Science of the Total Environment 730 (2020) 139067

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Forgotten peatlands of eastern Australia: An unaccounted carbon capture and storage system

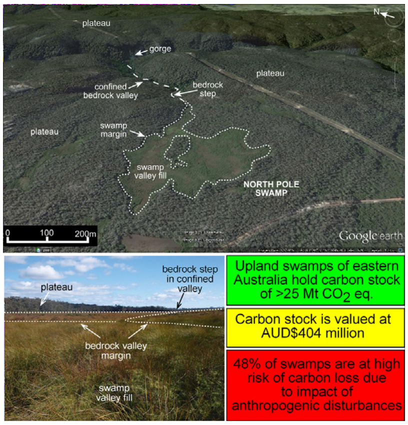
Kirsten L. Cowley, Kirstie A. Fryirs *

Department of Earth and Environmental Sciences, Macquarie University, North Ryde, NSW 2109, Australia

HIGHLIGHTS

- Temperate Highland Peat Swamps on Sandstone (THPSS) are poorly recognised.
- THPSS store over 25 Mt CO_2 eq. in two regions of Eastern Australia
- 50% of peatlands are at risk of impairment due to anthropogenic disturbance.
- Potential CO_2 emissions from high risk THPSS are 8.6 Mt CO_2 eq.
- Pricing stocks and emissions recognise THPSS as carbon capture and storage systems.

GRAPHICAL ABSTRACT



Upland swamps of eastern Australia hold carbon stock of >25 Mt CO_2 eq.

Carbon stock is valued at AUD$404 million

48% of swamps are at high risk of carbon loss due to impact of anthropogenic disturbances

ARTICLE INFO

Article history:
Received 6 March 2020
Received in revised form 22 April 2020
Accepted 26 April 2020
Available online 30 April 2020

Editor: Jay Gan

Keywords:
Carbon stocks
Carbon sequestration
Peatlands
Carbon emissions
Anthropogenic disturbance
Risk mapping

ABSTRACT

In a carbon-constrained world, global peatlands are vital carbon capture and storage systems. Here we calculate regional carbon stocks, sequestration rates and potential carbon emissions of Temperate Highland Peat Swamps on Sandstone (THPSS) found in low order headwater streams in eastern Australia. We find that total carbon stocks within THPSS in two regions are 25 Mt CO_2 eq. with annual carbon sequestration rates at 60.5 kt CO_2 eq. A risk assessment model, based on anthropogenic activities known to impair the carbon storage functions of THPSS is used to identify swamps most at risk of carbon loss. Potential CO_2 emissions from at risk swamps could be up to 8.6 Mt CO_2 eq. When carbon stock is valued at the current carbon abatement price of $\$AUD16.10\ t^{-1}$ CO_2 eq, the total value of THPSS is over AUD$404 million dollars (US$281 million). This makes a strong economic case for the implementation of sustainable swamp conservation and restoration activities.

---

* Corresponding author.
E-mail address: kirstie.fryirs@mq.edu.au (K.A. Fryirs).

https://doi.org/10.1016/j.scitotenv.2020.139067

1. Introduction

Peatlands are known to be effective carbon sinks. While they only cover 3% of the Earth's surface, they store the equivalent of 75% of atmospheric carbon (Garneau et al., 2014; Gorham, 1991; Yu, 2012;). However, globally many peatlands have been dewatered, degraded and destroyed by agricultural activities, mining and urbanisation (Carnell et al., 2018; Knox et al., 2015; Pemberton, 2005). These activities can transform peatlands from carbon storage systems to sources of carbon emissions to the atmosphere (Cowley et al., 2018; Danevčič et al., 2010; Eickenscheidt et al., 2015). Carbon sequestration within soils and coastal ecosystems has been identified as one important part of biological climate change mitigation and resilience (Duarte et al., 2013; Hiraishi et al., 2014; Lal, 2004; Serrano et al., 2019). By quantifying carbon stocks and sequestration rates of ecosystems at a regional scale and identifying peatlands that are at risk of impairment or loss, a value can be placed on peatland restoration and an incentive provided for peatland conservation (Carnell et al., 2018; Department of Agriculture, Water and the Environment, 2005).

Recent work on carbon stocks and sequestration rates of soils and biomass of vegetated coastal ecosystems (VCE) in Australia found that these ecosystems have sizable carbon stocks and sequestration rates, and CO_2 emissions from ecosystem loss can be considerable (Serrano et al., 2019). While other Australian peatlands such as Temperate Highland Peat Swamps on Sandstone (THPSS), located in the valley bottoms of low order headwater streams in Eastern Australia (Fig. 1a, b, c) are not as large in area as VCE, they do have substantial water and carbon storage capacities relative to their size. Most THPSS are located in the Sydney water supply catchment and act as water storage and filtering ecosystem service providers, supporting some 4.6 million people (Fig. 2). They occur in two main regions, the Blue Mountains 100 km west of Sydney and the Southern Highlands 100 km southwest of Sydney (Fig. 2a, b). However, these systems are threatened by anthropogenic disturbances such as urbanisation, underground mining, and climate change, putting at risk both the water and carbon storage capacity of these systems (Baird and Burgin, 2016; Cowley et al., 2016; Cowley et al., 2018; Department of Agriculture, Water and the Environment, 2005). Once impaired (i.e. channelised, dewatered or disturbed; Fig. 1d), THPSS transition from carbon sinks to carbon sources (Cowley et al., 2018).

The Intergovernmental Panel on Climate Change (IPCC) provides methodologies for compiling national inventories of annual greenhouse gases from direct land use and management activities occurring on impaired wetlands, drained soils and constructed wetlands (Hiraishi et al., 2014). While the guidelines are useful for calculating greenhouse gas emissions arising from anthropogenic activities within these ecosystems, they provide little guidance on how to calculate emissions from ecosystems already impaired from perturbations to biogeochemical cycling by indirect anthropogenic activities. World-wide, carbon exports and emissions from impaired swamps and peatlands are much higher than from intact swamps and peatlands, potentially reaching 2 Gt per annum (Joosten, 2009).

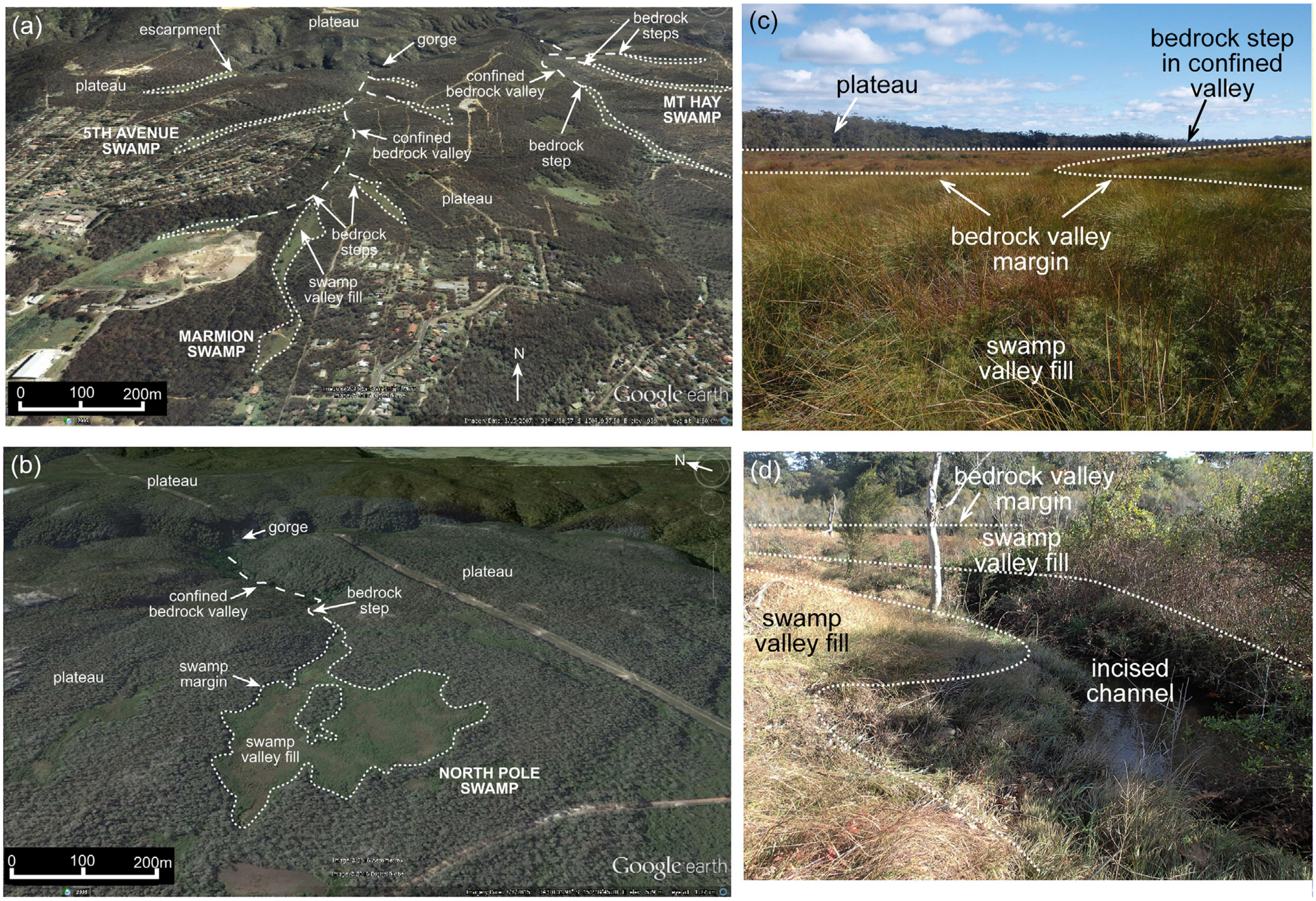


Fig. 1. THPSS are valley bottom swamps that occur in low order headwater streams upstream of the escarpment of the Great Dividing Range in Eastern Australia. (a) THPSS in the Blue Mountains region are often located close to anthropogenic influences associated with urbanisation. (b) THPSS in the Southern Highlands are often impacted by mining activities, particularly underground mining. (c) an intact THPSS in the Southern Highlands region (Photo: K. Fryirs). (d) an impaired, incised THPSS in the Blue Mountains region (Photo: K. Fryirs).

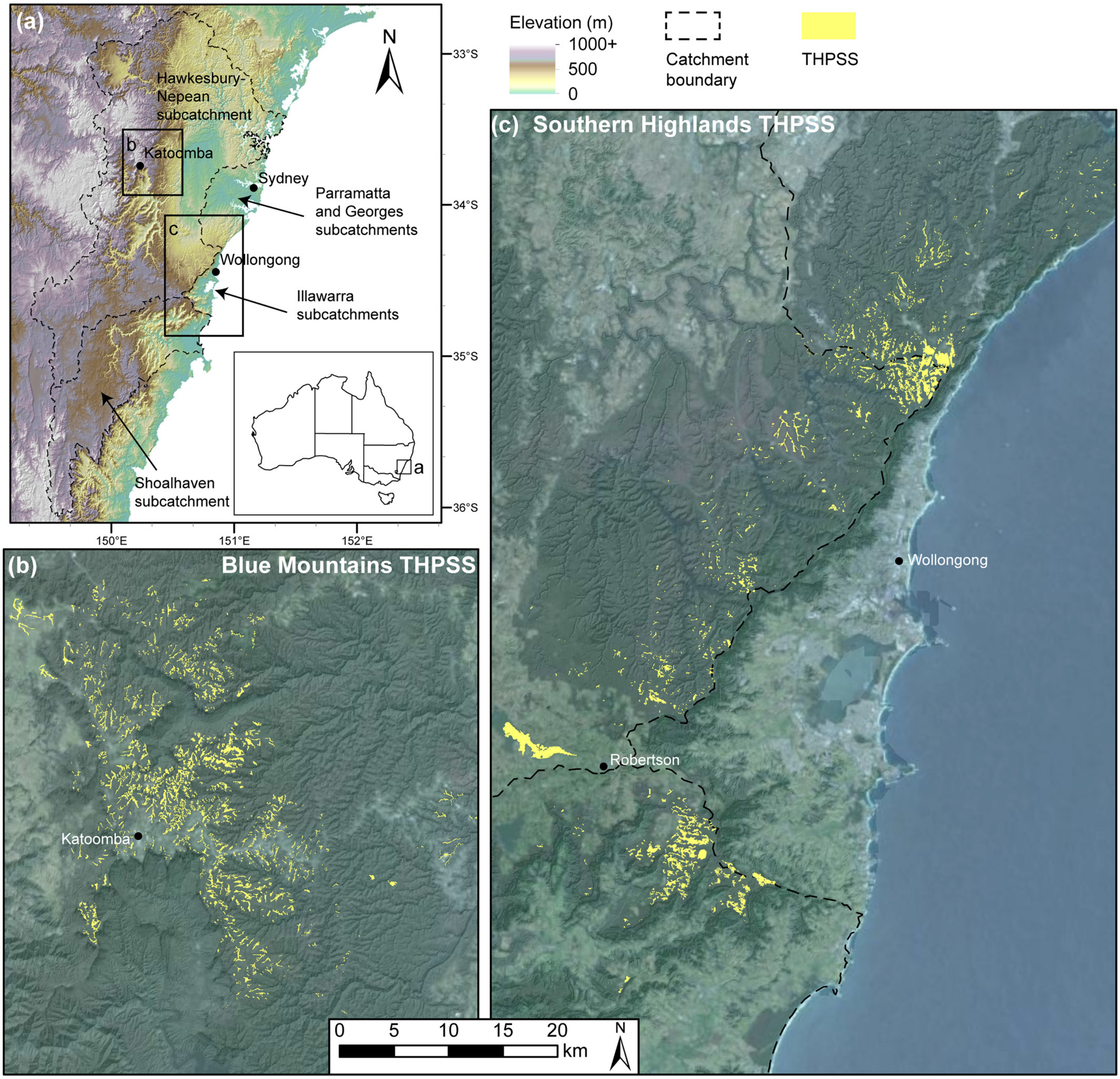


Fig. 2. Location of the Blue Mountains and Southern Highlands THPSS within the Sydney Basin and water supply area.

This paper has three aims;

1) to calculate carbon stock and sequestration rates of THPSS in two regions of Eastern Australia;
2) to identify and quantify the number of swamps at risk of loss or impairment due to anthropogenic disturbance;
3) to quantify the potential region-wide carbon emissions that may result from swamp degradation due to anthropogenic disturbance.

By converting carbon stock, sequestration rates and potential carbon emissions of THPSS to CO_2 equivalency (CO_2 eq.) and placing a carbon price on these, we make a case for appropriate recognition, conservation, management and rehabilitation of these important carbon capture and storage systems. Management of these carbon capture and storage systems is particularly relevant in mitigating anthropogenic climate change.

2. Methods

2.1. Data acquisition

Analysis of the geomorphic condition of intact and channelised swamp types uses the framework outlined in Fryirs et al. (2016) and Kohlhagen et al. (2013). Carbon stocks in the Blue Mountains were calculated using sediment analysis data from 13 THPSS documented in Cowley et al. (2016) and 15 Southern Highlands THPSS documented in Fryirs and Hose (2016) (see Supplementary Tables 1 and 2).

Radiocarbon ages (^{14}C) of four THPSS in the Blue Mountains and 10 THPSS in the Southern Highlands were sourced from Fryirs et al. (2014). All radiocarbon dates were calibrated to calendar years (see Fryirs et al., 2014 for complete methods). Bulk density and organic matter content (based on loss on ignition (LOI) analysis) for each sedimentary unit was obtained from Cowley et al., 2016 and Fryirs et al., 2014 (see Supplementary Tables 1 and 2).

The physical attributes of THPSS, such as surface area and total swamp area in the region were taken from the Open Access THPSS mapping database available at https://datasets.seed.nsw.gov.au/dataset/temperate-highland-peat-swamps-on-sandstone-thpss-vegetation-maps-vis-ids-4480-to-4485 and reported in Fryirs and Hose (2016) and Fryirs et al. (2019).

Data on anthropogenic disturbances for the Blue Mountains' swamps were acquired from Blue Mountains City Council and NSW Local Land Service shapefiles that include information on stormwater infrastructure, groundwater bores and degree of urbanisation. For the Southern Highlands, mining data were derived from WaterNSW shapefiles that describe mining leases, locations, area, mining methods, operating time and opening and closing dates.

2.2. Data analyses

Carbon stock (tC) for each study swamp was calculated using the carbon density approach as detailed in Yu et al., 2010 as:

$$C_{stock} = A \times CD \tag{1}$$

where **A** is swamp area in hectares and **CD** is carbon density in t C ha^{-1}. Carbon density was calculated for each sedimentary layer as:

$$CD_{density} = (BD \times D \times \%C_{org}) \tag{2}$$

where **BD** is the bulk density in g cm^{-3}, **D** is the thickness of each sedimentary layer in cm and **%C$_{org}$** is organic carbon calculated by using loss on ignition (LOI) and total organic carbon (TOC). Data from Cowley et al. (2016) was used to construct a TOC-LOI relationship using linear regression which was then applied to the remaining LOI datasets to more accurately constrain mean organic carbon (OC) percentages for both regions.

Carbon stock was converted to t CO$_2$ eq. by multiplying by 3.67 (known as the Greenhouse Gas Equivalency Factor; see Carnell et al. (2018)).

To derive an estimate of present-day carbon **sequestration rates**, carbon sequestration was calculated from the most recent Holocene accumulation rates from six swamps with dates between 85 yrs. BP and 693 yrs. BP. The calculation of carbon sequestration was modified from Page et al. (2004) and expressed as g C m^{-2} yr^{-1} using the following equation:

$$CS = (R \times 1000) \times \tilde{n} \times C \tag{3}$$

where **CS** is carbon sequestration in g C m^{-2} yr^{-1}, **R** is the sediment accumulation rate in mm yr^{-1} derived from depth (mm) divided by calibrated ^{14}C age, **$\tilde{N}$** is averaged dry bulk density for each sedimentary layer within the date range in g cm^{-3} and **C** is organic carbon calculated from loss on ignition values as above, expressed as g C g^{-1} dry weight. Carbon dioxide (CO$_2$) equivalency (eq.) was calculated by converting sequestration rates per swamp to t CO$_2$eq. by multiplying the accumulation rate by swamp area, converting to t C yr^{-1} and multiplying by the Greenhouse Gas Equivalency Factor of 3.67 (see Carnell et al., 2018).

Anthropogenic risk maps were developed to quantify potential carbon emissions resulting from swamp degradation caused by anthropogenic disturbances. Fryirs et al. (2016) identified anthropogenic disturbances for Blue Mountains swamps as the amount of impervious surface area in the catchment, distance to stormwater infrastructure, number of stormwater connection points in a swamp, and distance to groundwater bores. A numerical risk rating was applied to these anthropogenic threats based on thresholds in Tables 6–9 in Fryirs et al. (2016) (Table 1). Anthropogenic disturbances for the Southern Highlands include potential impacts from mining activities in the region, determined as distance to closest mine boundary, mining method (the bord and pillar method of extraction is considered to have less impact on groundwater fed ecosystems than the longwall method (Booth, 2006; Krogh, 2007; State of New South Wales, 2008)), time since mine was operational (based on mine closure date) and years of mine operation. For the anthropogenic threats in the Blue Mountains, numerical risk ratings were applied based on thresholds derived for each disturbance type (Table 1) (see Fryirs et al. (2016) and Kohlhagen et al. (2013) for condition assessment method). The numerical values for each disturbance type were then summed for each swamp and the total categorised according to five anthropogenic risk ratings; low, low-medium, medium, medium-high and high.

Potential carbon loss from swamp degradation and loss was calculated for swamps classified as medium, medium-high and high risk from anthropogenic activities. Carnell et al. (2018) and Siikamäki et al. (2013) used carbon loss rates of 90%, 59% and 27% derived from Murray et al. (2011) and Donato et al. (2011) to delineate upper, intermediate and lower estimates of carbon demineralisation. Here, we use these estimates and apply them to high, medium-high and medium swamps respectively to calculate potential emissions by multiplying the losses by the Greenhouse Gas Equivalency Factor of 3.67. Potential losses were calculated only for swamps deemed at medium risk and higher because previous work has identifying a condition threshold whereby swamps deemed to be in moderate or poorer condition require significantly more intervention to return to good condition (Chessman et al., 2006; Fryirs et al., 2014).

Table 1
Anthropogenic risk rating scores for swamps in the Blue Mountains and Southern Highlands.

Blue Mountains						
Impervious surface area in swamp catchment	<10%	10–40%	40–70%	70–100%		
Score	0	1	2	3		
Distance to groundwater bores (m)	>2000	<2000	<1500	<1000	<500	
Score	0	1	2	3	4	
Number of stormwater outlets in swamps	=0	=1	>1	>5	>6	>10
Score	0	1	2	3	4	5
Distance to stormwater outlets	>2000	<2000	<1500	<1000	<500	
Score	0	1	2	3	4	
Southern Highlands						
Distance to mine boundary (m)	>1000	<1000	<500	<200	<100	=0
Score	0	1	2	3	4	5
Mining method	No mining within 1000 m	Bord & Pillar	Longwall			
Score	0	1	2			
Time since mine was operational	No mining within 1000 m	>50	>30	>20	>5	Operational
Score	0	1	2	3	4	5
Operating time (years)	No mining within 1000 m	1–30	31–60	61–100	101–130	>130
Score	0	1	2	3	4	5

The carbon stock, sequestration and loss datasets were joined to the swamp attributes tables in ARCGIS 10.4 to calculate the carbon budgets of all mapped THPSS in the Blue Mountains and Southern Highlands regions.

3. Results

Total carbon stocks for THPSS across the two regions are over 6.8 Mt. C with a CO_2 equivalency of over 25 Mt. The Southern Highlands swamps hold 3.6 Mt. C while Blue Mountains swamps hold a total of 3.3 Mt. C with a CO_2 equivalency of over 13 Mt. and 12 Mt., respectively (Table 2). Mean carbon density per hectare in each region is 805 t ha^{-1} for the Blue Mountains swamps and 811 t ha^{-1} for the Southern Highlands swamps (Table 2).

Carbon sequestration rates derived from late Holocene ages within the study swamps in each region were measurably different,with a mean sequestration rate of 289 g C m^{-2} yr^{-1} for the Southern Highlands swamps and 93 g C m^{-2} yr^{-1} for Blue Mountains swamps with total carbon sequestration rates estimated at 46.4 kt yr^{-1} CO_2 eq. and 14.1 kt yr^{-1} CO_2 eq. respectively (Table 2). This makes an annual carbon sequestration total for THPSS in these regions of 60.5 kt CO_2 eq. (Table 2).

Forty-eight percent or 769 swamps in the Blue Mountains and 47% or 590 swamps in the Southern Highlands are classified as being at medium to high risk of impairment due to anthropogenic disturbance (Fig. 3a, b). Most of these swamps are located on the urban fringe in the Blue Mountains or where underground mining occurs in the Southern Highlands (Fig. 3c, d). When the three carbon loss rates (27%, 59% and 90%) are used to calculate potential CO_2 emissions from the medium, med-high and high risk swamps respectively, potential total emissions from both regions range from 372.8 kt CO_2 eq. for swamps classified as medium risk (27% loss) to 6.5 Mt CO_2 eq. for swamps classified as high risk (90% loss) and 8.6 Mt. of CO_2 eq. for all swamps at medium, medium-high and high risk (Table 3).

Potential emissions from swamps in both regions are highest for those at high risk (90% carbon loss rate) at 4.5 Mt CO_2 eq. and 1.9 Mt CO_2 eq. for high risk Southern Highlands and Blue Mountains swamps, respectively (Table 3). Some of the larger Blue Mountains swamps that are under threat could potentially lose up to 104 kt CO_2 eq. under these different carbon loss rates (noted with asterisk in Fig. 3c) while for Southern Highlands high risk swamps could potentially lose up to 487 kt CO_2 eq. (noted with asterisk in Fig. 3d).

4. Discussion

For the first time, we have provided region-wide estimates of carbon stock, sequestration rates and potential loss for the forgotten peatlands of Eastern Australia – the Temperate Highland Peat Swamps on Sandstone (THPSS). The total carbon stock of THPSS in the Blue Mountains and Southern Highlands regions are almost double that of the well-recognised and studied peatlands in the Australian Alps, despite THPSS occupying a similar area (Hope and Nanson, 2015). THPSS carbon stocks per hectare are almost eight times that of the open freshwater wetlands and almost three times that of alpine wetlands documented in the state of Victoria (Carnell et al., 2018). Therefore, THPSS should also be recognised as a nationally important carbon sink. Sequestration rates of THPSS also compare well with that of other global peatlands that sequester between 20 and 230 g C m^{-2} yr^{-1} (Belyea and Malmer, 2004; Heathwaite, 1993; Hope and Nanson, 2015). This makes THPSS one of the regions' most important terrestrial carbon sequestration systems.

When the carbon stocks of THPSS in both regions are calculated in terms of per capita annual CO_2 emissions, they hold almost as much carbon as the annual CO_2 emissions of 28% of Sydney's population, based on a per capita CO_2 emission rate of 17.2 t yr^{-1} (Janssens-Maenhout et al., 2017). Annual carbon sequestration rates are comparable to the annual CO_2 emissions of 3515 people. If the carbon stocks held within THPSS were valued in terms of a carbon price, then based on the Australian Government's emissions reduction fund spot carbon abatement price for the end of the third quarter of 2019 of $AUD16.10 ton CO_2 equivalent (Clean Energy Regulator, 2019), this would equate to a total value of almost AUD$210 million for Southern Highlands swamps and over AUD$195 million for the Blue Mountains swamps, a total of almost AUD$404 million dollars (or over US$281 million, €253 million, £216 million, as of December 2019). The capture and storage of carbon in the biosphere and lithosphere are considered amongst the most efficient and effective ways of mitigating anthropogenic CO_2 emissions (Lewis et al., 2019; Villa and Bernal, 2018). The IPCC 2013 Wetland Supplement (Hiraishi et al., 2014) outlines methodologies for quantifying anthropogenic GHG emissions from peatlands that are already actively managed, either in terms of agricultural usage or as part of restoration practice. However, the Wetland Supplement does not cover peatland systems that are subject to indirect catchment scale anthropogenic activities such as mining or urbanisation. As shown here and elsewhere, CO_2 emissions from impaired carbon storage systems can be significant. In the case of Australian vegetated coastal ecosystems, impairment and loss could increase Australian annual emissions from land use change by around 20%, and in the case of tropical peatlands in southeast Asia impairment and loss could increase global greenhouse gas emissions by up to 3.1% (Hooijer et al., 2010; Page and Dalal, 2011; Serrano et al., 2019). Wijedasa et al. (2018) found that 35% of peatland conversion to agriculture in Southeast Asia resulted in emissions of 1.46–6.43 Gt CO_2 eq. between 1990 and 2010. Permafrost thaw in peatlands has been linked to significant positive emissions feedback loops with serious implications for fossil fuel emissions budgets aimed at constraining global temperatures to 1.5 °C (Comyn-Platt et al., 2018).

Bonn et al. (2014) demonstrated that restored or re-wetted peatlands are net GHG sinks in the order of 5 to 31 t CO_2-eq ha^{-1} yr^{-1}. Climate change mitigation policy that includes accounting for potential carbon emissions from at-risk biological carbon sinks has not been developed in any meaningful way (Howard et al., 2017; Joosten, 2009; Page and Dalal, 2011). Currently in Australia, carbon emissions mitigation projects are funded from the Emissions Reduction Fund that provides Australian Carbon Credit Units (Clean Energy Regulator, 2019; Department of Environment and Energy, 2019). However, to date we know of no peatland or THPSS restoration projects that are funded from this program. The prime focus of current and past restoration programs for THPSS has been to improve biodiversity values and not for carbon emissions mitigation (Hensen and Mahony, 2010). By assessing THPSS in terms of potential carbon loss and using the current carbon abatement spot price of AUD$16.10 ton CO_2 equivalent, almost AUD $140 million (almost US$88 million) could be made available for the protection and restoration of swamps deemed at medium, medium-high and high risk in the Blue Mountains and Southern Highlands regions alone. Carbon credit units could also apply to annual sequestration rates. If the carbon abatement price were applied to the annual sequestration rate of THPSS in the two regions, around AUD$973,413 per year

Table 2
Carbon stocks and sequestration rates.

	Southern Highlands	Blue Mountains	Total
Mean C density (t ha^{-1})	811 (±482)	805 (±221)	NA
Total swamp area (ha)	4376	4108	8483
Total C stocks (t)	3,547,744	3,304,546	6,852,290
CO^2 eq. (t)	13,020,219	12,127,684	25,147,903
Carbon valuation of C stock ($) at $16.10 t^{-1}	209,625,525	195,255,714	404,881,239
Mean C sequestration (g C m^{-2} yr^{-1})	289 (±217)	93 (±24)	NA
Carbon sequestration rate per year CO^2 eq. (t)	46,400	14,060	60,461
Carbon valuation of C sequestration ($) at $16.10 t^{-1}	747,037	226,377	973,413

Standard deviation in brackets where relevant.

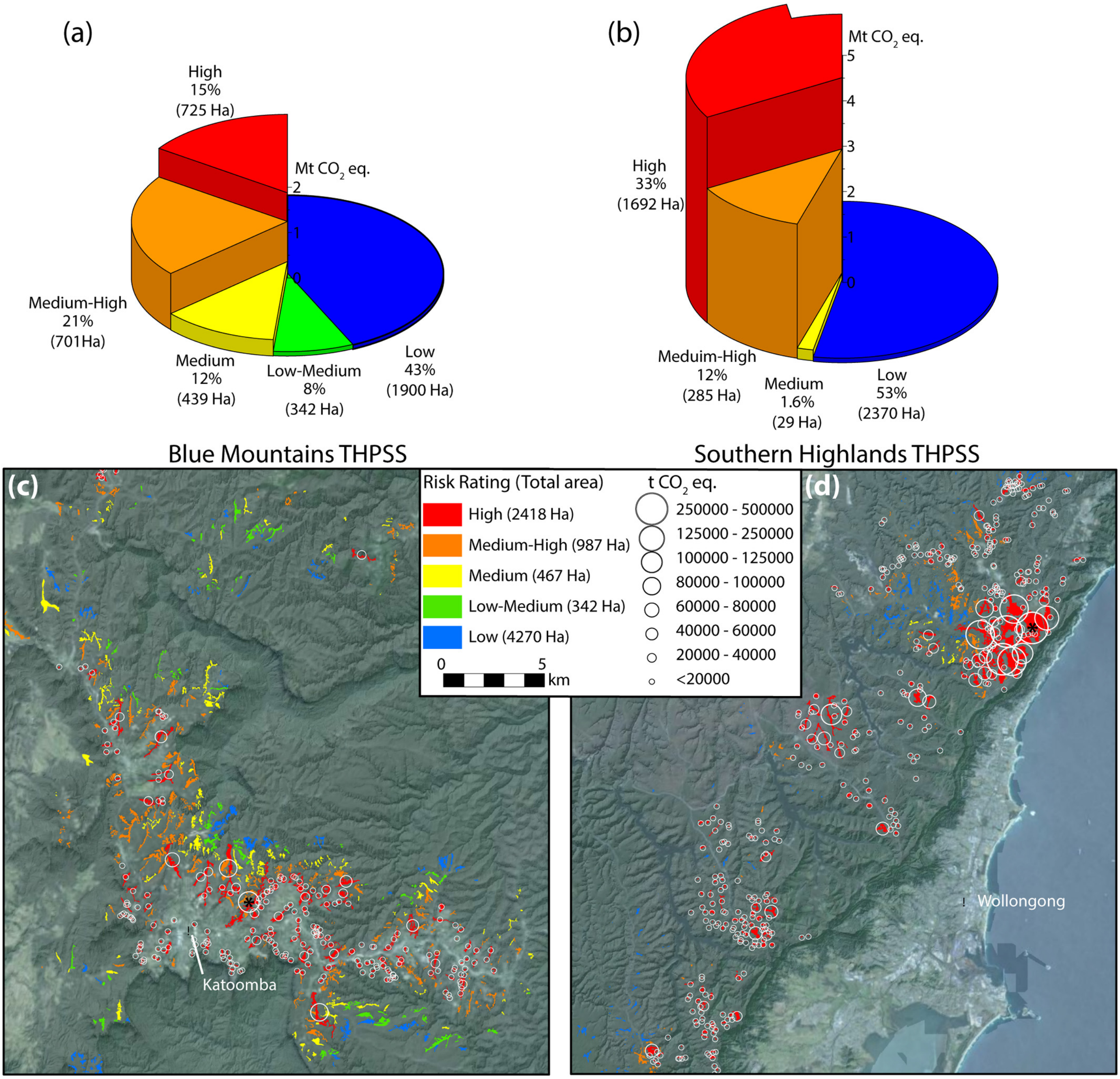


Fig. 3. Percentage, area and carbon stocks (in Mt CO$_2$ eq.) of swamps at risk from anthropogenic disturbance for (a) Blue Mountains and (b) Southern Highlands. Anthropogenic risk maps and potential carbon emissions for swamps classified at high risk with the potential for 90% carbon loss for (c) Blue Mountains and (d) Southern Highlands.

Table 3
Potential carbon loss (CO$_2$ eq.) for three loss rates applied to medium, medium-high- and high-risk swamps.

	Southern Highlands	Blue Mountains	Total
Total 27% C loss for swamps at medium risk (t CO$_2$ eq.)	23,129	349,700	372,829
Total area loss at 27% (Ha)	7.8	119	127
Total 59% C loss for swamps at medium-high risk (t CO$_2$ eq.)	500,675	1,221,847	1,722,522
Total area loss at 59% (Ha)	168	414	582
Total 90% C loss for swamps at high risk (t CO$_2$ eq.)	4,531,647	1,927,828	6,459,475
Total area loss at 90% (Ha)	1523	653	2176
TOTAL C loss (t CO$_2$ eq.)	5,055,451	3,499,375	8,554,826
TOTAL loss (Ha)	1699	1186	2885

(US$676,565) could be made available. This makes a strong economic case for the conservation and management of these important carbon capture and storage systems in the face of climate change.

For the practical application of pricing mechanisms for the funding of conservation and rehabilitation, a swamp-by-swamp assessment of anthropogenic risks as well as potential carbon losses is required. For swamps in the Blue Mountains and Southern Highlands this has been provided as risk maps like those in Fig. 3. Given that this analysis is available in an interactive ArcGIS environment, agencies are able to use this tool in planning and management activities to identify swamps that would return the largest carbon emissions reduction for the restoration investment dollar.

Although we conclude that conservation and rehabilitation can maintain and enhance carbon capture and storage in THPSS, further research is required to model and quantify how changes in climate (rainfall and temperature) will affect swamp hydrology, organic matter input and decomposition, and therefore the ability of these peatlands to continue to provide such functions into the future (Badiou et al., 2011).

5. Conclusions

Carbon storage remains the most efficient method by which to mitigate anthropogenic greenhouse gas emissions to the atmosphere. This study has found that THPSS in just two regions of Eastern Australia store in the order of 25Mt within relatively shallow peat sediments, or the equivalent of 28% of the annual CO_2 emissions of the population of Sydney. Despite their significance as carbon capture and storage systems, these peatlands are at risk from anthropogenic activities such as mining and urbanisation. Once peatlands become degraded, they are very likely to become a source rather than a sink of greenhouse gas emissions to the atmosphere. If a pricing mechanism were applied to potential CO_2 emissions from at-risk THPSS, then these peatlands could be valued appropriately for their carbon capture and storage properties, and their conservation and rehabilitation recognised as part of the mix of mitigation measures for Australia's rising anthropogenic greenhouse gas emissions.

CRediT authorship contribution statement

Kirsten L. Cowley: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Kirstie A. Fryirs:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project was supported by an Australian Research Council Linkage grant (LP130100120) awarded to KF. Fieldwork was approved under NSW National Parks and Wildlife Service Scientific License No. SL101129, a Sydney Catchment Authority License (D2014/69166) and with permission of the Blue Mountains City Council. We thank Rory Williams for drafting some of the figures.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139067.

References

Badiou, P., McDougal, R., Pennock, D., Clark, B., 2011. Greenhouse gas emissions and carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Wetl. Ecol. Manag. 19 (3), 237–256. https://doi.org/10.1007/s11273-011-9214-6.

Baird, I.R., Burgin, S., 2016. Conservation of a groundwater-dependent mire-dwelling dragonfly: implications of multiple threatening processes. J. Insect Conserv. 20 (2), 165–178. https://doi.org/10.1007/s10841-016-9852-3.

Belyea, L.R., Malmer, N., 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. Glob. Chang. Biol. 10 (7), 1043–1052. https://doi.org/10.1111/j.1529-8817.2003.00783.x.

Bonn, A., Reed, M.S., Evans, C.D., Joosten, H., Bain, C., Farmer, J., Emmer, I., Couwenberg, J., Moxey, A., Artz, R., Tanneberger, F., 2014. Investing in nature: developing ecosystem service markets for peatland restoration. Ecosystem Services 9, 54–65. https://doi.org/10.1016/j.ecoser.2014.06.011.

Booth, C.J., 2006. Groundwater as an environmental constraint of longwall coal mining. Environ. Geol. 49 (6), 796–803. https://doi.org/10.1007/s00254-006-0173-9.

Carnell, P.E., Windecker, S.M., Brenker, M., Baldock, J., Masque, P., Brunt, K., Macreadie, P.I., 2018. Carbon stocks, sequestration, and emissions of wetlands in south eastern Australia. Glob. Chang. Biol. 24 (9), 4173–4184. https://doi.org/10.1111/gcb.14319.

Chessman, B.C., Fryirs, K.A., Brierley, G.J., 2006. Linking geomorphic character, behaviour and condition to fluvial biodiversity: implications for river management. Aquat. Conserv. Mar. Freshwat. Ecosyst. 16 (3), 267–288. https://doi.org/10.1002/aqc.724.

Clean Energy Regulator, 2019. Quarterly carbonmarket report September quarter 2019. ACT Commonwealth of Australia, Canberra Retrievedfrom. http://www.cleanenergyregulator.gov.au/csf/Pages/quarterly-carbon-market-report.html.

Comyn-Platt, E., Hayman, G., Huntingford, C., Chadburn, S.E., Burke, E.J., Harper, A.B., Collins, W.J., Webber, C.P., Powell, T., Cox, P.M., Gedney, N., 2018. Carbon budgets for 1.5 and 2 C targets lowered by natural wetland and permafrost feedbacks. Nat. Geosci. 11 (8), 568–573. https://doi.org/10.1038/s41561-018-0174-9.

Cowley, K.L., Fryirs, K.A., Hose, G.C., 2016. Identifying key sedimentary indicators of geomorphic structure and function of upland swamps in the Blue Mountains for use in condition assessment and monitoring. Catena 147, 564–577. https://doi.org/10.1016/j.catena.2016.08.016.

Cowley, K., Looman, A., Maher, D.T., Fryirs, K., 2018. Geomorphic controls on fluvial carbon exports and emissions from upland swamps in eastern Australia. Sci. Total Environ. 618, 765–776. https://doi.org/10.1016/j.scitotenv.2017.08.133.

Danevčič, T., Mandic-Mulec, I., Stres, B., Stopar, D., Hacin, J., 2010. Emissions of CO_2, CH_4 and N_2O from Southern European peatlands. Soil Biol. Biochem. 42 (9), 1437–1446. https://doi.org/10.1016/j.soilbio.2010.05.004.

Department of Agriculture, Water and the Environment, 2005. Temperate highland peat swamps on sandstone. Australian Government, Canberra. Retrieved from. http://www.environment.gov.au/node/14561.

Department of Environment & Energy, 2019. Climate Solutions Fund - Emissions Reduction Fund, Australian Government. Retrieved from. https://www.environment.gov.au/climate-change/government/emissions-reduction-fund.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4 (5), 293–297. https://doi.org/10.1038/ngeo1123.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Chang. 3 (11), 961–968. https://doi.org/10.1038/nclimate1970.

Eickenscheidt, T., Heinichen, J., Drösler, M., 2015. The greenhouse gas balance of a drained fen peatland is mainly controlled by land-use rather than soil organic carbon content. Biogeosciences 12 (17), 5161–5184. https://doi:10.5194/bg-12-5161-2015.

Fryirs, K., Hose, G., 2016. The spatial distribution and physical characteristics of temperate highland peat swamps on sandstone (THPSS). Ecol. Manag. Restor. Retrieved from. https://site.emrprojectsummaries.org/2016/04/20/the-spatial-distribution-and-physical-characteristics-of-temperate-highland-peat-swamps-on-sandstone-thpss/.

Fryirs, K., Freidman, B., Williams, R., Jacobsen, G., 2014. Peatlands in eastern Australia? Sedimentology and age structure of temperate highland peat swamps on sandstone (THPSS) in the Southern Highlands and Blue Mountains of NSW, Australia. The Holocene 24 (11), 1527–1538. https://doi.org/10.1177/2F0959683614544064.

Fryirs, K.A., Cowley, K., Hose, G.C., 2016. Intrinsic and extrinsic controls on the geomorphic condition of upland swamps in Eastern NSW. Catena 137, 100–112. https://doi.org/10.1016/j.catena.2015.09.002.

Fryirs, K.A., Farebrother, W., Hose, G.C., 2019. Understanding the spatial distribution and physical attributes of upland swamps in the Sydney Basin as a template for their conservation and management. Aust. Geogr. 50 (1), 91–110. https://doi.org/10.1080/00049182.2018.1449710.

Garneau, M., van Bellen, S., Magnan, G., Beaulieu-Audy, V., Lamarre, A., Asnong, H., 2014. Holocene carbon dynamics of boreal and subarctic peatlands from Québec, Canada. The Holocene 24 (9), 1043–1053. https://doi.org/10.1177/0959683614538076.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1 (2), 182–195. https://doi.org/10.2307/1941811.

Heathwaite, A.L., 1993. Disappearing peat-regenerating peat? The impact of climate change on British peatlands. Geogr. J., 203–208 https://doi.org/10.2307/3451411. https://www.jstor.org/stable/3451411.

Hensen, M., Mahony, E., 2010. Reversing drivers of degradation in Blue Mountains and Newnes Plateau Shrub Swamp endangered ecological communities. Australasian Plant Conservation: Journal of the Australian Network for Plant Conservation 18 (4), 5.

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G., 2014. 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. IPCC, Switzerlandhttp://www.ipcc-nggip.iges.or.jp/.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H., Jauhiainen, J., 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences 7 (5), 1505–1514. https://doi https://doi.org/10.5194/bg-7-1505-2010.

Hope, G.S., Nanson, R.A., 2015. Peatland carbon stores and fluxes in the Snowy Mountains, New South Wales, Australia. Mires and Peat 15, 1–23.

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., ... Simpson, S., 2017. Clarifying the role of coastal and marine systems in climate mitigation. Frontiers in Ecology and the Environment 15 (1), 42–50. https://doi.org/10.1002/fee.1451.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Olivier, J.G., Peters, J.A.H.W., Schure, K.M., 2017. Fossil CO_2 & GHG Emissions of All World Countries. 107877. Luxembourg: Publications Office of the European Union.

Joosten, H., 2009. The Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in All Countries of the World. Wetlands International, Wageningen, Netherlands, p. 35.

Knox, S.H., Sturtevant, C., Matthes, J.H., Koteen, L., Verfaillie, J., Baldocchi, D., 2015. Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO_2 and CH4) fluxes in the Sacramento-San Joaquin Delta. Glob. Chang. Biol. 21 (2), 750–765. https://doi.org/10.1111/gcb.12745.

Kohlhagen, T., Fryirs, K., Semple, A.L., 2013. Highlighting the need and potential for use of interdisciplinary science in adaptive environmental management: the case of endangered upland swamps in the Blue Mountains, NSW, Australia. Geogr. Res. 51 (4), 439–453. https://doi.org/10.1111/1745-5871.12029.

Krogh, M., 2007. Management of longwall coal mining impacts in Sydney's southern drinking water catchments. Australasian Journal of Environmental Management 14 (3), 155–165. https://doi.org/10.1080/14486563.2007.10648713.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123 (1–2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032.

Lewis, S.L., Wheeler, C.E., Mitchard, E.T., Koch, A., 2019. Restoring natural forests is the best way to remove atmospheric carbon. Nature 568, 25–28. https://doi.org/10.1038/d41586-019-01026-8.

Murray, B.C., Pendleton, L., Jenkins, W.A., Sifleet, S., 2011. Green Payments for Blue Carbon: Economic Incentives for Protecting Threatened Coastal Habitats. Nicholas Institute for Environmental Policy Solutions, Durham, USA, p. 42. https://nicholasinstitute.duke.edu/environment/publications/naturalresources/blue-carbon-report.

Page, K.L., Dalal, R.C., 2011. Contribution of natural and drained wetland systems to carbon stocks, CO_2, N_2O, and CH_4 fluxes: an Australian perspective. Soil Research 49 (5), 377–388. https://doi.org/10.1071/SR11024.

Page, S.E., Wűst, R.A.J., Weiss, D., Rieley, J.O., Shotyk, W., Limin, S.H., 2004. A record of late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. J. Quat. Sci. 19 (7), 625–635. https://doi.org/10.1002/jqs.884.

Pemberton, M., 2005. Australian peatlands: a brief consideration of their origin, distribution, natural values and threats. J. R. Soc. West. Aust. 88, 81.

Serrano, O., Lovelock, C.E., Atwood, T.B., Macreadie, P.I., Canto, R., Phinn, S., ... Carnell, P., 2019. Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. Nature Communications 10 (1), 1–10. https://doi.org/10.1038/s41467-019-12176-8.

Siikamäki, J., Sanchirico, J.N., Jardine, S., McLaughlin, D., Morris, D., 2013. Blue carbon: coastal ecosystems, their carbon storage, and potential for reducing emissions. Environ. Sci. Policy Sustain. Dev. 55 (6), 14–29. https://doi.org/10.1080/00139157.2013.843981.

State of New South Wales, 2008. Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield: Strategic Review. NSW Department of Planning, Sydney, NSW.

Villa, J.A., Bernal, B., 2018. Carbon sequestration in wetlands, from science to practice: an overview of the biogeochemical process, measurement methods, and policy framework. Ecol. Eng. 114, 115–128. https://doi.org/10.1016/j.ecoleng.2017.06.037.

Wijedasa, L.S., Sloan, S., Page, S.E., Clements, G.R., Lupascu, M., Evans, T.A., 2018. Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes. Glob. Chang. Biol. 24 (10), 4598–4613. https://doi.org/10.1111/gcb.14340.

Yu, Z.C., 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences 9 (10), 4071. https://doi.org/10.5194/bg-9-4071-2012.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J., 2010. Global peatland dynamics since the Last Glacial Maximum. Geophys. Res. Lett. 37 (13). https://doi.org/10.1029/2010GL043584.