamite CMA's.

Aim 3. Estimated emissions from wetland losses since European settlement

Based on our carbon stock measurements, wetland ecosystems present at the time of European settlement that have since been lost had an estimated total carbon stock of over 82.5 million Mg CO_2 equivalents (Table 5). Forty-three percent of carbon stocks in these lost ecosystems were associated with permanent open freshwater wetland loss, while deep freshwater marshes and shallow freshwater marsh account for 22.7% and 22.5 % of carbon stocks, respectively. Looking at the impacts of disturbance down to the top meter of sediments, conservative, intermediate, and high estimates of emissions range between 22.5 million to 74.2 million Mg CO_2 equivalent (Table 5). Largest estimated carbon stock losses from deep freshwater marshes occurred in West Gippsland, with substantial losses of permanent open freshwater in Corangamite, totalling to almost 40% of the emissions resulting from wetland loss.

Table 5. Estimated sediment carbon emissions based on ecosystem loss since European settlement. CO_2 equivalent losses were calculated based off averages for each region, however for simplicity here this is presented by wetland type across all CMAs.

			CO_2 Equivalent loss		
Sites	**Area Lost (Ha)**	**Stock Mg C_{org} Ha^{-1} Avg.**	**27.25%**	**58.63%**	**90%**
Deep freshwater marsh	13,312	233	5,112,099	10,998,987	16,883,998
Freshwater meadow	24,749	126	2162666	4653104	7142749
Permanent open freshwater	71,525	113	9,752,089	20,982,202	32,208,735
Saline	5,872	64	381,500	820,819	1,259,998
Shallow freshwater marsh	31,595	201	5,059,179	10,885,126	16,709,216
State Total	**260,530**	**281**	22,467,533	48,340,238	74,204,696

Discussion

This report provides the most comprehensive assessment of carbon stocks and sequestration rates of inland wetlands in Australia to date. Victoria's wetlands are storing substantial amounts of carbon, with a total carbon stock of 68 million Mg C_{org} estimated for the depths sampled. This equates to a potential value of $AUD 6 billion. And the estimated carbon sequestration of Victoria's freshwater wetlands is 3,117,682 tonnes of CO_2 equivalents per year. This has a value of $AUD 76.74 million per year, equivalent to the CO_2 emissions of 176,538 Australians. At the same time, disturbance and loss of wetlands has the potential to release significant quantities of CO_2 back into the environment. Since European settlement, the loss of wetlands has released an estimated 22.5 million to 74.2 million Mg CO_2 equivalents, depending on the emission factor applied.

Assessing Victorian wetland carbon stocks and sequestration rates

There was significant variation in carbon stocks between wetland types and across CMA regions. Carbon stock accumulation typically depends on: 1) availability of carbon supply (whether externally-derived carbon travels into the wetland due to its low geomorphic setting in the landscape, or whether carbon is internally-derived from the deposits of plant material); 2) quality of carbon supply (less complex carbon forms are more easily decomposed, and therefore do not remain long in the soil profile); and 3) the conditions available to the decomposer community (the environment conditions both impact the rate of decomposition directly, and select for different microbial communities). All of these factors can contribute to explaining patterns observed at the study sites.

Permanent open freshwater wetlands (typically freshwater lakes with minimal fringing vegetation) had relatively low average carbon stocks compared to the other wetland types (Figure 4, Table 1). This is not surprising given the ecology of these systems. While permanent freshwater lakes can be sinks for catchment carbon, their hydrology means they may be relatively isolated from major waterways (such as the Murray), and fed only by small-scale runoff from their own catchment. In addition, as they are typically too deep to sustain emergent vegetation, there is little internally produced carbon to sequester. While these water bodies are important to the landscape for their other functions, our results appear to confirm other research that suggests these ecosystems are not particularly important for blue carbon sequestration.

Inland saline waterbodies are an interesting addition to our study. As indicated in Table 3, they make up a large proportion of Victoria's inland waterbodies, and are therefore critical to understand. While the carbon stocks are not particularly high, this is partly because most saline wetlands could not be sampled past 30 cm depth. If these stocks were to be extrapolated to 50 or 100 cm, this value would be significantly higher. While the estimates here suggest that, because of their large area, saline wetlands make important contributions to the whole stock of the state, it is important to note that all present measurements were made in vegetated areas, and it is unclear how carbon stocks and sequestration rates may differ in vegetated and unvegetated areas. Thus, further work is needed to clarify how the unvegetated components of inland saline wetlands (e.g. Lake Corangamite) contribute to carbon storage. While we have no data on sequestration rates in saline wetlands, rates are likely to be high due to the reduced decomposition fostered by more saline conditions. As saline areas also inhibit methanogenesis, such waterbodies also present an important comparison for future research into the greenhouse gas emissions of freshwater wetlands.

Freshwater meadows and shallow freshwater marshes were on average in the mid-range for wetland carbon stocks across the state. These wetlands are some of the most variable because they encompass such a large range of inundation regimes. While it is convenient to use these wetland categories in this study, future work should attempt to tease apart the relative contribution of hydrology (inundation source, frequency, interval, and volume, among other factors), and factors such as climate, geomorphology (elevation on the landscape), and vegetation (though the latter is often tied to hydrologic regime). Inundation regime impacts soil conditions contributing to decomposition rates, as well as the overlying carbon supply (aboveground vegetation). In permanently inundated sites, anaerobic conditions prevail, which reduces the rate of decomposition and enhances the storage of carbon. It is as yet unclear how varying wetting and drying regimes impact carbon storage rates, but this will be another important avenue for future research on this class of wetlands. In addition, periods of prolonged drying may result in loss of entire vegetation communities for periods of time.

Deep freshwater marshes contain large carbon stock, as well as cover a large area across the state. For this reason, these areas represent a key frontier for inland wetland carbon reserves. Deep freshwater marshes, while variable, tend to have several characteristics in common. These areas are flooded for a relatively long proportion of the year, and sustain dense vegetation year-round. Despite these commonalities, we still found the highest variation within this class. One explanation for this is that the Corrick and Norman classification scheme is not completely accurate across the state. The integrity of future state-wide research will rely on continuing to improve the state-wide wetland databases.

As expected, our study found the highest carbon stock values in alpine peatlands. Peat is terrestrial soil composed of at least 20% organic matter. Peatlands occur in areas with higher water inflow than outflow, or where there is a large supply of groundwater. Waterlogged soil produces the reduced, anaerobic conditions that inhibit activity of microbial decomposers, allowing carbon-rich, undecomposed plant matter to accumulate. Accumulation of plant detritus into peat can produce dams, which further modify hydrology to favour continuing peat formation. While it is not surprising that these systems had the highest stock, the results usefully validate the analysis methods used in this report. Alpine peatlands, while contributing the smallest area in Victoria, are ecologically critical carbon stocks, and also some of the most vulnerable to loss.

In this study, wetlands contained carbon stocks equivalent to (and often higher than) those reported for other freshwater wetlands in Australia (Webb 2002, Page and Dalal 2011, Whitaker et al. 2015). For the sub-tropical wetlands of Queensland, Bryant et al. (2008) reported average total carbon (%) values from 0.25 % to 25.45% in the top 10 cm of soil, with large variation between wetland types and regions. In comparison, the Victorian wetlands sampled show an even wider range of values, from 0.0007 to 52.31 %, with an average stock of 7.86 ± 0.31%. The Queensland study also encompassed wetlands across the state, which suggests that Victoria's diversity of climatic regions (semi-arid, temperate, coastal and alpine) and wetland types creates substantial variation. Understanding the factors driving this variability in carbon stocks is an important next step in the analysis of the data collected in this study.

Identifying carbon sequestration hotspots

Carbon stocks varied markedly across the ten Victorian regions, but all wetlands sampled represent valuable carbon sinks, providing both ecological and economic benefits (Table 4, Figure 7). McKenzie's Rd had the highest carbon stocks per hectare. Located within Won Wron state forest, McKenzie's Rd Swamp is relatively pristine, with limited vehicle access. While Long Swamp in Glenelg Hopkins CMA is more remote, the mixture of pine plantations to the north and a history of modified hydrology, highlights areas for improved management of this important wetland. Fortunately, a number of wetland rehabilitation efforts have recently taken place in Long Swamp to restore the natural hydrology. Tracking the improvement in carbon stocks with wetland restoration such as this is an important next step for wetland carbon research.

Lang Lang swamp is located near to what used to be the Koo Wee Rup swamp, which was drained since European settlement. This small wetland, is probably indicative of the wetlands that made up the Koo Wee Rup swamp complex. Boneo Swamp is also precariously placed in the landscape. Boneo Swamp is surrounded by urban development, golf courses, a sewage treatment plant, waste transfer station, is bisected by roads, and has a modified hydrology (Chinaman's Creek, which feeds the swamp, has been channelized).

Notably, the highest carbon sequestration values were often associated with sites located along some of the major rivers in Victoria (or closer to fluvial inputs), such as the Murray, Goulburn, and Yarra (Table 2). This is contrary to a study in Ohio, which found higher carbon sequestration rates in isolated, depressional wetlands (Bernal and Mitsch 2012). However, the age dating studies in Victoria have been predominantly conducted along riverine billabongs, so it is difficult to determine if this is a real pattern, or part of sampling bias. Additional data on carbon sequestration rates in isolated, depressional wetlands is needed to determine this pattern.

The carbon hotspot maps we provide are a useful tool to help managers easily identify wetlands with high carbon stocks. This will enable managers to prioritise, for protection or rehabilitation, those wetlands at greatest risk of disturbance through development, agriculture or altered hydrology. The carbon hotspot maps can also be overlain with GIS layers of other ecosystem values such as biodiversity and flood mitigation, to identify areas that may be protected for multiple ecosystem services. Assessing the opportunities for both protection and rehabilitation of wetlands, and the likely carbon offset value of such moves, is a vital next step if we are to move forward with carbon offset opportunities in Victorian inland wetlands (Figure 8).

Figure 8. a) Cattle grazing in wetlands can cause significant loss of blue carbon through **b)** pugging and disturbance of the soil. Large feral herbivores can also have impacts on wetlands and carbon, including **c)** horses. This can occur through **d)** the grazing activity on the wetland plants, and through soil disturbance via trampling. Wetland restoration activities can involve restoring natural hydrological flow. This may involve **e)** filling drains that were put in by early Europeans to keep water in the wetland (Image from http://natureglenelg.org.au/), and **f)** installing culverts to re-connect water flow that may have been disrupted by roads or other human structures.

Potential emissions from previous wetland degradation and loss

We estimate a loss of 22.5–74.2 million Mg CO_2 eq., or 0.022–0.074 Pg CO_2 eq., due to loss of wetlands since European settlement in Victoria. This is equivalent to the annual emissions of 1,248,196 – 4,122,483 people or 4,780,326 – 15,788,234 cars. It is important to note that these values are estimates only, and are based on current values reported in the international literature for how wetland loss influences carbon stocks. These values are quite high, given that loss of Indonesian mangroves has been estimated to have released 0.175 Pg CO_2 eq. into the atmosphere (Murdiyaso et al 2015). The high emissions from wetland loss in Victoria highlights the need to ensure sufficient protection of wetlands to avoid ongoing carbon emissions.

One way to guard against continuing carbon losses is by protecting wetlands that may be used for grazing or cropping. The impact of such activities are stark. For example, Sigua et al. (2009) measured a 96% reduction in soil organic carbon (%) when a wetland was converted to beef cattle pasture, while Meyer et al. (2008) estimated an 80% loss of soil carbon after roughly 40 years of soybean and corn cultivation. This conversion to agriculture likely promoted soil moisture fluctuations, which then stimulated decomposition and re-release of carbon (Sigua et al. 2009). Further research is needed to confirm the impact of conversion on Victorian inland wetlands in a controlled study.

It is here that wetland rehabilitation works may help to restore wetlands' carbon sequestration capacity. A recent study in the Murray Local Land Services region of New South Wales has demonstrated how wetland rehabilitation activities can increase the soil organic carbon stock: carbon stocks increased with time since protection (Carnell et al. 2016b). And globally, studies have shown that wetland rehabilitation increases the carbon storage capacity of previously degraded wetlands (Badiou et al. 2011). In a study of rehabilitated wetlands in the Canadian prairie pothole region, Badiou et al. (2011) estimated soil organic carbon stocks to 30 cm at 121, 165, and 205 Mg organic carbon ha^{-1} for newly re-habilitated (1–3 years), long-term rehabilitated (5–12 years), and reference wetlands, respectively.

This study and others (Meyer et al. 2008, Ballantine and Schneider 2009) suggests that we can make meaningful carbon offsets in inland wetlands through protection and rehabilitation measures (Erwin 2009). Various wetland rehabilitation projects are currently occurring across the state of Victoria (Bachman and Holland 2015, Goulburn Broken CMA pers. comm.), and in future, measuring the carbon offset benefit of these activities will provide important insights. With a number of methods for measuring carbon gains through management activities recently developed for wetlands (VCS 2014, Carnell et al. 2016a), management agencies are now well placed to undertake wetland protection and rehabilitation activities for the purpose of carbon offsetting.

Future research priorities

Below we outline the five key research steps to developing and implementing carbon offset opportunities in Victorian wetlands (Figure 9). The soil carbon measurements in this study represent one half of the net carbon budget for freshwater wetlands: while freshwater wetlands are important soil carbon stores, they are also the largest natural source of methane. Thus, to account for release of greenhouse gases from wetlands (namely methane (CH_4) and nitrous oxide (NO_2)), seasonal or ideally, continuous measurements of these greenhouse gases wetlands, across wet and dry cycles (a 1–3 year period) would enable us to build a more complete picture of carbon dioxide and methane dynamics in these wetlands (similar to Badiou et al. 2011). These data could be combined with those collected here on carbon stock and sequestration rates, to calculate the *net* carbon budget for such wetlands. This step should be a priority for ongoing work (Table 6).

To move forward with carbon offset initiatives in wetlands, we also need to better understand how wetland restoration activities influence carbon sequestration. While some preliminary work on carbon stocks in rehabilitated wetlands in the Murray Local Land Services region in NSW is promising (Carnell et al. 2016b), it is only through monitoring carbon sequestration rates before and after wetland rehabilitation that we can calculate the carbon offset from that activity. Carnell et al. (2016a) have developed a wetland carbon monitoring manual to track increases in carbon sequestration following wetland rehabilitation activities. The priority now is to implement these recommendations across a range of rehabilitated wetlands.

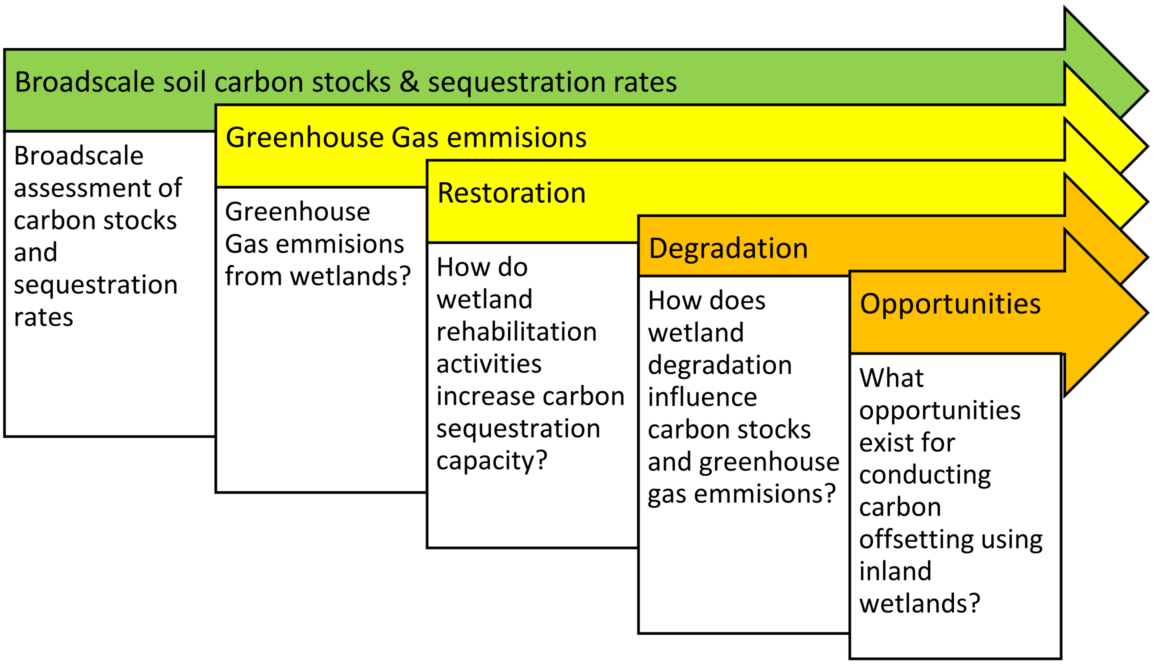


Figure 9. Steps for developing knowledge on wetlands' capacity to store carbon, and how different management activities can promote higher carbon storage. Steps in green have been completed, steps in yellow are soon to get underway (or have been completed in nearby areas), and steps in orange still need to be undertaken.

Table 6. Research portfolio questions and nominal ranking.

Research Questions	Funded? If not, rank
Q 1. What is the opportunity in Victoria to offset carbon emissions by restoration or protection of wetlands?	1
Q 2. How do different wetting and drying cycles in wetlands influence greenhouse gas emissions from wetlands? • Focus of recently successful ARC Linkage (LP160100061) with Blue Carbon Lab/Deakin University, Southern Cross University and Murray LLS in the semi-arid wetlands of Murray LLS region in NSW. • Katy Limpert from the Blue Carbon Lab will also be working on similar questions in Wimmera and North Central CMA's in Victoria for her PhD.	Funded in particular regions, not Victoria-wide
Q 3. Are particular plant communities or plant traits associated with higher carbon gains? • Current focus of a University of Melbourne and Blue Carbon Lab PhD project by Saras Windecker.	Mostly (Holsworth Wildlife Research Endowment)
Q 4. How do different wetland rehabilitation interventions influence soil accretion (carbon sequestration) rates over time?	2
Q 5. What is the effect of long-term protection and rehabilitation of wetlands on methane and carbon dioxide release?	3
Q 6. Does the inundation regime influence the response of wetlands to rehabilitation (ie. do more frequently wet sites increase in carbon sequestration capacity faster?)	4
Q 7. What is the effect (short-term and long-term) of livestock trampling on soil carbon stock and greenhouse release from wetlands?	5

Final remarks

This study provides the largest and most comprehensive carbon stock and sequestration rate measurements for any region in Australia. This is an important step to developing wetland carbon projects regionally, and given a growing carbon offset market, provides an added incentive for rehabilitating and protecting wetlands. With the Australian Federal Government recently announcing their intention to include wetlands in the National Greenhouse Gas Inventory, research into the carbon offset capacity of wetlands will continue to fill an important scientific and applied research knowledge gap.

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