Peatland carbon stores and fluxes in the Snowy Mountains, New South Wales, Australia

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SUMMARY

Peatlands in the Snowy Mountains cover nearly 8000 ha and preserve 49 million m^3 of peat, of which 27.1 million m^3 is stored in *Sphagnum* shrublands and restiad moorlands and 21.9 million m^3 is stored in sedge fen. The total carbon store is estimated to be about 3.55 Tg. Peat accumulation over the past 60 years indicates that the historical carbon accumulation rate is only 4950 Mg yr^{-1} for the entire peat estate. This equates to net carbon storage rates of 0.8–1.6 Mg ha^{-1} yr^{-1} which is similar to the rates of 0.2 to 2.3 Mg ha^{-1} yr^{-1} found in other temperate peatlands. Peat sections covering the last 3000 to 4000 years, however, retain a millennial-scale net long-term storage of 0.09 to 0.21 Mg ha^{-1} yr^{-1} totalling 2340 Mg yr^{-1}. The lower storage value of the older peats is partly due to continuing slow peat decay but may also represent accelerated decay due to disturbance by a 100-year phase of stock grazing and intentional burning in the mountains.

Some peatlands are recovering strongly since grazing was stopped but they are still vulnerable to hydrological changes caused by trampling by large mammals. Rates of carbon sequestration will be sensitive to climate change, as the peatlands are already stressed by these former land management practices and many are at their climatic limits. The active management of peatland hydrology and surface stabilisation is essential to peatland recovery and the conservation of these significant carbon stores.

KEY WORDS: climate change; disturbance; peatlands; restoration

INTRODUCTION

Peats that have accumulated in bogs and fens, together with other organic soils (Histosols), constitute major environmental stores of carbon, providing less than 3 % of global land cover but preserving around 10 % of terrestrial carbon stocks (Joosten 2010). Degradation of the 500,000 km^2 of peatlands globally leads to emissions of 1.3 Gt yr^{-1} of the greenhouse gases (GHG) CO_2 and CH_4, which is about 4 % of all human-caused GHG emissions (Tanneberger & Wichtmann 2011). While the bulk of peatlands occur in boreal and tropical settings, temperate regions also contain significant peatland resources. Their carbon content can accumulate over millennia and so is relatively stable if the sites retain their moisture. However, the stores are vulnerable to disturbances that may be deliberate (such as drainage and agriculture) or inadvertent, for example the result of fire or trampling. Although peatlands are usually sinks, they may also become sources of significant fluxes of carbon compounds; hence, the quantification of their extent and the identification of factors contributing to positive or negative carbon balances within them are key management issues.

Two approaches can be used to determine the role of peatlands in fixing atmospheric CO_2. Direct measurement of the fluxes of gases and water on a small area of a peatland can determine whether its carbon balance is positive or negative over the period of measurement (Tanneberger & Wichtmann 2011). The measurement of net CO_2 flows aims to detect the balance between photosynthesis and respiration. Gaseous methane emissions from peat breakdown, and dissolved carbon compounds (DOC) in streams, are also measured and added to the total of carbon leaving the peatland to obtain a comprehensive carbon budget (e.g. Bubier *et al*. 2005). DOC export is a substantial portion of the overall C budget of peatlands and in disturbed systems may be similar to carbon accumulation rates (Nieveen & Schipper 2005). The results have been shown to vary from year to year and a proportion of any carbon being fixed will be in a temporary store that is released by respiration on a seasonal basis (e.g. Roulet *et al*. 2007). Hence it is difficult to measure the long-term (decadal) addition to the peatland carbon store from these measurements.

An alternative approach is to measure the carbon content per unit volume of peat at intervals down a dated peat profile. From these data the net long-term carbon storage rate can be calculated (e.g. Turunen *et al*. 2002). But because peat slowly loses carbon through time (Clymo 1984), the apparent rate of carbon storage in older sections will not be comparable with values from less decayed younger sections. However, such an historical approach does demonstrate the actual long-term performance of a peatland as a carbon store and its potential for future sequestration. If numerous peatlands in a region are measured, a comparison of well-preserved sites with disturbed ones can show the sensitivity of the stores to disturbance. For example, cattle grazing in sub-alpine bogs in Victoria was shown by Grover *et al*. (2005, 2012) to have resulted in major oxidation and collapse of the peat column.

Although long-term eddy flux measurements on peatlands have not yet been made in Australia, short-term measurements have been carried out in *Sphagnum* shrub peatlands in Victoria (Grover & Baldock 2010). In New Zealand, Nieveen & Schipper (2005) studied a lowland bog dominated by the restiad *Empodisma minus* and found that the carbon sequestration rate was 1.85 Mg ha^{-1} yr^{-1} in 1999 and 2.10 Mg ha^{-1} yr^{-1} in 2000 in intact bog; whereas drained areas that were used for dairying showed a net annual loss of carbon of 0.048 Mg ha^{-1} yr^{-1} and continued lowering of the surface. Studies in Belarus demonstrated carbon gains of 0.2–2.2 Mg ha^{-1} yr^{-1} on unexploited sedge fens while cutover peatlands were strong emitters of CO_2 with losses of 1.2–3.4 Mg ha^{-1} yr^{-1} (Tanneberger & Wichtmann 2011).

In this article we combine new mapping and depth data to provide the first estimate of the size of the organic store in the montane and sub-alpine peatlands of the Snowy Mountains, which are part of the southern Great Dividing Range, Australia. We then use a set of previously dated peat sections in the region to derive the recent and longer-term accumulation rates of the peatlands. These data provide a first approximation of the significance of these Australian montane peatlands as a sink or potential source of carbon over decadal and millennial timescales.

SITES AND METHODS

Peatlands in south-eastern Australia

While peatlands are a minor component of land cover in most of Australia they are more important in cool, higher-rainfall areas such as the mountains of south-eastern Australia and Tasmania or places with high water tables, such as coastal plains near sea level (Whinam & Hope 2005). The Snowy Mountains region has the most extensive montane peatlands in mainland south-eastern Australia (Figure 1, inset). Peatlands are particularly common above 750 m in Kosciuszko National Park, New South Wales (NSW), where they form up to 2.5 % of the higher altitude (1800–2200 m) land cover (Hope *et al*. 2012). Peatlands also extend northwards into Namadgi National Park in the Australian Capital Territory (ACT). Within this region, annual rainfall varies from 800 mm at 1000 m altitude to over 3000 mm at 2240 m altitude (Worboys *et al*. 2011). The climate is cool temperate with little seasonal rainfall variation, and winter snow-lie increases with altitude from 1400 m. The geology consists of Palaeozoic sedimentary and granitic rocks.

The peatlands have formed under five main vegetation covers, namely: 1. *Carex* fen; 2. Montane *Sphagnum*-shrub bog; 3. Sub-alpine *Sphagnum*-shrub bog; 4. Alpine *Sphagnum*-shrub bog; and 5. *Empodisma* restiad moorland. At lower altitudes (700–1100m), extensive *Carex gaudichaudiana* sedge fens fill broad valleys fed by rain supplemented with surface and hillslope seepage (Figure 2). These have a pH of 5.5–6 and peat depths of 2–4 m. At higher altitudes the hummock moss *Sphagnum cristatum* and an array of shrubs and graminoids dominate montane, sub-alpine and alpine bogs (Figures 3–5), the three *Sphagnum*-shrub communities being distinguished by the height of the shrub layer and the floristics (Whinam & Hope 2005). The pH range and nutritional status of a sub-alpine *Sphagnum* shrub peatland in Victoria (Australia) agreed well (Grover *et al*. 2005) with measurements for ombrogenous bogs (rain-fed mires) in, for example, The Netherlands and Canada. This poor nutrition relates to Australian soils and supports the use of the term “bog” for these communities. The bogs have a pH of 4–5 and peat depths of 0.9–1.4 m though occasionally deeper. However, as they follow drainage lines and seepage areas on slopes, and saddles on ridge lines, they may not be exclusively rain-fed. The fifth community, termed *Empodisma* moorland, is a transitional peatland on shallow mineralised peats around the margins of the bogs and is dominated by a restiad, *Empodisma minus* (Figure 6). This community is now extensive, may in part mark former bog areas, and has been previously referred to as “dried peat”, for example by Grover *et al*. (2012). In the moorland, peat depth is 0.3 m and pH around 5. A similar restiad community occurs in New Zealand, where Hodges & Rapson (2010) regard it as transitional between fen and bog.

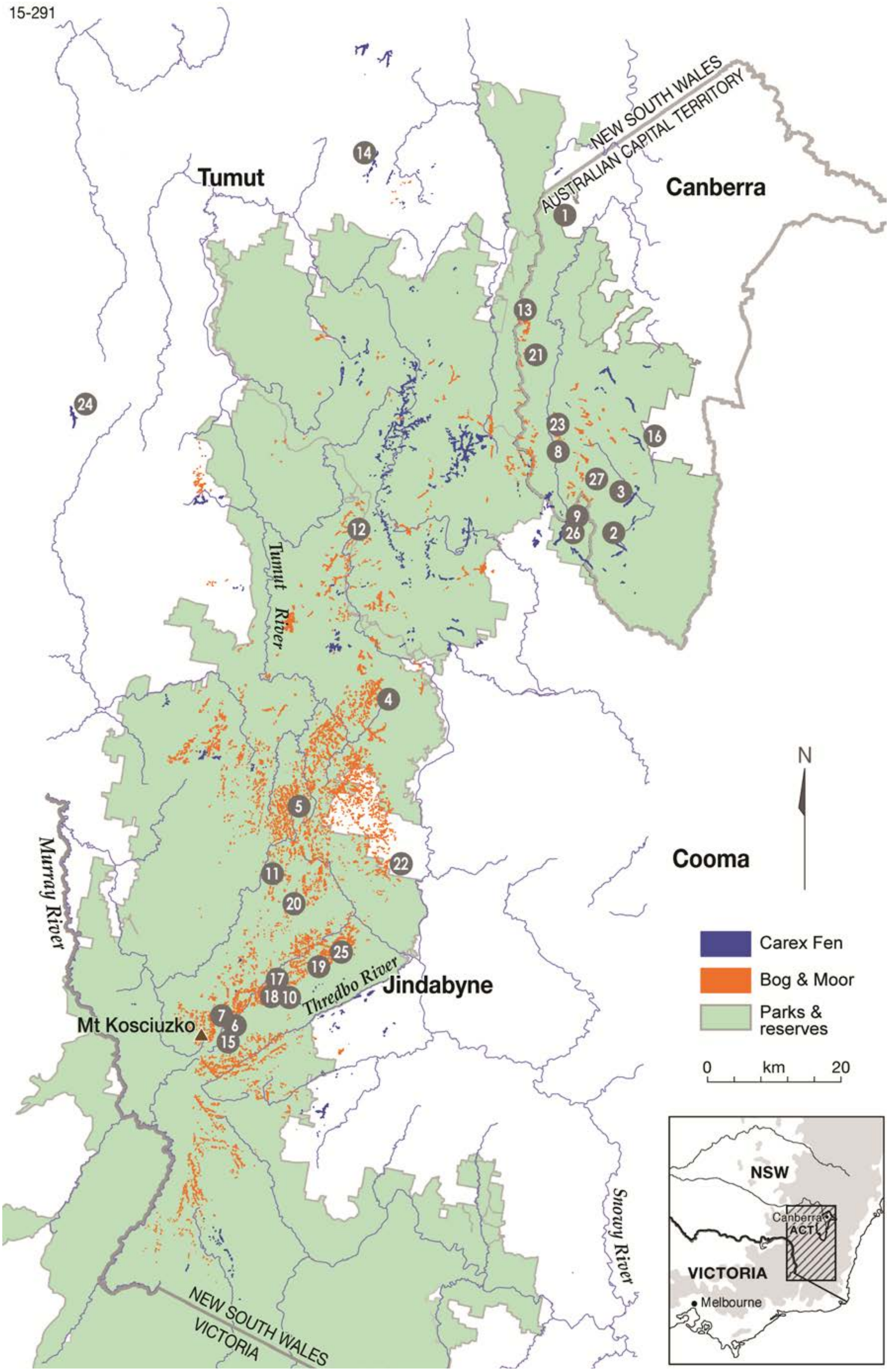

Figure 1. Location diagram, also showing the extent of peatlands in the Snowy Mountains region.

Figure 2. Large *Carex gaudichaudiana* dominated fen at 1158 m in Namadgi National Park, ACT.

Figure 3. *Sphagnum cristatum*-shrub bog: montane, 1193 m.

Figure 4. *Sphagnum cristatum*-shrub bog: sub-alpine, 1606 m.

Figure 5. *Sphagnum cristatum*-shrub bog: alpine, 1978 m.

Figure 6. *Empodisma minus* moorland at 1726 m in Namadgi National Park, ACT.

Over the past 150 years, most mountain peatlands in the Snowy Mountains region have been significantly affected by cattle grazing and fire (Costin 1954, Worboys *et al*. 2011, Clarke *et al*. 2015). Trampling has caused destruction and alteration through compaction and increased drainage accompanied by seasonal burning. Many fibric peats have been converted to mineralised humic peats (Grover *et al*. 2005, 2012). Across the mountains many other peatland areas have lost all their peat and been converted to tussock grassland. Some recovery of peatland vegetation has occurred within protected areas in the Snowy Mountains since cattle were removed after 1940 (Good 1992). Widespread fires in 2003 reversed this recovery across the NSW and Victorian mountains. In response to these fires, the first comprehensive mapping of peatlands above 800 m in the region was undertaken (Hope *et al*. 2012).

Peatland area and volume

Peatlands in the Snowy Mountains of NSW and the ACT were mapped at a scale of 1:3,000 using orthorectified aerial photographs recorded one month after very extensive wildfires in January 2003. These data were supplemented by earlier orthomaps (1:25,000) and Google Earth satellite images from 2004 and 2006. A 25 m digital elevation model (DEM) derived from 10 m contour files held by NSW Land and Information Section was used to determine mean slope and altitude for each peatland 'shapefile' (mapping unit). Depending on morphology, individual peatlands may be made up of one or several shapefiles. Extensive ground truthing on foot and by helicopter between 2003 and 2012 was undertaken to improve the identification of peatland boundaries and to aid in the determination of the five categories of peatland defined on the basis of their living vegetation cover, i.e. *Carex* sedge fen, montane, sub-alpine and alpine *Sphagnum* shrub bogs, and *Empodisma* moorland (Hope *et al.* 2012). These data were augmented with stratigraphic data collected using Livingstone and Russian D-section corers (Belokopytov & Beresnevich 1955) during ground surveys. Previous studies of peatlands (e.g. Martin 1986, 1999) were combined with the survey data to provide estimates of average peat depths for peatland types. The mapped peatland extents were multiplied by depth slices based on observed depths of peat and organic-rich mineral sediments to obtain an estimate of peat volume.

Peat characterisation and carbon density

Peat samples were collected from sections taken from the five peatland categories (fen, three *Sphagnum*-shrub bog types and moor) across a range of altitudes. Peat was classed in terms of fibre content as fibric, hemic or sapric (Boelter 1969, Isbell 1996) (corresponding to von Post humification classes H1–4, H5–7 and H8–10 respectively, Faegri & Iversen 1975). Water content, dry bulk density and carbon content were measured (Chambers *et al*. 2011). A sharpened graduated plastic tube 14 mm in diameter was pressed into the cores to take a 10^{-5} m^3 (10 cm^3) sample which was weighed to provide moist bulk density (Mg m^{-3} = g cm^{-3}). Very fibrous or woody peats were sawn from sections and cut into measured cubes. These samples (sometimes multiple samples when very high water content was suspected) were dried at 90 °C for 64 hours and re-weighed so that the water content and dry bulk density (Mg m^{-3} = g cm^{-3}) could be calculated.

To approximate the organic content of each class of peatland, 178 dried peat samples were ignited in a muffle furnace at 550 °C for four hours (cf. Heiri *et al*. 2001). While percentage loss on ignition (% LOI) is typically proportional to carbon content, a wide range of conversions has been found to apply to peats from different settings and with different states of preservation. Results as % LOI can be affected by loss of pore water in clay, or of other volatile inorganic components such as CO_2 from carbonates. For example, increasing inorganic content (e.g. clay and silt) may affect the results, making % LOI estimates of the organic content of peaty silts and clays unreliable. Another source of variation is the different organic makeup of fresh peat compared with humified peats. Fresh peat has a lower carbon content per gram dry weight owing to the presence of organic components with less carbon in their molecules, such as sugars and proteins. Humification, including microbial digestion, preferentially attacks these, converting them to phenols (Freeman *et al*. 2004). Less oxidisable components such as partially combusted plant material (carbonised particles) are concentrated. To identify these potential sources of error, % LOI was compared with direct elemental analysis (EA) for a subset of 90 samples from selected peat profiles. Samples were milled, sub-sampled and analysed using a Carlo Erba EA-1110 CHN-O Elemental Analyser. The relationship of % LOI to % carbon was used to calculate carbon values for a range of fresh to oxidised peats and organic sediments from each class of peatland in the region.

Peat and carbon accumulation rate estimates

Thirty-six peatlands of various types across the region have been cored and radiocarbon dated. A marker for the historical period (since *ca.* 1860 AD) is the appearance of the pollen of pine and other exotics which can be used to define young peat and moss sections. Average peat accumulation rates between dated levels can be calculated from age-depth models based on calibrated ages derived from Costin 1972, Martin 1986, Thomas 1991, Dodson *et al*. 1994, Mooney *et al*. 1997, Clarke & Martin 1999, Martin 1999, Hope & Clark 2008, Hope *et al*. 2009, Marx *et al*. 2010, Kemp & Hope 2014 and unpublished data. Most peatlands typically accumulated over 8,000–11,000 years but several seem to have formed only in the last 3,000–4,000 years. The carbon content of the peat divided by the accumulation rates from the dated core sections can then provide a measure of the net annual rate of carbon storage.

RESULTS

Peatland extent, depth, and volume

A total of 9120 individual patches (7985 ha) of peatland were identified and mapped across the Snowy Mountains region (Figure 1). This represents 0.073 % of the study region. Peatland patches are generally < 0.5 ha (70 × 70 m) in extent, the largest *Sphagnum*-shrub bogs being 10 ha or less and the *Carex* fens generally smaller than 20 ha (450 × 450 m) although the largest is 160 ha (0.4 × 4 km). The peatlands occupy valley floors, valley edges or gentle slopes up to 9° (range 0–22°) and are described in more detail elsewhere (Hope *et al*. 2012).

Typical peat sections (Table 1) consist of a surface layer of undecomposed mosses or sedges over brown fibric peats 0.3–0.8 m in depth, above increasingly sapric dark brown peat with few discernible plant structures other than occasional wood fragments. Fine charcoal often forms dark grey horizons. There may be a gradual or an abrupt transition to peaty silts above pale grey clays and sandy silts, sometimes gleyed blue or green. Sand lenses are common in the sections.

Fibric peat, and often hemic peat, contains recognisable plant material from which the source vegetation can be assessed. Peat derived from *Sphagnum* can be distinguished from the more coarsely fibrous *Carex* peat. Woody stems are often present in peat derived from shrub bogs, even when the matrix is well humified. Silt and clay layers often reveal traces of vertical, well-preserved *Carex*

Table 1. Potential sediments found in peatland profiles in the Snowy Mountains region.

Sediment	**Peat grade (Boelter 1969)**	**Colour range**	**pH range**
Rootmat trapping litter and sediment		Dark grey, dark brown, brown	4.5–7
Fresh dead *Sphagnum*	fibric	Pale yellow, light brown	3.5–5
Fresh fibrous peat - fibrous plant material > 0.15 mm	fibric	Dark brown, brown, reddish brown	3.5–6.5
Humified peat with 33–67 % fibre remaining	hemic	Dark brown, brown, light brown	4–5.5
Fully humified peat with less than 33 % fibre	sapric	Dark brown, brown	4–5.5
Clayey peats	sapric/hemic	Very dark grey, light brown	4.5–6.5
Peaty clay and silts		Dark grey, grey, pale grey, blue, green	5–6.5
Peaty fine to medium sands		Grey, pale grey, yellow	5–6.5

leaves, indicating that the sediment was being washed into a sparse sedgeland when deposited.

Cross sections based on probing and coring from more than 100 peatlands indicate that peat thickness is highly variable, though it tends to be predictable within altitudinal zones which reflect the bioclimatic controls on peat accumulation; namely temperature, cloudiness and precipitation (Costin 1954, Hope *et al*. 2012). Our stratigraphic data were used to create a standard stratigraphy for the five peatland categories (fen, three bog types and moor) for five 300 m altitude slices above 700 m. Table 2 shows the estimates of mean depth for each horizon that were used to calculate peat volumes by peatland category and altitude slice. These means are derived from transect data which include the shallower peats around the margins of small peatlands. However, several peatlands larger than 1 ha were examined individually and estimates of mean depths were increased for these where stratigraphic information suggested that this provided a truer picture. For example, in the large *Carex* fens the sedge peat layer usually has uniform thickness across much of the peatland and may be up to 4 m in depth, as at Micalong Swamp (Kemp & Hope 2014). A value of 2.2 m was used as the average depth of fibric sedge peat for this peatland.

For each mapped peatland the mean or specified thickness of each layer was multiplied by the mapped area and the results were summed to calculate total peat volume by peatland type and altitudinal zone. The results are summarised in Table 2 and show that the bogs and fens of the Snowy Mountains region of NSW and the ACT contain 49 million m^3 of peat.

Carbon storage

There is a reasonably robust relationship ($y = 0.5012x$, $R^2 = 0.917$) between % LOI (y) and % carbon (x) for all sediment types (Figure 7). Carbon content is highest (22–57 %) in fibrous and sapric peats, and lower (11–18 %) in hemic peat from *Empodisma* moor, suggesting that the latter is partially humified or even mineralised. However, the *Empodisma* moor samples came from the margin of the peatland, where slope wash may have introduced sand and clay to the peat. Sapric peat tends to have a higher carbon content (5–8 % more) in relation to % LOI than the fibrous peats.

When the C values are converted to carbon concentrations per unit volume of fresh sediment (Table 3), the low-density, high-water-content fibrous peats have lower values of carbon per unit volume than the more compressed hemic and sapric peats. Hemic *Carex* peats have slightly lower C concentration than fibric-hemic shrub bog peats.

Because conservative values for mean peat depths were used to calculate peat volume, it is likely that the carbon stock estimates in Table 4 are minimum values. The average carbon store in *Sphagnum* bogs in the sub-alpine and alpine areas is 200 Mg ha^{-1}, while for montane and sub-alpine *Carex* fen it is about 750 Mg ha^{-1}. However, individual peatlands may preserve much larger stores. The 4 m peat column at Micalong Swamp represents around 2600 Mg ha^{-1} and a 1.5 m hemic-

Table 2. Estimated mean thicknesses (in cm) and volumes (in thousands of cubic metres) of fibric/hemic and sapric peat and organic rich clays in the Snowy Mountains region of NSW and the ACT. The altitude slices overlap montane (< 1100 m), sub-alpine (1100–1700 m) and alpine (> 1700 m) zones. SSB = *Sphagnum* shrub bog.

Altitude zone (m)	**Alpine SSB**			**Sub-alpine SSB**			**Montane SSB**			***Empodisma* moor**			***Carex* fen**		
	fibric/ hemic	sapric	humic clay	fibric/ hemic	sapric	humic clay	fibric/ hemic	sapric	humic clay	fibric/ hemic	sapric	humic clay	fibric/ hemic	sapric	humic clay
	Thickness [cm]														
700–1000							30	25	20	10	10	15	40	20	60
1000–1300				30	25	20	40	30	20	15	10	20	75	20	80
1300–1600	30	25	20	35	30	25	35	30	25	20	15	20	45	15	30
1600–1900	30	15	15	30	35	15				20	15	15	40	10	20
>1900	10	10	10							10	5	5	15	10	10
	Volume [m^3 (1000)]														
Snowy Mountains region	**3480**	**1970**	**1950**	**7880**	**7290**	**5320**	**620**	**470**	**1090**	**3120**	**2310**	**3140**	**17020**	**4850**	**12100**
Kosci NP	3480	1970	1950	7130	6640	4700	365	280	190	2430	1795	2430	8340	2510	6300
ACT Mountains				510	380	260	45	34	23	295	215	320	3940	600	2570

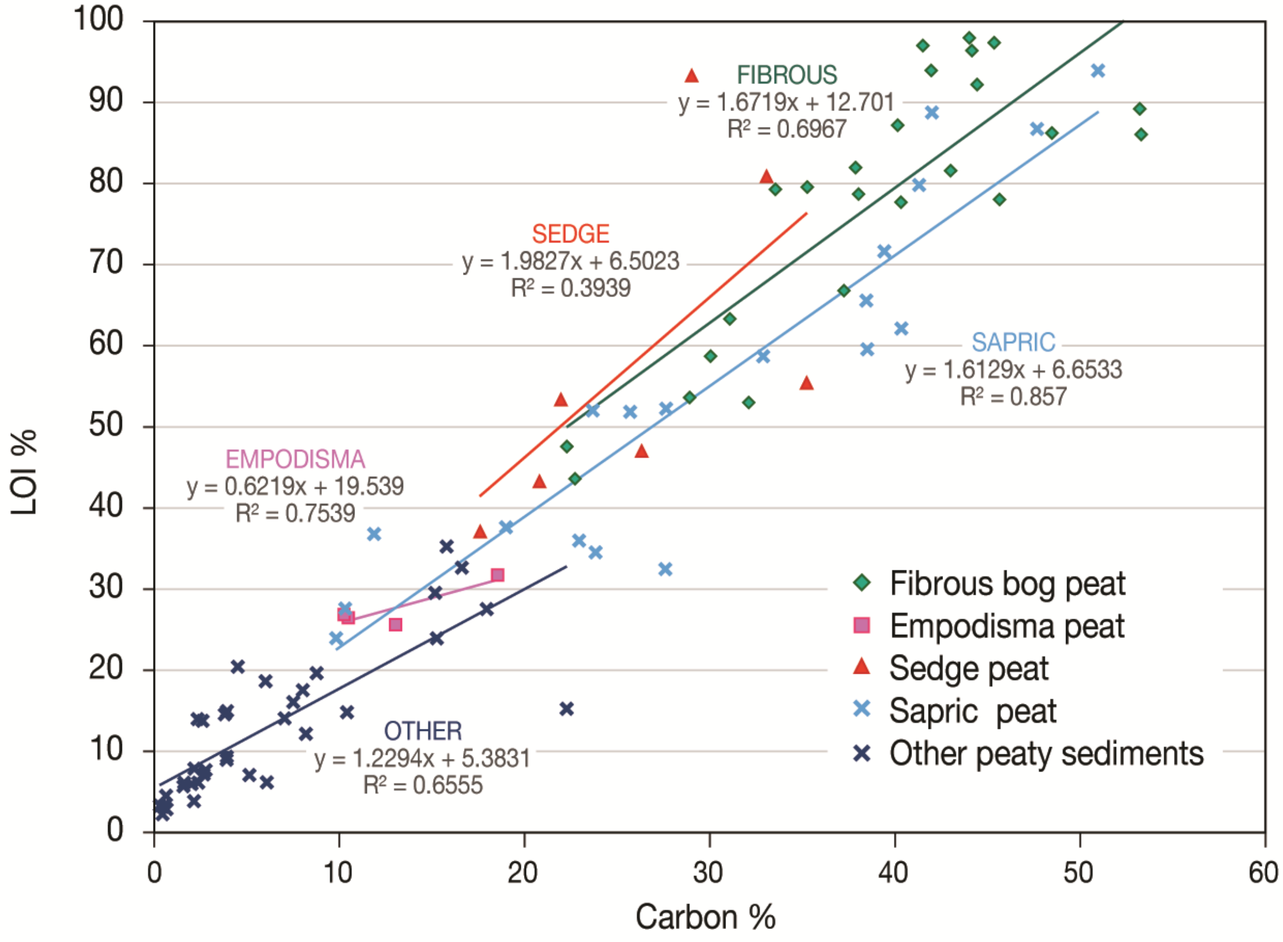

Figure 7. Organic content (% LOI) *vs.* elemental carbon for five peatland sediment types.

sapric profile at Rennix Gap in the sub-alpine area represents 950 Mg ha^{-1}.

Net carbon accumulation rates using dated sections

There are 28 radiocarbon dated peat sections from *Sphagnum*-shrub bogs, 12 from *Carex* fens and two from *Empodisma* moor in the Snowy Mountains region which, together, provide a general picture of net long-term peat accumulation rates over the past 5000 years or so. Details of the sites and 125 radiometric dates are given in the Appendix.

Late Holocene (5000–300 cal yr BP) accumulation rates

For Ginini Bog (ACT), a sub-alpine *Sphagnum* shrub bog which has not been damaged by grazing, the long-term net accumulation rate of hemic *Sphagnum* peat is, at maximum, 32 mm per century over 3000 years (Hope *et al.* 2009). This can be compared to Diggers Creek Bog (near Smiggins Holes), which was lightly grazed prior to 1950 (Martin 1999). Here the deepest hemic-sapric peats built up at 8.5 mm per century from 4880 to 2000 cal yr BP, then averaged 23 mm per century for the next 1900 years. Rennix Gap Bog, which is drier and was heavily grazed, preserves sapric peat with a mean accumulation rate of 11 mm per century between 8000 and 1000 years ago (Martin 1999). Growth rates of 10 mm per century were recorded for fibric peat in an alpine shrub bog by Marx *et al.* (2010). Montane *Sphagnum*-restiad peatlands such as Bega Swamp, east of Nimmitabel (at 1080 m), built up sapric peats at mean rates of 22 mm per century from 3500 to 1000 years ago (Donders *et al.* 2007). The only estimate for *Empodisma* moor suggests a long-term rate of only 8 mm per century, but complications in the dating make this estimate very unreliable (Hope & Clark 2008).

Under extremely good conditions, *Carex* fens can accumulate peat at 60–90 mm per century, and many seem to have been in a growth phase for the

Table 3. Averages for water, LOI and carbon used to derive estimates for the carbon content of compressed moss, peat types and sediments. *n* is the number of samples used in each determination. Values for Wellington Plains, Victoria (Grover *et al*. 2005) are included in the averages for moss and fibric-hemic and sapric peats. Summaries for each peat type ('**ALL**') are in bold. ASSB = Alpine *Sphagnum* shrub bog; SSSB = Sub-alpine *Sphagnum* shrub bog; EM = *Empodisma* moor; CF = *Carex* fen.

Vegetation type	Peat type	Water content (Mg m^{-3})	Organics LOI (%)	*n*	Carbon (%)	n	Carbon (Mg m^{-3})
ASSB	Moss	0.88	74±17.1	6	34±7.3	6	0.042
ALL	**Moss**	**0.89**	**78**±13.2	**13**	**36±6.5**	**9**	**0.045**
ASSB	Fibric-Hemic	0.83	86±8.3	8	43±3.5	8	0.074
SSSB	Fibric-Hemic	0.85	67±17.7	7	38±12.3	7	0.055
ALL	**Fibric-Hemic**	**0.83**	**77±18.5**	**15**	**41±8.9**	**15**	**0.065**
EM	Hemic	0.65	28±30.2	4	13±3.8	4	0.046
CF	Fibric sedge	0.83	61±19.1	25	26±6.5	7	0.059
ASSB	Sapric	0.81	59±21.8	14	33±11.6	14	0.061
CF	Sapric	0.72	33±14.5	8	16±7.6	5	0.065
ALL	**Sapric**	**0.81**	**55±19.4**	**35**	**30±12.4**	**16**	**0.063**
ASSB	Peaty-Clay	0.76	23±8.4	6	13±4.2	6	0.028
CF	Peaty-Clay	0.49	16±8.6	17	10±6.2	4	0.026
ALL	**Peaty-Clay**	**0.57**	**17±8.5**	**6**	**12±4.9**		**0.027**
ASSB	Clayey sand	0.44	10±5.3	6	10±2.9	6	0.017
CF	Clayey sand	0.28	6±4.5	25	3±1.5	10	0.018
ALL	**Clayey sand**	**0.29**	**6±4.6**	**50**	**4±2.0**	**17**	**0.017**
CF	Sand	0.19	3±0.9	4	0.5±0.1	4	0.003

past 3500–2700 years. For example, Micalong Swamp built up dense fibrous sedge peat at 38 mm per century from 7740 to 3600 cal yr BP (Kemp & Hope 2014). After that the average rate was 37 mm of less dense peat per century. The highest rates found are for fibrous sedge peat in Boboyan and Bogong Creek swamps in the ACT, where the averages over the past 2500 years are 84 and 92 mm per century, respectively (Hope *et al.* 2009, Hope unpublished results). Under the *Carex* peats in these sites, about 2 m of humic clays built up between 9000 and 2700 cal yr BP, at long-term net accumulation rates of 33–37 mm per century.

Post-grazing (AD 1900–2000) accumulation rates

The grazing era ended at various times due to concerns about soil erosion, water quality and the establishment of reserves. In the ACT, cattle were removed by 1910 to protect water supply catchments (Hope *et al.* 2009) while the alpine and, subsequently, the sub-alpine of the Snowy Mountains was de-stocked from 1945 (Worboys *et*

Table 4. Estimated peat volume and carbon mass in the Snowy Mountains Region peatlands.

Zone	**Mire area (ha)**	***Sphagnum* peat**	***Empodisma* peat**	***Carex* peat**	**Sapric peat**	**Organic clays**	**Total**
		Volume of sediment [m^3 (1000)]					
Alpine	1530	3520	140	40	2455	2085	
Sub-alpine	4030	7380	2680	2230	9300	9015	
Montane	1880	1080	305	14745	5150	11620	
Totals	**7440**	**11980**	**3125**	**17015**	**16900**	**22720**	**74300**
		Carbon mass (Gg)					
Alpine	1530	260	5.5	2.5	150	60	
Sub-alpine	4030	410	123	130	590	245	
Montane	1880	60	14	870	335	305	
Totals	**7440**	**730**	**143**	**1003**	**1075**	**610**	**3560**

al. 2011) following the declaration of Kosciuszko National Park.

In some cases, recovery by *Sphagnum* since the cessation of grazing has been impressive, with up to 700 mm of compressed *Sphagnum* accumulating in about 100 years at Snowy Flats (ACT) (Hope 2006). Depths of 32, 20 and 18 mm of *Sphagnum* moss peat had built up (Martin 1999) at Wilsons Valley, Rennix Gap Bog, and Diggers Creek, respectively, presumably over about 60 years since cattle were removed. On the alpine Swampy Plain at 2000 m altitude we noted 10–15 mm of litter and peat in wet areas. These materials have built up over the past 60 years and are underlain by gravel fans that were probably caused by erosion following grazing. Marx *et al*. (2010) used ^{210}Pb measurements at two alpine sites to show historical rates of *Sphagnum* accumulation of 92 and 86 mm per century. These accumulation rates provide a guide to potential short-term (decadal) carbon sequestration rates.

Applying a range selected from observed net moss and sedge peat accumulation rates to the carbon density values derived in Table 4 allows estimation of the apparent recent rate of sequestration of carbon by peatlands over the last century and the average net rates for carbon storage over 2 to 5 millennia before that time (Table 5).

Sphagnum bogs with little disturbance have the highest rates of carbon accumulation (0.5–1.6 Mg ha^{-1} yr^{-1}) reflecting the good conditions for peat preservation. By comparison, the sedge fens, which accrete peat more quickly, have a lower sequestration rate (0.2–0.6 Mg ha^{-1} yr^{-1}), reflecting the low bulk density of the peat. For older sapric and hemic peats the late Holocene net carbon storage rates (0.07–0.2 Mg ha^{-1} yr^{-1}) are similar for the sedge fens and *Sphagnum* shrub bogs.

The whole peatland estate of the Snowy Mountains has an historical (last 50–80 years) annual mean carbon sequestration rate of only 5000±2400 Mg yr^{-1}, as calculated from the sum of the estimated volumes of the three fresh-peat categories *Sphagnum*, *Empodisma* and *Carex*. The wide spread in the estimate reflects the imprecision in values for the rate of vertical accretion and that peat accumulation can vary widely across and between individual bogs. The estimate of the late Holocene (last 3000 years) net accumulation rate is 2350±930 Mg yr^{-1}, a reduction of 53 % from the historical rate.

DISCUSSION

Peat volumes

Although *Carex* fens cover about a quarter of the peatland area (1870 ha or 25 %), they contain an estimated 21.9 million m^3 of peat, equal to the 21.7 million m^3 in the three *Sphagnum* shrub bog communities, moorland making up the rest of the 49 million m^3 total. *Carex* fen peats contribute 74 % of the peat volume in the ACT, which lacks very

Table 5. Estimates of long-term carbon accumulation rates in the Snowy Mountains mires based on maximum and minimum observed peat accumulation rates (AR). Fresh *Sphagnum* peat sections span several decades and the other rates are based on dated sections. Average carbon density is taken from Table 3. SR is net storage rate of carbon.

	Fresh *Sphagnum* peat	**Hemic *Sphagnum* peat**	**Hemic *Empodisma* peat**	**Fibric-hemic *Carex* peat**	**Sapric peat**	**Organic clays**
Maximum AR (mm/100 years)	350	32	9	92	15	33
Minimum AR (mm/100 years)	120	15	7	36	9	8
Carbon density (Mg m^{-3})	**0.045**	**0.065**	**0.046**	**0.059**	**0.063**	**0.027**
Maximum SR (Mg ha^{-1} yr^{-1})	1.57	0.21	0.04	0.54	94.9	89.8
Minimum SR (Mg ha^{-1} yr^{-1})	0.54	0.10	0.03	0.21	0.06	0.02
	Carbon storage for the Snowy Mountains Region					
Area (ha)	3930	3930	1620	1870	7430	7430
Maximum annual SR (Mg yr^{-1})	6240	820	70	1010	710	670
Minimum annual SR (Mg yr^{-1})	2139	384	52	397	423	162
Average annual SR (Mg yr^{-1})	**3560**	**600**	**60**	**700**	**560**	**410**

extensive wet sub-alpine areas but has large montane fens. By contrast, the Victorian Highlands have few *Carex* fens so peat there is mainly in shrub bogs (Lawrence *et al*. 2009, Wild & Magierowski 2015). Only 50 % of the peat volume in *Carex* peatlands surveyed in the NSW Snowy Mountains lies within a national park, compared with 93 % of the peat underlying the *Sphagnum* shrub bogs.

Carbon storage

Grover *et al.* (2005) recorded mean carbon values of 41.5 % for fresh *Sphagnum* peat (fibric), 43.0 % for hemic and 41.3 % for sapric peat from a 2.3 m section in sub-alpine *Sphagnum* shrub bog at Wellington Plain, Victoria. They suggest that carbon bulk density increases down the profile as a result of preferential removal of less carbon-dense molecules. Their bulk density values are higher than the mean values found in this study, particularly for sapric peat, but some individual values from the Snowy Mountains match or exceed theirs. Our standard deviations of 20−50 % show that a wide range of values can occur for all components and that many more measurements using standardised techniques will be required to improve accuracy.

The range of 0.6 to 1.6 Mg ha^{-1} yr^{-1} for storage of fresh *Sphagnum* peat over the last few decades is similar to the values for carbon flux by eddy covariance of 1.8 to 2.1 Mg ha^{-1} yr^{-1} noted for restiad peatland in New Zealand by Nieveen & Schipper (2005). The total sequestration of around 5000 Mg yr^{-1} for the 70 km^2 of peatland in the Snowy Mountains is, of course, only a small fraction of the carbon fixed each year by the peatlands because much of this carbon is quickly lost to respiration, oxidation, decay and removal as DOC in streams. The peatlands are possibly the most carbon-dense ecosystems in the region, with a carbon store of 3.5 Tg. Although the carbon content of living biomass in most peatlands is much smaller than in old growth forests, the stored carbon can exceed that held in other ecosystems. For example, the 4 m sedge fen peat profile in the 20 ha Micalong Swamp may store almost as much carbon (2575 Mg ha^{-1}) as *Eucalyptus regnans* forests in Victoria, which store 2800 Mg ha^{-1} and are claimed to be the most carbon-dense ecosystems in the world (Keith *et al.* 2009).

The lower net accumulation rates in older (millennial time span) peat sections is presumably partly due to the gradual loss of easily degraded components as predicted by Clymo *et al*. (1998). However, the long-term rates may also reflect the impacts of drought and fire events, especially if they led to peat humification or erosion. The range of values for long-term net accumulation rates derived from individual peat columns presumably reflect both the range of productivity in different peatlands and the conditions of storage of peat once formed. The lower values may thus reflect the damage done to thousands of years of peat 'capital' by a few decades of intentional burning and cattle grazing which compressed and drained the acrotelm. Fibric and hemic peat may have been converted into sapric peat and organic-rich clays. This process was quantified by Grover & Baldock (2010) and Grover *et al*. (2012) who analysed damaged and undamaged peat profiles at Wellington Plain, Victoria.

Our estimates for peat growth given above indicate that such a conversion from hemic to sapric peat involves a loss of around 50 %, and to organic-rich clays a further 60–80 %, of the carbon. In addition, at least part of the area of extant *Empodisma* moor may once have supported shrub bog and, similarly, some proportion of tussock grasslands on valley bottoms (not included in our mapping) supported peatlands prior to grazing by stock. The very large loss of carbon store caused by these changes has not been quantified for the Snowy Mountains as a whole, although some individual cases are well known (Costin 1954).

Damage to bogs by grazing, ditching and fire since European settlement has created significant gaps in many records which may reflect the loss of many centuries of peat accumulation. At its most extreme, nearly all of the peat record is removed, as at Yaouk Swamp, where the top of a sapric sedge peat is about 8000 years old and buried beneath grazing era clays. This may reflect a former deep peat profile that became mineralised after being ditched and burned repeatedly (Ben Keaney, personal communication). This has also been the fate of extensive areas of *Sphagnum* shrub bog such as that around the Valentine River and the upper Geehi, where 0.01 to 0.02 m of *Sphagnum* and peaty silts on peaty gravels mark the former presence of deep peatlands.

For many *Sphagnum*-shrub bogs the balance between net carbon storage and net loss is clearly precarious, and it was firmly tipped towards carbon loss by the era of grazing by stock. Monitoring of the current carbon budgets of some representative peatlands will be necessary to understand whether climate change and current management have allowed these systems to recover their long-term role as a store of carbon by sequestration or if they continue to degrade and release more carbon to the atmosphere and groundwater flows.

Climate change

Given that the peatlands have persisted on millennial timescales, are they at risk from the warming and precipitation changes that have been forecast (Worboys *et al*. 2011) for the Australian Alps? Whinam & Chilcott (2002) showed that the Snowy Mountain *Sphagnum* shrub bogs were near the limits for *Sphagnum* growth, with summer heat and UV radiation commonly causing bleaching. They found that the area under bog had declined over the past thirty years. It seems likely that dry warm phases, particularly hot summers, probably cause most peatlands in the region to record negative growth and become carbon sources. Freeman, *et al.* (2001a, b) have suggested that peat is preserved in waterlogged conditions by an inhibitor that prevents phenols from being metabolised by phenol oxidase, an enzyme produced by bacteria. Drying episodes depress the concentration of this inhibitor, allowing peat to be metabolised. Grover & Baldock (2010) found that although fresh peat was readily oxidised and lost its structure, this process slowed as the more resistant components such as waxes, phenols, cuticles and carbonised material came to make up a larger proportion of the peat. Hence the peatlands of the Snowy Mountains may be resilient even under such negative growth conditions, because the bulk of the deposit has probably already lost most of its readily oxidisable components.

Clark (1980) found that the surface of *Sphagnum* peatlands with a good source of water could fluctuate seasonally between rapid growth and loss of height. Under the projected 2–4 °C increase in mean temperatures by 2045 and possible reductions of summer rainfall (Worboys *et al*. 2011), we may expect that *Sphagnum* will spend longer periods recording negative growth and so will become restricted to well-shaded sites. Soil desiccation on peatland margins may convert *Sphagnum* shrub bog to moorland or tussock grassland at lower altitudes. This, in turn, could result in the attrition of carbon stores and conversion of fibric peat to sapric peat. Worboys *et al*. (2011) also predict a reduction in forest cover and litter which would in turn lead to lower rates of groundwater recharge. As *Carex* fens depend on groundwater inputs in summer, this could affect some fens across the region. Longer episodes of summer desiccation will increase fire vulnerability. Thus, climate change is likely to have multiple interlinking negative consequences for the conservation of carbon stored in the Snowy Mountains peatlands.

Management of the carbon store and carbon credits

The general principles for enhancing carbon storage in peatlands have been listed by Good (2006) and consist of actively reducing disturbance and promoting water retention. At Kosciuszko National Park this has resulted in the stabilisation, by bog vegetation, of former gravel sheets that resulted from cattle damage to peatlands and streamlines. Maintaining effective recovery is key, and is threatened in several areas of the Snowy Mountains by feral horses which trample the vegetation, break down stream banks, and drain peatlands (Worboys & Pulsford 2013). Such drained bog areas are more vulnerable to the effects of fires while well-watered sites lose almost no peat even when litter and surface vegetation is burnt (Hope *et al*. 2012).

Retaining the carbon store has a possible monetary value. Tanneberger & Wichtmann (2011) state that a Verified Carbon Standard now recognises peatland restoration as an appropriate activity for carbon credits. Typically, in private carbon trading, buyers and sellers rely on third parties to verify that carbon stores are being retained. The carbon credits come from the avoidance of CO_2 emissions from fossil peat, not from the fixation of new carbon. In principle, conservation of the existing peats and Histosols of the Snowy Mountains could be sold as carbon credits. This would require verification protocols and, presumably, a guarantee by an independent authority such as the NSW government that the peatlands would be preserved.

Passive management assumes that a significant proportion of the mountain peatlands will persist under a range of disturbance and climate change scenarios (Clarke *et al*. 2015). But, given the loss of peatlands over the past century, it is more probable that active management will be needed to enhance mire community recovery and peat accumulation. To investigate this, field research to determine the carbon balance of the peatlands should be undertaken. Certainly, more intensive stratigraphy, dating, bulk density and carbon content data will be needed to validate the preliminary estimates for peat growth given here. The results could be statistically improved by analysing numerous peat sections to enable an assessment of variability, as demonstrated in Finland by Torrpa (2011). Such work would be valuable in devising management approaches to help preserve these ecologically significant landforms and their carbon stores.

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Appendix

Dated peat sections in the Snowy Mountains region, NSW and ACT. Site numbers refer to points marked on Figure 1; there are no points for Mulloon Swamp and Caledonia Fen. Radiocarbon dates are calibrated by CalPal and modern ages by CALIBomb, and given as cal years BP (1950 AD). Optically stimulated luminescence (OSL) and lead 210 (^{210}Pb) dates are also cal years BP. For (PINE) and (TOP) dating methods, first consistent appearance of *Pinus* pollen is taken as 50 cal yr BP (1900 AD) and peatland surface as -50BP (2000 AD). Peat accumulation rates are calculated between dated levels and generally refer to the peat type to the left of the estimate. Vegetation codes: ASSB - Alpine *Sphagnum* shrub bog; CF - Carex fen; EM - *Empodisma* (restiad) moorland; MSSB - Montane *Sphagnum* shrub bog; SSSB: Subalpine *Sphagnum* shrub bog.

Point # in Fig. 1	Site Name	State	Altitude (m)	Vege-tation	Depth (cm)	^{14}C Age	Cal Age	Laboratory number	Core material	Net accum-ulation rate (mm/100 yr)	Source
1	Blundells Flat	ACT	762	CF	50		50±25	(PINE)	sedge peat	58.0	Hope unpublished
			762	CF	188	2375±45	2430±70	Wk 17023	peaty sand		Hope unpublished
2	Boboyan Swamp	ACT	1154	CF	40		50±25	(PINE)	sedge peat	152.4	Hope unpublished
			1154	CF	56	192±23	156±124	DAMS-6718	sedge peat	162.4	Hope unpublished
			1154	CF	125	542±24	576±40	DAMS-6719	sedge peat	15.0	Hope unpublished
			1154	CF	131	1135±26	982±57	SSAMS-ANU 8307	sedge peat	57.8	Hope unpublished
			1154	CF	205	2247±26	2259±64	DAMS-6720	sedge peat	80.0	Hope unpublished
			1154	CF	233	2504±26	2611±84	DAMS-6721	sedge peat	64.3	Hope unpublished
			1155	CF	255.5	2855±40	2964±104	SSAMS-ANU 8309	sedge peat	107.9	Hope unpublished
			1154	CF	372	3694±29	4039±43	DAMS-6722	peaty silts	21.2	Hope unpublished
			1154	CF	425	5730±31	6540±51	DAMS-6723	peaty silts	185.7	Hope unpublished
			1154	CF	490	6041±29	6892±44	DAMS-6724	peaty silts	21.3	Hope unpublished
			1154	CF	536	8094±40	9046±39	DAMS-6725	peaty silts	3.2	Hope unpublished
			1155	CF	552	12015±43	13993±200	DAMS-6726	peaty silts		Hope unpublished
3	Bogong Creek Swamp	ACT	1000	CF	35		50±25	(PINE)	sedge peat	106.5	Hope unpublished
			1000	CF	174.5	1466±27	1356±25	SSAMS-ANU 3610	sedge peat	72.4	Hope unpublished
			1000	CF	265	2510±40	2608±92	D-AMS 005649	sedge peat	48.7	Hope unpublished
			1001	CF	320	3460±30	3742±57	SSAMS-ANU 3610	sedge peat	46.4	Hope unpublished
			1000	CF	365.5	4159±41	4717±92	SSAMS-ANU 3611	peaty sand	246.9	Hope unpublished
			1000	CF	405	4290±40	4881±36	D-AMS 005650	humic clay	61.3	Hope unpublished
			1000	CF	424	4351±31	5190±40	SSAMS-ANU 3612	humic clay	26.3	Hope unpublished

Point # in Fig. 1	Site Name	State	Altitude (m)	Vege-tation	Depth (cm)	^{14}C Age	Cal Age	Laboratory number	Core material	Net accum-ulation rate (mm/100 yr)	Source
3	Bogong Creek Swamp	ACT	1000	CF	577	9650±60	11005±145	SSAMS-ANU 3613	peaty sand		Hope unpublished
			1000	CF	560	13464±52	16418±410	D-AMS 005653	humic clay		Hope unpublished
5	Bogong Swamp 1	NSW	1590	SSSB	0			(TOP)	*Sphagnum* peat	81.8	
			1590	SSSB	225	2630±120	2695±147	n/a	peat		Martin unpublished
	Bogong Swamp 2	NSW	1590	SSSB	0			(TOP)	*Sphagnum* peat	34.4	
			1590	SSSB	120	3220±40	3443±39	SUA 1624	peat		Martin unpublished
4	Brooks Ridge	NSW	1450	SSSB	13		50±25	(PINE)	sapric peat	8.2	Mooney *et al.* 1997
			1450	SSSB	46.5	3730±300	4125±395	β-81387	sapric peat		Mooney *et al.* 1997
	Caledonia Fen	VIC	1280	CF-SSSB	35		50±25	(PINE)	sedge peat	5.8	Kershaw *et al.* 2007
			1280	CF-SSSB	90	8495±460	9514±590	GX6515	sedge peat	18.9	Kershaw *et al.* 2007
			1280	CF-SSSB	137	10300±280	12001±483	OZ 493	humic clay	8.3	Kershaw *et al.* 2007
			1280	CF-SSSB	239	20900±420	24246±570	OZ 494	humic clay		Kershaw *et al.* 2007
7	Carruthers Creek 1	NSW	1980	SSSB	0			(TOP)	peat	32.8	
			1980	SSSB	60	1835±180	1778±206	NZ 403	peat	8.5	Costin 1972
			1950	SSSB	195	14400±250	17575±330	NZ 401	peat		Martin 1999
	Carruthers Creek 2	NSW	1980	SSSB	0			(TOP)	peat	26.8	
			1980	SSSB	70	2490±110	2560±140	NZ 402	peat		Martin 1999
6	Charlottes Pass	NSW	1825	SSSB	0			(TOP)	*Sphagnum* peat	15.4	
			1825	SSSB	120	6870±160	7740±140	Gak 2787	sapric peat		Martin 1999
7	Club Lake Fen 1	NSW	1955	CF	40	1830±100	1756±117	Gak 2790	peaty silts	61.7	Martin 1986
			1955	CF	148	3260±90	3506±98	Gak 3931	peaty silts	400.0	Martin 1986
			1955	CF	200	3380±90	3638±121	Gak 3932	peaty silts	63.4	Martin 1986
			1955	CF	290	4400±90	5061±156	NZ 317	peaty silts	117.6	Martin 1986
			1955	CF	310	4580±220	5235±278	W 770	peaty silts	65.9	Martin 1986
			1955	CF	455	6520±100	7426±90	SUA 2250	peaty silts	241.9	Martin 1986
			1955	CF	530	6870±160	7738±140	Gak 2791	peaty silts		Martin 1986
8	Coronet Creek	ACT	1102	EM	15		410±65	OSL	peaty sand	7.4	Worthy 2012

Point # in Fig. 1	Site Name	State	Altitude (m)	Vege-tation	Depth (cm)	^{14}C Age	Cal Age	Laboratory number	Core material	Net accum-ulation rate (mm/100 yr)	Source
8	Coronet Creek	ACT	1102	EM	52		5400±800	OSL	peaty sand	20.9	Worthy 2012
			1102	EM	75		6500±800	OSL	peaty sand		Worthy 2012
9	Cotter Source Bog	ACT	1720	SSSB	9		50±25	(PINE)	*Sphagnum*	29.1	Hope & Clark 2008
			1720	SSSB	85	2600±110	2658±152	ANU 10816	sapric peat	25.3	Hope & Clark 2008
			1720	SSSB	105	3220±140	3450±168	ANU 10193	sapric peat	9.4	Hope & Clark 2008
			1720	SSSB	168	9040±80	10149±123	ANU 10194	peaty sand		Hope & Clark 2008
	Cotter Source Margin	ACT	1725	EM	2.5		50±25	(PINE)	*Empodisma* peat	57.1	Hope & Clark 2008
			1725	EM	10.5	150±140	188±155	ANU 10818	*Empodisma* peat	7.4	Hope & Clark 2008
			1725	EM	30.5	2750±160	2907±198	ANU 10817	*Empodisma* peat		Hope & Clark 2008
10	Diggers Creek	NSW	1690	SSSB	15	40±70	106±124	SUA 2988	*Sphagnum* peat	23.7	Martin 1999
			1690	SSSB	60	2030±90	2010±108	SUA 2312	humic peat	8.2	Martin 1999
			1690	SSSB	85	4390±100	5055±161	Gak 3930	humic peat	10.3	Martin 1999
			1690	SSSB	110	6580±80	7492±60	SUA 2311	humic peat	5.7	Martin 1999
			1690	SSSB	135	10170±150	11848±339	Gak 3929	humic peat		Martin 1999
11	Duck Creek	NSW	1790	ASSB	4.5	1.149±0.07	-13±0.5	Wk 21594	*Sphagnum*	1100.0	Marx *et al.* 2010
			1790	ASSB	10	1.015±0.03	-8±0.9	Wk 22374	*Sphagnum* peat	22.1	Marx *et al.* 2010
			1790	ASSB	13.6	184±30	155±125	Wk 23571	*Sphagnum* peat	9.3	Marx *et al.* 2010
			1790	ASSB	16.7	460±30	490±20	Wk 22375	*Sphagnum* peat		Marx *et al.* 2010
			1790	ASSB	18.9	350±70	380±70	Wk 21595	*Sphagnum* peat		Marx *et al.* 2010
			1790	ASSB	24.6	1231±37	1115±65	Wk 23572	*Sphagnum* peat		Marx *et al.* 2010
12	Giandarra Bog	NSW	1390	SSSB	2.6	1.262±0.04	-13±0.2	ANU 6954	*Sphagnum* peat	64.4	Thomas 1991
			1390	SSSB	39.5	520±80	563±62	ANU 6955	*Sphagnum* peat	55.3	Thomas 1991
			1390	SSSB	65.5	1100±170	1026±176	ANU 6956C	humic clay		Thomas 1991
			1390	SSSB	81.5	740±110	700±100	ANU 6957C	humic clay		Thomas 1991
13	Ginini Flat W-core06	ACT	1590	SSSB	10		50±25	(PINE)	*Sphagnum* peat	39.3	Hope unpublished
			1590	SSSB	72.5	1730±35	1642±49	Wk 18653	*Sphagnum* peat	33.3	Hope unpublished
			1590	SSSB	128	3082±45	3303±51	Wk 18654	peaty clay		Hope unpublished

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13	Ginini Flat W-trench	ACT	1592	SSSB	0			(TOP)	*Sphagnum* peat	30.8	
			1592	SSSB	110	3280±70	3521±79	GRN 249l	*Sphagnum* peat	21.6	Costin 1972
14	Micalong Swamp	NSW	1100	CF	35		50±25	(PINE)	sedge peat	24.5	Kemp & Hope 2014
			1100	CF	122	3330±180	3601±213	ANU 8827	sedge peat	37.7	Kemp & Hope 2014
			1100	CF	278	6870±200	7739±173	ANU-8828	sedge peat	25.6	Kemp & Hope 2014
			1100	CF	387	10260±230	11991±436	ANU 8829	peaty clay	1.2	Kemp & Hope 2014
			1100	CF	390	12330±250	14550±493	ANU-3342	humic clay		Kemp & Hope 2014
15	Mount Stillwell	NSW	1990	ASSB	0			(TOP)	*Sphagnum* peat	20.8	
			1990	ASSB	32	1570±100	1485±100	Gak 1402	peaty silts		Martin 1999
	Mulloon Swamp	NSW	799	CF	35		50±25	(PINE)	sedge peat	141.0	Hope unpublished
			799	CF	90	430±70	440±80	ANU 10751	sedge peat	116.7	Hope unpublished
			799	CF	195	1280±115	125	ANU 10752	sedge peat	63.3	Hope unpublished
			799	CF	345	3440±90	3710±115	ANU 10753	sedge peat		Hope unpublished
16	Nursery Swamp 1	ACT	1092	CF	27.5	240±110	355±95	ANU 3356B	sedge peat	19.8	Hope 2006
			1092	CF	147.5	5610±240	6430±20	ANU 3354B	clayey sedge peat		Hope 2006
	Nursery Swamp 2	ACT	1092	CF	57.5	99.14±1.9%M	50±10	ANU 3356B	sedge peat	38.1	Hope 2006
			1092	CF	173	2910±80	3065±68	ANU 11640	sedge peat	20.3	Hope 2006
			1092	CF	297.5	8200±250	9185±278	ANU 3357A	humic clay	9.0	Hope 2006
			1092	CF	345	12300±120	14470±375	OZI 144	humic clay		Hope 2006
17	Pengillys Bog	NSW	1750	ASSB	18		50±25	(PINE)	*Sphagnum* peat	43.6	Hope unpublished
			1750	ASSB	38.5	475±40	522±15	S_ANU 26429	*Sphagnum* peat	6.9	Hope unpublished
			1750	ASSB	44.5	1460±40	1395±35	β394156	*Sphagnum* peat	5.0	Mooney unpublished
			1750	ASSB	55.5	3350±50	3585±69	S_ANU 26430	*Sphagnum* peat		Hope unpublished
18	Perisher Creek	NSW	1675	SSSB	0	891±30	9004±317	W 769	sapric peat	8.8	Costin 1972
			1675	SSSB	80	8100±250	9004±317	W 769	sapric peat		Costin 1972
7	Pounds Creek	NSW	1960	SSSB	63	9000±275	10120±369	SUA 271	peaty silt	14.1	Martin 1986
			1960	SSSB	108	11400±300	13317±308	Gak 3935	peaty silt	71.2	Martin 1986

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7	Pounds Creek	NSW	1960	SSSB	145	11840±240	13845±357	ANU 3265	peaty silt	6.3	Martin 1986
			1960	SSSB	165	15730±420	17010±450	SUA 252	muds		Martin 1986
19	Rennix (Boggy Plain)	NSW	1580	SSSB	20	1.197±0.012	-12±0.3	SUA 2825	sedge peat	13.5	Martin 1999
			1575	SSSB	31.5	920±80	837±76	Gak 3927	sapric peat	4.5	Martin 1999
			1575	SSSB	63.5	7090±80	7910±73	Gak 3928	sapric peat	3.9	Martin unpublished
			1580	SSSB	80	10410±210	12192±359	Gak 2785	sapric peat		Martin 1999
			1575	SSSB	84	7200±150	8030±149	Gak 2784	sapric peat		Martin 1999
	Rennix Gap	NSW	1575	SSSB	7		50±25	(PINE)	peat	13.3	Hope unpublished
			1575	SSSB	47.5	2920±100	3086±139	SUA 563	peat	6.3	Martin 1999
			1575	SSSB	63.5	4865±110	5606±125	SUA 564	peat	9.0	Martin 1999
			1575	SSSB	76	6120±115	7005±148	SUA 565	peat	11.9	Martin 1999
			1580	SSSB	98	8010±100	8863±147	SUA 2819	sedge peat	8.8	Martin 1999
			1575	SSSB	110	9060±40	10226±17	ANU 2177	humic clay		Hope unpublished
27	Rotten Swamp	ACT	1445	SSSB	15		50±25	(PINE)	*Sphagnum* peat	10.7	Hope & Clark 2008
			1445	SSSB	21	620±110	610±65	ANU 9483	*Sphagnum* peat	13.9	Hope & Clark 2008
			1445	SSSB	85.5	4570±110	5243±180	ANU 4227	*Sphagnum* peat	14.2	Hope & Clark 2008
			1445	SSSB	100.5	5500±90	6300±90	ANU 9484	*Sphagnum* peat		Hope & Clark 2008
20	Schlinck Pass	NSW	1770	ASSB	0			(TOP)	*Sphagnum* peat	81.1	
			1770	ASSB	150	3000		?	*Sphagnum* peat		Martin unpublished
17	Smiggins Holes	NSW	1675	SSSB	0			(TOP)	sedge peat	14.5	Martin unpublished
			1675	SSSB	120	7450±130	8250±125	Gak 1193	sapric peat		Martin unpublished
21	Snowy Flat	ACT	1619	SSSB	0			(TOP)	*Sphagnum*	850.0	Hope unpublished
			1619	SSSB	85		50±25	(PINE)	*Sphagnum*	42.6	Hope unpublished
			1619	SSSB	95	250±70	285±130	ANU 11463	*Sphagnum* peat	11.7	Hope unpublished
			1619	SSSB	185	7130±70	7950±65	ANU 11464	sapric peat		Hope unpublished
22	Snowy Plains	NSW	1310	CF	0			(TOP)	*Sphagnum* peat	5.8	
			1310	CF	200	2050±70	2028±86	GRN 2340	peaty sand		Costin 1972

Point # in Fig. 1	Site Name	State	Altitude (m)	Vege-tation	Depth (cm)	^{14}C Age	Cal Age	Laboratory number	Core material	Net accum-ulation rate (mm/100 yr)	Source
23	Tom Gregory Bog	ACT	1025	MSSB	87.5	5140±160	5920±190	ANU 12022	*Sphagnum* peat	20.3	Hope unpublished
			1025	MSSB	240	11550±230	13455±255	ANU 12023	*Sphagnum* peat		Hope unpublished
7	Twynam SW cirque 2	NSW	1950	ASSB	0			(TOP)	peat	18.9	
			1950	ASSB	45	2290±90	2323±146	ANU 432	peat		Costin 1972
	Twynam SW cirque 1	NSW	2010	ASSB	0			(TOP)	peat	26.9	
			2010	ASSB	280	9160±160	10355±193	ANU 431	peat		Costin 1972
	Twynam NE cirque	NSW	2000	ASSB	~ 40	2520±160	2580±181	W768	sedge peat		Costin 1972
			1975	CF	~ 70	8620±100	9717±235	NZ 400	sedge peat		Costin 1972
15	Upper Snowy	NSW	1940	ASSB	4.6	1.057±0.03	-10±0.4	Wk 24475	*Sphagnum*	18.9	Marx *et al.* 2010
			1940	ASSB	6.4		83±1	K732 (^{210}Pb)	*Sphagnum*	56.0	Marx *et al.* 2010
			1940	ASSB	7.8	20±30	107±1	Wk 24476	*Sphagnum* peat	6.3	Marx *et al.* 2010
			1940	ASSB	9.8	456±46	425±95	Wk 21592	*Sphagnum* peat	41.1	Marx *et al.* 2010
			1940	ASSB	46	1460±30 BP	1352±26	β394156	*Sphagnum* peat	29.9	Mooney unpublished
			1940	ASSB	56	1730±30 BP	1643±46	β394157	*Sphagnum* peat		Mooney unpublished
	Upper Snowy 2	NSW	1830	ASSB	~ 40	15000±350	18195±375	NZ 399	sedge peat		Costin 1972
24	Willigobung	NSW	780	CF	12		50±25	(PINE)	sedge peat	54.4	Kemp & Hope 2014
			780	CF	367.5	5770±120	6583±132	ANU 4384	sedge peat	37.2	Kemp & Hope 2014
			780	CF	522.5	9420±110	10745±220	ANU 4385	humic clay		Kemp & Hope 2014
20	Valentine Falls	NSW	1740	ASSB	0			(TOP)	*Sphagnum* peat	28.5	
			1740	ASSB	105	3360±240	3640±296	SUA 1617	*Sphagnum* peat		Martin 1999
25	Wilsons Valley	NSW	1460	SSSB	33	60±70	112±121	Gak 3924	*Sphagnum* peat	13.6	Martin 1999
			1460	SSSB	52	1600±80	1505±90	Gak 3923	humic peat		Martin 1999
7	Wrights Creek	NSW	1835	ASSB	0			(TOP)	sedge peat	9.2	
			1835	ASSB	85	7460±110	8265±100	SUA 2821	sapric peat		Martin 1999
26	Yaouk Swamp	NSW	1120	CF	134	8250±40	9229±73	ANU 11101H	sedge peat	49.8	Keany unpublished
			1120	CF	193	9250±40	10415±80	ANU 11439H	humic clay		Keany unpublished