Developing a model of upland swamp structure, function and evolution for biodiversity conservation and rehabilitation: The case of threatened Temperate Highland Peat Swamps on Sandstone (THPSS)

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Key Points

- Temperate Highland Peat Swamps on Sandstone (THPSS) in eastern Australia are listed as an endangered ecosystem. The geo-ecological integrity of these systems is threatened by activities such as long wall mining, coal seam gas extraction and catchment urbanisation.
- To design and implement an effective monitoring strategy, the abiotic and biotic structure and function of these systems require characterisation. Here we present a model of THPSS structure, evolution and function.
- The THPSS are accumulations of mineral sands and organic peats. Some are as old as 44ka, but most are younger than 15ka and have continued to accumulate throughout the Holocene, to today.
- The THPSS contain unique assemblages of stygofauna, the evolution of which is directly linked to the physical and hydrological structure and function of these systems.
- Work is underway to determine when, and to what extent, these systems have been disturbed by past human impacts, what trigger levels of abiotic and biotic disturbance threaten the integrity of these systems, and whether this information can be used to develop monitoring programs and 'early warning systems' for use in currently intact or 'natural' systems threatened by human activity.

Abstract

Temperate highland peat swamps on sandstone (THPSS) (called upland swamps) are a form of topogenous mire which occur on the plateau areas of eastern Australia. These systems are well recognised for their ecological value, under several State and Federal policies. However, our understanding of their structure, function and evolution remains limited. This study examines the sedimentology, age structure, hydrological function and stygofauna diversity of 19 valley-bottom swamps in the Blue Mountains and Southern Highlands of NSW to produce a regional model of THPSS geo-ecological function. This regional model provides a template for environmental health assessment and rehabilitation of these systems, and to inform State and Federal policy making on the conservation status of these systems.

Keywords

Upland swamp, swamp structure, function and evolution, endangered ecosystem, monitoring program

Introduction

Temperate Highland Peat Swamps on Sandstone (THPSS) are a distinctive feature of low-relief plateau areas in eastern Australia (Young, 1986; Dodson *et al*., 1994; Freidman and Fryirs, subm.; Fryirs *et al*., 2014, in press.) and are key features of water supply catchments in this area. The areas in which THPSS are concentrated (in the Blue Mountains and Southern Highlands of NSW) are in the water supply catchment for Australia's largest city, Sydney. These THPSS play a role in determining the quantity and quality of water in those catchments (Fryirs *et al*., 2014). THPSS are also listed as an endangered ecological community under the National *Environment Protection and Biodiversity Conservation Act 1999,* and the NSW *Threatened Species Conservation Act 1995*, and are threatened by activities such as long wall mining, coal seam gas extraction and catchment urbanisation (Hensen and Mahony, 2010; DECC, 2011, Kohlhagen *et al.,* 2013).

Recent recognition of their value has prompted policy that prioritises the conservation and maintenance of intact swamps, and their reinstatement where they have been degraded or destroyed. However, these activities are occurring without a sound knowledge of the geomorphic structure, function and evolution of these systems. This understanding provides the physical template atop which biological, hydrological and chemical interactions occur. Based on 19 study sites, we present a regional, evolutionary model of THPSS structure and function, and discuss implications for biodiversity, conservation and rehabilitation.

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Regional setting and methods

Regional setting

The 19 study swamps are located on the western and south-western margins of the Sydney Basin around 100 km from metropolitan Sydney (**Figure 1**). The sites in the Blue Mountains (33°30'S:150°30'E) occur largely within the World Heritage Listed Blue Mountains National Park, while the sites on the Southern Highlands occur within the Budderoo National Park and the Woronora region. The Woronora sites are within the Sydney Catchment Authority Special Areas (Sydney's water supply catchment) (34˚37'S:150˚40'E). The Blue Mountains rise to 1200 m a.s.l. and the Southern Highlands to 800 m a.s.l.. Both landscapes comprise plateau country that is incised by steep dendritic gorges. The plateau rises steadily from the Cumberland Plain, and is capped by the horizontally bedded Triassic Hawkesbury Sandstone group that forms a gently undulating plateau of low relief (± 30 m). On the plateau, valley slopes comprise of tall eucalypt forests, progressing to silt and sand rich peat swamps on valley floors. The mean annual rainfall across the study areas is between 1100 and 1600 mm (BOM, 2013). The mean maximum temperatures range from approximately 10˚C in winter to 26˚C in summer. Mean minimum temperatures can be as low as 1.3˚C in winter.

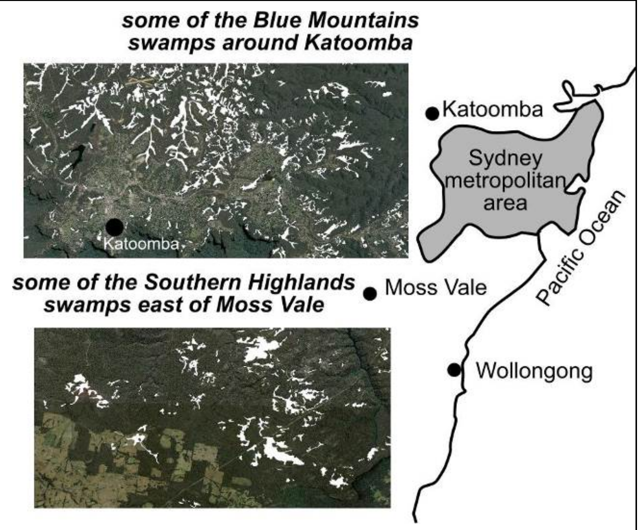

Figure 1: The location of THPSS around Sydney.

Methods

The methods used to determine the geomorphic structure, evolution and peat forming potential of THPSS have been reported in Fryirs *et al.* (in press.) and in Freidman and Fryirs (subm). The methods used to establish the hydrological function of these systems can be found in Fryirs *et al.* (2014). Methods used to determine the stygofauna diversity of these systems can be found in Hose (2008) and flora surveys were conducted as per Hose *et al.* (2014). All analyses were conducted at Macquarie University, except ^{14}C radiocarbon dating which was undertaken at Beta Analytic, Florida, USA and at the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney. Carbon:nitrogen (C:N) ratio analysis was conducted at the National Measurement Institute (NATA Certified Laboratory), Sydney.

For context, the ratio of Total Organic Carbon (TOC) to Total Kjeldahl Nitrogen (TKN) reflects the rate of organic matter decomposition in sediments (Rayment and Lyons, 2010). Interpretation of TOC:TKN (C:N ratios) required a scaling profile (see Rayment and Lyons 2010). Organic matter accumulation exceeding decomposition produces a C:N ratio > 25 and is indicative of peat formation. A ratio of 16–25 indicates accumulation and decomposition in dynamic equilibrium. C:N ratios < 16 reflect the large-scale absence of organic matter and are often associated with mineral subsoils.

Results and discussion

The spatial distribution of THPSS

Across the Blue Mountains and Southern Highlands study areas there are around 3200 valley-bottom THPSS (**Figure 1**). These swamps, ranging from 400 m^2 to 422,000 m^2, drain catchment areas from 0.036 km^2 (36,000 m^2) to 0.852 km^2 (852,000 m^2) and occur on slopes averaging 4.3 %. Their position in the valley bottoms of dissected plateau sandstone country makes them elongate in shape. In many cases a large trunk stream swamp is connected to smaller tributary swamps, forming a dendritic configuration that terminates at the escarpment, bedrock constrictions or bedrock steps.

The sedimentology, age structure and peat forming potential of THPSS

As reported in Fryirs *et al.* (in press.), four distinct sediment classes were detected in the study swamps and tend to occur in a consistent sequence within the valley fills of all 19 study swamps. At the base of the valley fill ***basal sand and***

gravel are encountered (**Figure 2**). These sediments have low organic content and low C:N ratios, suggesting a lack of peat formation at this time. Just above saprolite in 6 swamps, the age structure spans 15564 – 14920 cal BP to 9123 – 8775 cal BP, with an outlier back to 45080 – 43570 cal BP in SCA3. This suggests that sand trapping and accumulation in these valleys was initiated at the Pleistocene-Holocene transition, or earlier.

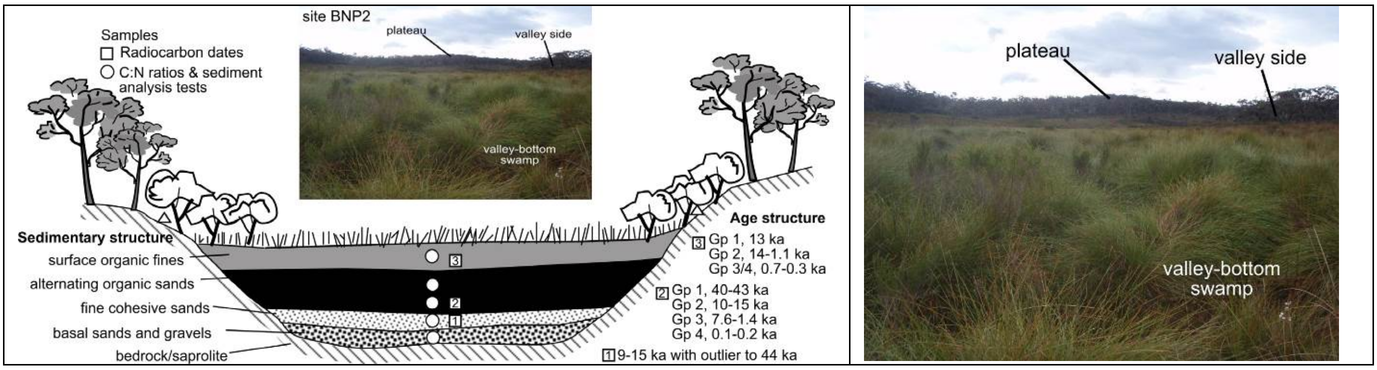

Figure 2: Summary model of the sedimentology and age structure of THPSS. Photo of a Budderoo swamp.

The transition to 'swamp' conditions is recorded in sequences of layered units, starting with ***fine cohesive sands*** at depth, then stacks of ***alternating organic sands*** (Fryirs *et al.* in press.; **Figure 2**). These beds vary in texture from loams to sands and have a range of organic matter contents (7.6– 79.9%) and C:N ratios (15– 58). Occasional, thin (<10 cm) coarse sand sheet deposits punctuate these sequences. The overall thickness of these units can be as much as 2.3 m. These units are considered the sapric component of the swamp sediments. Seventeen swamps were used to determine timing of the transition from the basal sand and gravel unit to 'swamp' conditions. For two swamps (SCA2 and SCA3; called Group 1) this transition is dated at 41161 – 39926 cal BP and 43309 – 42188 cal BP respectively. In seven swamps this transition is dated in the late-Pleistocene from 15564 – 14920 cal BP to 10500 – 10195 cal BP (Group 2). Six swamps have the transition occurring in the Holocene from 7720 – 7576 cal BP to 1520 – 1348 cal BP (Group 3) with all but two occurring in the last 5000 years. These ages suggest that the transition to some form of 'swamp' accumulation was occurring most extensively across the region at the Late-Pleistocene and throughout the Holocene. Three smaller, shallower swamps are modern, with ages between 277 – 0 cal BP and 254 – 0 cal BP (Group 4).

At the surface of all swamps a ***surface organic fines*** layer occurs (Fryirs *et al.* in press.; **Figure 2**). The surface organic fines layers are around 20–100 cm in depth. These layers have a higher organic matter content (LOI averages 31.7 %) and are poor in mineral sediment. A high proportion of live and dead coarse organic matter makes up the bulk of these layers. This layer is considered the fibric component of the swamp sediments. One swamp in Group 1 (SCA3) has a surface age of 13209 – 12980 cal BP. Across the swamps of Group 2 (7 swamps), surface age structures range from 14590 – 14026 cal BP to 1288 – 1092 cal BP. Five of the swamps in this category have surface organic fines older than ~4400 cal yrs BP. The remainder of the swamps (Groups 3 and 4) have surface sediments between 730 – 655 cal BP and 254 – 0 cal BP.

For the oldest swamps (Groups 1 & 2), C:N ratios for the layers immediately above the basal sands (i.e. reflecting the transition to 'swamp' forming conditions) range from 27 to 42, indicating that peat formation has occurred in these swamps early in their evolution. For the younger swamps in Group 3, the C:N ratios at this transition range from 15 to 29, placing them in the accumulation–equilibrium category where peat formation is in its infancy. The C:N ratios at 70 cm depth are highly variable and range from 14 to 42. In almost all cases, the C:N ratio drops to less than 30 at the surface (0–30 cm).

A geomorphic model of THPSS

For the swamps studied here, a representative evolutionary sequence of THPSS formation can be presented (Fryirs *et al.* in press.; **Figure 2**). In the period post-Last Glacial Maximum (LGM), sand and gravel trapping and accumulation on low-slope valley floors is initiated. The initial onset of sediment trapping is dated at between 15.3 and 9 ka cal yrs BP, but may have been occurring since 44 ka cal yrs BP.

With increased temperature and rainfall at the onset of the Holocene, vegetation became well established on valley floors and adjacent hillslopes (Cohen and Nanson, 2007). This likely produced the conditions conducive for fine sand and organic matter input and trapping in these valley bottoms. This transition to a 'swamp' system occurred between 15.2 and 10.3 ka cal yrs BP in some systems, and between 7.6 and 1.4 ka cal yrs BP in other, adjacent valleys (**Figure 2**). Some valleys did not develop 'swamp' systems until recently (within the last couple of hundred years). The variability in 'swamp' ages suggests that although a significant transition to swamp forming conditions occurred in the Late-Pleistocene, there have also been phases of swamp development throughout the Holocene. The fine cohesive sand and alternating organic sand units in the valley fill are a result of these major 'swamp' building phases. A carbon accumulating system formed in some swamp fills due to the extent of plant matter compaction and an anaerobic environment induced by waterlogged conditions (Grand-Clement *et al*., 2013). With the maintenance of a wetter climate over decadal timescales, conditions may have been locally favourable for peat formation (Pemberton, 2005).

However, the sedimentology of the fills suggests that peat formation was not a continuous process. Recurrent layering of coarse sands and peat-like organic material may reflect the transport and deposition of coarser, mineral-rich, sand sheet sediments following fire or high-intensity storm/runoff events and subsequent re-establishment of vegetation on hillslopes and valley floors (Cohen and Nanson, 2007). These events not only disrupted the stratigraphy of the fill, but also the peat-forming conditions within the fill. The relatively low C:N ratio values throughout the valley fill profiles suggest that while peat can form in these systems it is not well developed and has only occurred at certain times during the evolution of the fill. Across the study swamps, near surface ages range from 13.1 to 0.7 ka cal yrs BP (**Figure 2**). This suggests that swamp surfaces have been well established for some time and the conditions for these systems to develop has remained in place to the present.

We propose that given the THPSS of eastern Australia have formed under climate conditions that experience significant inter-annual variability in rainfall and La Niña–El Niño cycles, conditions for peat formation are localised and are not directly equivalent to those documented in the northern hemisphere. For extended periods of time, water levels within the fill can be low, exposing organic matter to aerobic conditions with subsequent decomposition and loss from the system (Fryirs *et al.* 2014). The evolution of these systems is analogous to other systems in the region, suggesting that a regional model of THPSS is emerging.

Hydrological function of the THPSS

Within one of the THPSS study sites (swamp BNP6), Fryirs *et al.* (2014) found that each sediment class had different rates of water throughflow, conductivity, discharge and water storage, suggesting that swamp structure drives the overall hydrological function. In general, these swamps have highly variable water level conditions that respond relatively rapidly to rainfall of various magnitudes and duration. Over a two year monitoring period, mean water level occurs at depth within the valley fill and water level fluctuations expose the fibric and upper parts of the sapric layers to dry, aerobic conditions for extended periods of time (inhibiting peat formation). During wet periods, common in La Niña times, the swamps often exceed their storage capacity, triggering periods of saturation and excess overland flow. However, in the presence of porous, mineral-rich swamp sediments, steep recession of water levels back to mean condition occurs in a matter of days. In terms of flow generation, these THPSS have a dual function whereby the swamp can act as both a 'sponge', sequestering water inputs, and as a 'conduit' for the rapid transfer of water, depending on the antecedent water level and the hydraulic conductivity of different layers within the swamp sediments.

Biodiversity (vegetation & stygofauna) of the THPSS

The flora and fauna of upland swamps are adapted to the regime of groundwater depth (Hose *et al.* 2014). Changes in groundwater depth are likely to change the structure and function of the ecosystems. Water logging is critical to the development of the fibric and sapric soils, which in turn determines the nature of the swamp vegetation. Indeed, the combination of topography and average groundwater levels influence the vegetation most, rather than the extreme values, partly because of the high water holding capacity of the organic rich soils (Hose *et al.* 2014).

With many swamps forming after the LGM, there has been a considerable period of isolation of the fauna inhabiting swamps. This is the case for terrestrial fauna with low dispersal capabilities, such as the Blue Mountains skink and dragonfly. The invertebrate fauna living within the swamp groundwater, the so-called stygofauna, show similar patterns, such that swamps separated by only hundreds of metres contain genetically distinct populations of related invertebrate taxa. Consequently, the biodiversity value of swamps is high because of these isolated and endemic populations. Unfortunately, however, assemblages of groundwater invertebrates are particularly sensitive to disturbance and are notably absent from swamps that are subject to urban encroachment, storm water inputs and changes to hydrology (Hose, 2008). The swamp stygofauna are also acutely sensitive to changes in groundwater levels associated with dewatering.

Progress on the conservation and rehabilitation of THPSS

Activities such as long wall mining, coal seam gas extraction and catchment urbanisation currently threaten the THPSS (Hensen and Mahony, 2010; DECC, 2011; Kohlhagen *et al.,* 2013). This has been particularly evident in the Sydney Catchment Authority (SCA) areas and the Blue Mountains World Heritage Area. As part of the protection of these systems, a noticeable shift towards developing monitoring programs has occurred in recent years (Hensen and Mahony, 2010). The design and implementation of monitoring strategies, however, requires a detailed understanding of the abiotic and biotic structure and function of these systems. The work presented here will contribute to this process. In addition, doctoral research is under way to determine timeframes and extent of human disturbance, what trigger levels of abiotic and biotic disturbance threaten the integrity of these systems, and whether this information can be used to develop early warning systems for use in currently intact or 'natural' systems threatened by human activity. In the SCA area, for example, a moratorium on coal seam gas exploration is in place until these findings are available. Restrictions on longwall mining under THPSS are already in place (http://www.environment.nsw.gov.au/determinations/LongwallMiningKtp.htm. In other places, such as the Blue Mountains, passive swamp rehabilitation measures are being trialed by the Greater Sydney Local Land Services and Blue Mountains City Council (see Hensen and Mahony, 2010; BMCC, 2010; and Fryirs *et al.* 2012) on swamps that are degraded or dewatered. This information will be used to gauge whether (and over what timeframes) rehabilitation will reinstate 'natural' structure and function in these endangered ecosystems.

Little discussion has occurred surrounding the impacts of future climate change on the hydrological function of these systems and what effect this may have on maintenance of swamp structure (including peat formation), and associated biodiversity. The effects of climate change are likely to be manifest initially in sensitive subalpine and highland areas where changes in the intensity and duration of rainfall are forecast. The threat to THPSS, in particular, is high and questions about the preservation and conservation of these systems remain.

Conclusion

Conservation and rehabilitation activities in threatened environments are a critical component of modern-day environmental management. The THPSS of eastern Australia are no different in this regard. However, these activities require a solid understanding of the geomorphic and hydrological condition, coupled with the biodiversity of these systems as a template for designing monitoring programs that are sensitive enough to detect the extent to which human and climate change will impact on these systems, and to develop early warning systems for environmental management (whether conservation or rehabilitation).

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