Dendrobium Extension Project, New South Wales

Expert report: Dr Tanya Mason

Requesting agency: EDO / Protect Our Water Alliance

Date of request: 24th November 2020

Date of submission: 14th December 2020

Background: I am a plant ecologist and Research Fellow at UNSW. My CV is attached. I have worked extensively on the upland swamps within Dharawal National Park, to the north of the proposed Dendrobium Extension Project area. I have also undertaken a monitoring project researching the effects of underground mining on swamp vegetation in the Avon and Cordeaux catchment areas. My research study sites include swamps above longwalls of Dendrobium Area 3B.

As author of this expert report, I acknowledge that I have read and agree to comply with Part 31 Division 2 of the Uniform Civil Procedure Rules 2005 (NSW) and the Expert Witness Code of Conduct.

Summary: From the available documentation and my ecological understanding of Coastal Upland Swamp community dynamics, Upland Swamps will be significantly affected by the proposed underground mining disturbance. Longwall development results in subsidence disturbance which affects surface and groundwater distributions. Reversal of flow, draining of aquifers, surface fracturing and declines in groundwater levels, along with creation of knick points and valley closures will reduce water availability in the plant root zone. Drying trends may then affect swamp vegetation distributions and fire regimes in the medium to long-term.

Persistent mining-related decline in hydrological function of upland swamps has implications for the sustainable supply of potable water to Australia's largest city. Sydney's major water storage dams have upland swamps in their catchments that attenuate stream flows, sustain flows in dry periods and regulate water quality. Transition of upland swamp communities to terrestrial communities will adversely affect water regulation and filtration ecosystem services at the catchment scale. To date, the costs of biodiversity loss and reduced water supply and quality – which are likely to extend well beyond mine life - have not explicitly been quantified or addressed by regulatory decisions on mine design.

Developer reliance on remediating or offsetting mine impacts would be ineffective in conserving Upland Swamps. These communities are endangered and geographically restricted. An offset approach cannot therefore appropriately conserve swamps. A review of mitigation and remediation techniques for upland swamps found that "no strategies - other than changes in mine plan layout - have been proven to effectively mitigate longwall mining impacts", and that "existing remediation techniques are unproven and appear insufficient without destruction of the surface environment" (Commonwealth of Australia 2014). As there is no evidence that losses could be compensated with gains of similar magnitude, impact avoidance through changes in mine design is the only strategy within the mitigation hierarchy that could ensure no-net-loss of biodiversity and hydrological function.

Requested focus of expert opinion:

a) **In your opinion, is the assessment of the Project's impacts on upland swamps adequate?**

The assessment does not adequately account for the irreversible and ecologically lagged response of vegetation to hydrological disturbance. The Proponent proposes to offset hydrological impacts to upland swamps. However, the geographically restricted and endangered status of upland swamp communities means that **offsetting is an inappropriate application of the mitigation hierarchy** and Ecologically Sustainable Development principles.

The Project has **inadequately assessed the cumulative landscape effect of hydrological disruption** to upland swamps across numerous mining areas over decades of underground mining activity. The proposed Mining Areas 5 and 6 are proximate to extant Mine areas in the Avon and Cordeaux Catchments. Swamps above the mine path have already been affected by hydrological disturbance. My research (Mason et al. in review) has demonstrated that swamps **undermined in Mining Area 3B were persistently drier, retained water for shorter durations and exhibited less spatial differentiation than unmined swamps**. If the proposed mine disturbance continues across the landscape, the cumulative effect on ecosystem services such as water retention and regulation offered by the swamps will be significantly impaired. The heterogeneity of the woodland-swamp mosaic will be significantly affected at a landscape level. In my opinion, this important cumulative disturbance effect has not been adequately addressed by the Proponent. Offset proposals are unable to compensate for incremental swamp loss at the landscape level.

The Project has not adequately addressed a key conclusion by the Independent Advisory Panel for underground mining: "The risks of permanent loss of swamps, due to the combination of mining impacts and severe bushfire, need to be further considered in the context of the impacts of the 2019-2020 bushfires observed at other locations." (p. vi). As swamp soils dry after the mining disturbance, they may become particularly susceptible to peat fire. Upland swamps currently provide considerable carbon storage services (Cowley and Fryirs 2020). Imposition of multiple disturbances, through mining and fire, risks swamps becoming a source rather than a sink of greenhouse gas emissions (Cowley and Fryirs 2020).

b) **In your opinion, what are the likely impacts of the Project on upland swamps if the Project is approved as proposed?**

Endangered upland swamp communities above the longwall mine will experience significant hydrological disturbance. In my opinion, the communities will transition to novel non swamp (i.e. terrestrial) communities. The transition may lag the mining disturbance or it may be accelerated by multiple disturbance such as wildfire or hazard reduction burning. I am currently researching the trajectory of intact swamp turfs in a glasshouse experiment which has simulated both the effects of undermining on swamp hydrology and the effects of a hazard reduction burn. I am monitoring species compositions and biomass. The DPIE Assessment Report (DPIE 2020) notes that questions about swamp community transitions remain unanswered (Section 6.6.61). In my opinion, it is contrary to a precautionary approach to irreversibly affect a primary driver of swamp expression (namely hydrology) when the long term trajectories of endangered swamp communities, and their flammability potential post-mining are unknown.

In my opinion, the cumulative loss of upland swamps across the incrementally increasing mine footprint will adversely affect water retention, regulation and quality ecosystem services provided by swamp communities.

Characteristic species of upland swamps have adapted to waterlogged, anaerobic soil conditions. A change in hydrology will adversely affect the biodiversity value of these communities. Restioid heath – a swamp sub-community - has some of the highest species richness (numbers of species) values in the world (at 1-15m^2 scale) for shrub/sedge-dominated vegetation (Keith and Myerscough 1993).

Furthermore, populations of swamp- and stream-dependent threatened species such as the Giant Dragonfly (*Petalura gigantea*), Giant Burrowing Frog (*Heleioporus australiacus*) and Littlejohn's Tree Frog (*Litoria littlejohnii*) will be adversely affected by removal of habitat and diminution of water resources.

My research provides evidence that longwall mining is responsible for cumulative, intergenerational loss of high-value public ecosystem services provided by upland swamps (Mason et al. in review). A review which evaluated mitigation and remediation techniques following longwall mining could not find any examples of successful remediation of swamps affected by longwall mining (Commonwealth of Australia 2014). It is therefore appropriate to assume that undermined swamps will irreversibly dry and transition to terrestrial communities. The implications for landscape heterogeneity, ecosystem services, biodiversity value and water quality have been discussed above and, in my opinion, these assets are universally devalued by the proposed longwall disturbance.

c) **In your opinion, are there further actions that the Proponent could take to avoid or minimise impacts on upland swamps or the species dependent on them?**

The Proponent has acknowledged that the 'minimum case' of setbacks from streams and avoiding Upland Swamps is 'technically feasible'. In my opinion, impact avoidance by exclusion of upland swamps from the mine footprint is the only action to conserve upland swamp communities. Options for impact minimisation, such as partial extraction of the coal seam based on bord and pillar mine designs, require further research on the magnitude of associated (and as yet unquantified) hydrological impacts.

d) Provide any further observations or opinions which you consider to be relevant.

- I have concerns about how upland swamp monitoring and reporting were conducted as contracted by the Proponent. A Biosis (2017) report used total species richness as a metric to observe mining impacts. However the use of this metric in a Before-After-Control-Impact (BACI) analysis would not necessarily address the null hypothesis that there is no vegetation change due to mining disturbance. It is reasonable to expect that species richness may remain unchanged even if species abundances shift from wet- to dry-associated communities. Species composition was analysed, although it is unclear whether site was appropriately assigned as a random factor. Each analysis only incrementally addressed compositional changes over two consecutive years. Therefore changes in species compositions over more realistic 5-10 year periods were not assessed. In my opinion, the statement by Niche (2019) "…there is strong evidence that indicates native vegetation…would still persist following mining..in fact, there is little evidence to the contrary…" (p. 109) is not supported by the monitoring data as presented in the report. There are problems both with how the data have been analysed and with the timeline of monitoring. An ecological lag due to species turnover extending beyond the disturbance timeline means that vegetation changes may not yet be expressed**. It is therefore incorrect for the Proponent to assert that "extensive monitoring…demonstrates swamp vegetation persists following undermining"** (Letter from Chris McEvoy to Stephen O'Donoghue dated 8th September 2020 Re: Dendrobium mine – biodiversity conservation division supplementary information)
- Recognition of biodiversity and ecosystem service values of *insitu* endangered upland swamps both at the swamp and landscape scale has been insufficient during the EIS process. Few attempts have been made by the Proponent to enact stewardship and conserve *insitu* swamp communities. As an example, Upland Swamp Den98 is considered of special significance: it meets statutory thresholds as a TEC, it has unusual complexity and has closely proximate habitat. Den98 is located at the eastern edge of the longwall footprint in Area 5. The Proponent could conserve this significant swamp, with minimal financial implications, by avoiding the longwall disturbance in the vicinity. A lack of conservation concern for this significant swamp illustrates a prevailing financial model that prioritizes finite coal resources over ongoing biodiversity and ecosystem service values of swamp systems and, in my opinion, contravenes Ecologically Sustainable Development.
- During the Commission hearing, Mr Howard Reed (DPIE) asserted that upland swamps on the Woronora Plateau have formed fundamentally as a result of orographic rainfall (Commission Transcript p. 62 Lines 2-10). I disagree with this assertion. While rainfall is a factor contributing to hydrological resources, groundwater dependence is also important. And it is groundwater resources that are threatened by longwall mining. As part of my research I undertook a qualitative comparison of hydrological signatures for Cyperoid heath in unmined and mined states. The signatures showed that groundwater

levels and soil moisture responded to rainfall events more closely in the mined upland swamp than in the unmined upland swamp. The unmined upland swamp retained higher soil moisture and elevated groundwater levels for long durations after a rainfall event. In contrast, the mined upland swamp exhibited short-lived spikes in both soil moisture and groundwater levels, with the magnitude of spikes corresponding to the magnitude of contemporaneous rainfall events. The different hydrological signatures I observed for Cyperoid heath vegetation with and without underground mining appear to indicate a shift from groundwater dependency to rainfall responsiveness following underground mining. **Upland swamps are dependent on shallow aquifers as well as rainfall to maintain hydrological thresholds**.

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Research interests

I am a community plant ecologist with particular interest in long term vegetation dynamics, disturbance ecology and invasion ecology. In my current research, I use field survey, glasshouse and microcosm experiments and remote sensing approaches to investigate the effects of disturbance on vegetation communities. My research informs both ecological theory and conservation practice.

Education

2002-2006: PhD, University of Wollongong. Recipient of APA and CSIRO scholarships

1994-1998: Bachelor of Science, University of New South Wales. First class Honours in Environmental Science (Biology)

Employment history

2018-present: Senior Scientist (Level 9), Department of Planning, Industry and Environment, Lidcombe
2012-present: Research Fellow (Level B), University of New South Wales
2006-2011: Associate Research Fellow (Level A), University of Wollongong
July 2008-December 2008: Casual Lecturer (Level B) and Subject Coordinator, University of Technology Sydney
February-June 2008 Part time Lecturer (Level B), University of Wollongong
April-December 2006: Casual Research Assistant, University of Wollongong
2002-2006: PhD candidate, University of Wollongong
2002-2006: Casual Lecturer, Demonstrator, Tutor and Marker University of Wollongong
2005: Casual Teaching Associate, Illawarra Environmental Education Centre
2000-2002: Project officer *Bushfire & Environmental Services Pty Ltd*, *Bush & Land Care Services*
Feb-April 1999: Volunteer for the Sagarmatha Community Agro-Forestry Project (SCAFP) World Wide Fund for Nature Nepal Programme, Everest Region, Nepal
Oct 1998-Nov 1998 Temporary Research Assistant UNSW, Sydney

Major research projects

Senior scientist research 2018-present: *Effects of environmental flows on vegetation of wetlands in the northern Murray-Darling Basin*
Postdoctoral fellow research 2015-present: *Predicting swamp community persistence after underground mining*
Postdoctoral fellow research 2012-present: *Vegetation, biogeography and conservation status of temperate highland swamps*
Postdoctoral fellow research 2006-2011: *Understanding and determining mechanisms to prevent invasion in coastal vegetation*
Herman-Slade Foundation and Natural Heritage Trust Grant research 2006: *Understanding seed bank and competition dynamics of fore dune communities*
PhD thesis 2002-2006: *Impacts of plant invaders and management techniques on native communities: ecological and social perspectives at regional and global levels*
Honours thesis 1998: *Weed invasion and native vegetation responses at urban edges in Northern Sydney*

Fellowships and Scholarships

2018-present: NSW Environmental Trust $349 757
2015-2018: NSW Environmental Trust $149 133
2012-2015: Temperate Highland Swamps on Sandstone $223 730
Dec 2006-2011: Land and Water Defeating the Weed Menace (Prof French principal investigator) $286 371
2008: NSW Environmental Trust – Restoration and Rehabilitation Community Grants Program (Prof French principal investigator) $88 465
2008: NSW Environmental Trust - Environmental Research Program Seeding Grant (Prof French principal investigator) $19 840

2002-2005: Australian Postgraduate Award $60 000
2004-2010: Institute for Conservation Biology and Environmental Management travel grants $2 500
2002-2004: CSIRO Doctoral Scholarship including stipend, project funding and travel assistance $38 000

Other skills and qualifications

2013 & 2019 **Statistics and R workshop**, UNSW
2013 **St John Ambulance Australia Apply First Aid** and **Remote Area First Aid**
2008 **4WD skills course**
2003-present Journal reviewer (*PLOS One*, *Conservation Biology*, *Journal of Ecology*, *Austral Ecology*, *Biological Invasions*, *Natural Areas Journal*)
2006 Recertification for **Senior First Aid Certificate**
2005 **Science-writing Workshop**, University of Wollongong
2001 **Bushlands Regeneration Certificate 4**, TAFE, Yallah Campus
2001 **National Farm Chemical Users Accreditation**
1993-present Current unblemished **driver's licence**

Selected publications

Mason, T.J., Krogh, M., Popovic, G., Glamore, W. and Keith, D.A. (in review) Persistent effects of underground longwall coal mining on freshwater wetland hydrology. *Science of the Total Environment*.

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Mason, T.J., Lonsdale, W.M. and French, K. (2005) Environmental weed control policy in Australia: current approaches, policy limitations and future directions. *Pacific Conservation Biology* **11 (4)**: 233-245

Professional societies

2015-present Associate Editor *Austral Ecology* and member Ecological Society of Australia

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

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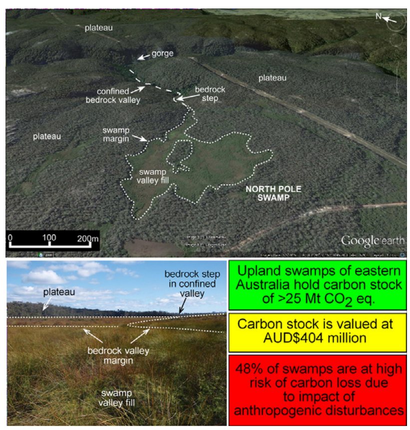
HIGHLIGHTS

- 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



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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.

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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).

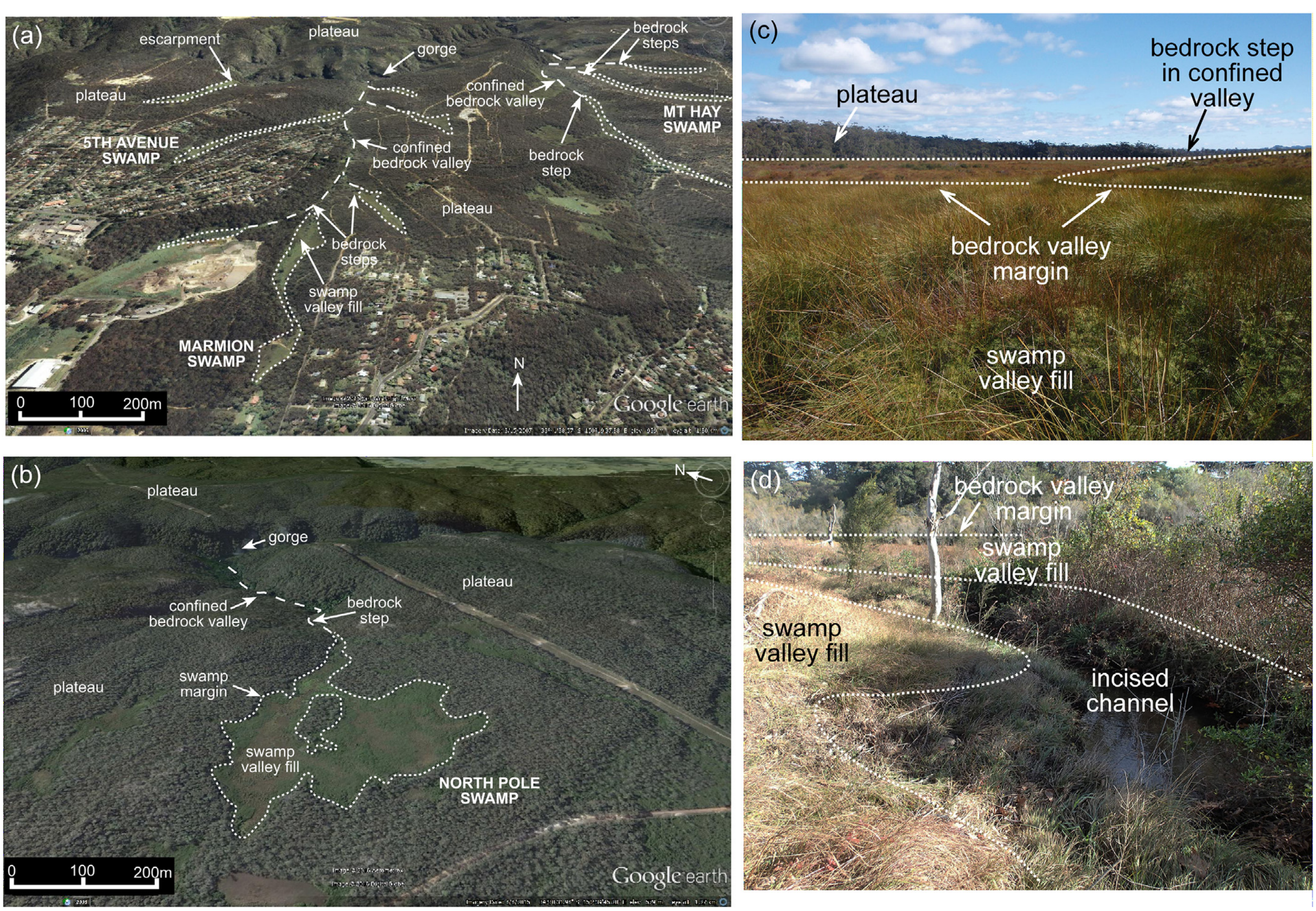

Fig. 1. THPSS are valley bottom swamps that occur in low order headwater streams upstream of the escarpment of the Great Dividing Range in Eastern Australia. (a) THPSS in the Blue Mountains region are often located close to anthropogenic influences associated with urbanisation. (b) THPSS in the Southern 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).

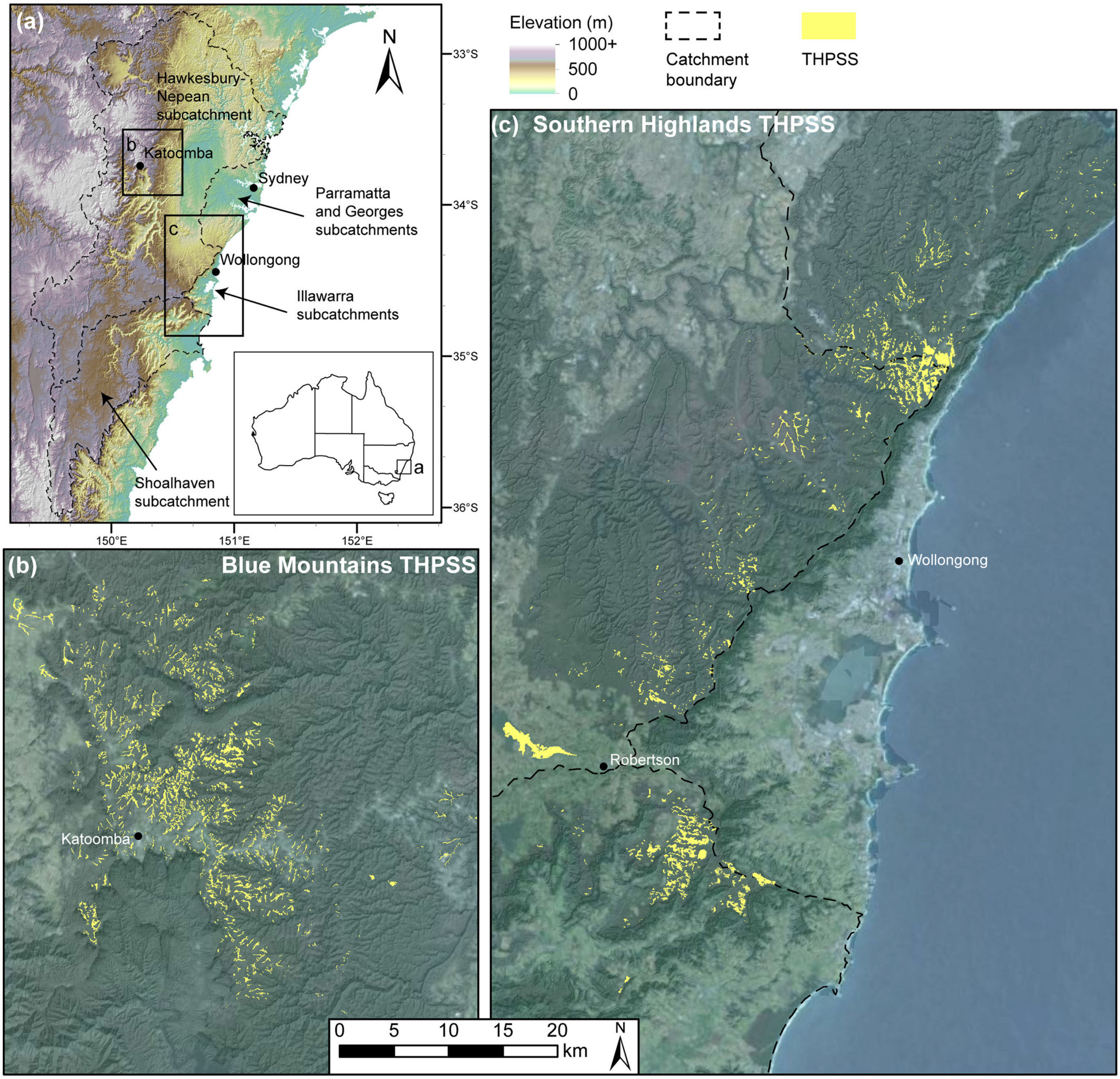

Fig. 2. Location of the Blue Mountains and Southern Highlands THPSS within the Sydney Basin and water supply area.

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_2eq. 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.

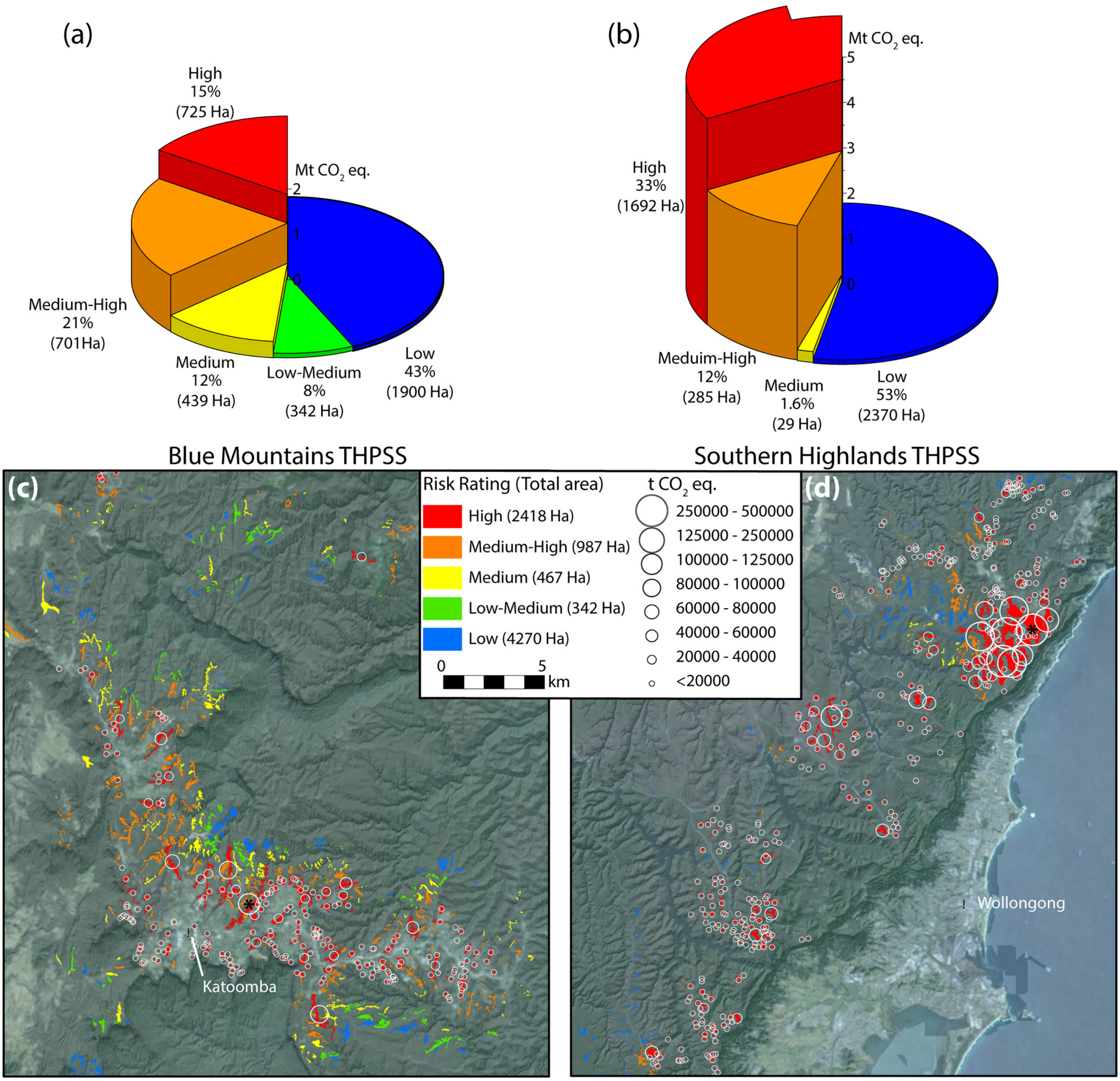

Fig. 3. Percentage, area and carbon stocks (in Mt CO_2 eq.) of swamps at risk from anthropogenic disturbance for (a) Blue Mountains and (b) Southern Highlands. Anthropogenic risk maps and potential carbon emissions for swamps classified at high risk with the potential for 90% carbon loss for (c) Blue 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.

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Appendix A. Supplementary data

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

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