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Loss of soil carbon in a world heritage peatland following a bushfire

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ABSTRACT

Background. Climatic events can have rapid and widespread environmental impacts on peatlands. This is concerning because peatlands are restricted environments in Australia and are vulnerable to degradation. **Aims.** This study aimed to investigate the loss of carbon from a burnt and eroded peatland. The cumulative effects of drought, bushfire and erosion events in south-eastern Australia was documented in a peatland in the Kings Tableland region within the Greater Blue Mountains World Heritage Area in New South Wales, Australia. **Methods.** Following a fire and subsequent rain event, soil classification and the total export of soil materials and nutrients were quantified. **Key results.** The fire and erosional events caused an estimated loss of 28.80 t of organic material and 3.46 t of carbon from this site in a single 3-month period. **Conclusions.** Peatlands are slow-forming accretionary systems and this study highlights the potential for considerable loss of organic material and carbon from peatland systems due to rapid, climatic-driven changes. **Implications.** Peatland degradation in world heritage areas can have implications for carbon accounting and soil erosional loss, which may impact downstream environments and the functioning of these sensitive systems.

Keywords: bushfire, carbon, carbon storage, ecosystems: temperate, mass movement, organosol, peatland, pollutants: soil.

Introduction

Peatlands cover approximately 3% of Earth's land surface, extending from tropical climates to arctic regions, and forming in depositional landscapes where organic matter may accumulate over time under suboxic conditions (Rydin and Jeglum 2006; Page and Baird 2016). Forming from the late Pleistocene to early Holocene, these environments provide valuable ecosystem services including significant carbon (C) storage, accounting for approximately 10% of global terrestrial carbon stocks (Page and Baird 2016). They also play important roles in flood mitigation, act as nutrient and contaminant sinks that improve water quality, and provide habitat that supports biodiversity (Pemberton 2005; Maltby and Acreman 2011).

Although peatlands are predominantly found in the Northern Hemisphere, covering an estimated 4 million km^2 across this region (Xu *et al.* 2018), they also form important ecosystems in the Southern Hemisphere, including Australia. Total peatland area (defined as greater than 30 cm peat with over 30% organic material) in Australia has been estimated at 1350 km^2, predominantly restricted to south-eastern Australia (Joosten and Clarke 2002). Peatlands are unique and diverse ecosystems, being commonly small, specialised to occupy specific habitats with distinct vegetation communities, and found across coastal, temperate and alpine environments (Black and Mooney 2005; Whinam and Hope 2005). Australia's typically arid climate and potential for significant bushfire events pose a threat to its limited distribution of peatlands. Furthermore, the effects of extreme climatic events (such as fire and erosion) on nutrient cycling and carbon storage of these systems is not well-known.

The degradation, compaction and potential loss of peat soils due to natural (such as climatic events) and human-induced disturbance (such as mining and grazing) is of concern worldwide (Rydin and Jeglum 2006; French et al. 2016; Page and Baird 2016). Peatlands typically have some resilience to disturbance, climatic variability and severe weather events due to their saturated state (Turetsky et al. 2014; Baird and Burgin 2016; Page and Baird 2016). However, their dependency on hydrology for functioning makes them vulnerable to degradation under persistent dry conditions (Bragg and Tallis 2001). Prolonged droughts can lead to a reduction in surface water and groundwater recharge, causing desiccation of the peat layers (Turetsky et al. 2014; Zaccone et al. 2014; French et al. 2016; Page and Baird 2016). The immediate impacts associated with burning of desiccated peatlands include loss of vegetative cover and organic material. The exposure of peat materials also makes them predisposed to erosional activity, and there is potential for the rapid export of materials (Bragg and Tallis 2001; Macdonald et al. 2007). Erosion of peatlands can lead to incised channels or gullies forming in place of preferential drainage lines, which can further modify natural hydrology and cause the deposition of sand and organic material downstream (Bragg and Tallis 2001; Cowley et al. 2016a). The combination of drought, fire and erosion can alter the functioning of peatlands, particularly due to increased frequency and severity of climatic events (Sulwiński et al. 2020), contributing to modified vegetation communities, lower water retention capability, reduced peat formation and a significant loss of organic material and carbon stored in peat systems (Turetsky et al. 2014; French et al. 2016; Page and Baird 2016).

Globally, peatlands are estimated to store approximately 597.8 Gt of carbon (Leifeld and Menichetti 2018). Within the Greater Blue Mountains World Heritage Area of south-eastern Australia, wetland and peatland systems have been calculated to store approximately 3.3 Mt of carbon or 12 Mt CO_2 equivalent (eq.) of carbon stocks (Cowley and Fryirs 2020). Estimates of carbon loss have been made both worldwide (Leifeld and Menichetti 2018) and in Australian peatlands (Cowley and Fryirs 2020), with a focus on degraded peatlands such as those impacted by mining, grazing and development. For example, an estimated 1.91 Gt CO_2 eq. are lost from degraded peatlands globally (Leifeld and Menichetti 2018). Within the Greater Blue Mountains World Heritage Area, it is predicted that 8.6 Mt CO_2 eq. will be lost from disturbed peatlands, which has significant implications for nutrient cycling and carbon emissions.

Although previous research has been conducted on post-fire impacts, including vegetation dynamics and recovery, and carbon storage on south-eastern Australian peatlands (Black and Mooney 2005; Good et al. 2010; Clarke et al. 2015), less is known about how nutrient cycling is impacted after fire and erosion events in these sensitive landscapes. The research undertaken in this work aimed to investigate the loss of carbon from a burnt and eroded peatland. It sought to explore the potential for irreversible changes to sensitive montane peatland ecosystems due to rapid environmental disturbance.

Materials and methods

Study area

The Greater Blue Mountains World Heritage Area, located west of Sydney, New South Wales, Australia, is an area of ecological, cultural and economic significance (United Nations Educational, Scientific and Cultural Organization (UNESCO) 2018). Montane peatlands are characterised by typically saturated, highly organic, low nutrient, acidic peat soils, with distinct vegetation communities (comprised of sedge, heath and shrub species), and in the Blue Mountains region are typically underlaid by sandstone geology. Peatlands in this region are often also commonly referred to as Temperate Highland Peat Swamps on Sandstone (Department of Agriculture, Water and the Environment (DAWE) 2022). These areas are recognised as having high conservation significance and are listed in Australia as an 'endangered ecological community' under the Federal *Environment Protection and Biodiversity Conservation Act 1999* and State *Biodiversity Conservation Act 2016;* they are also a focus for management and restoration at the local level. Peatlands across the World Heritage Area are under increasing pressure due to a range of factors, including urbanisation and mining (Belmer et al. 2015; Cowley et al. 2016b, 2019; Carroll et al. 2020) as well as extreme climatic events such as bushfires and erosion (Fryirs et al. 2021; Shaygan et al. 2022).

The Kings Tableland plateau (33° 48' 38" S, 150° 24' 42" E) is located south-east of Katoomba within the Blue Mountains National Park and the World Heritage Area. There are numerous peatland ecosystems present in this area. The study site for this research (referred to as Kings Tableland peatland) consists of a broad basin, headwater peatland (Fig. 1), with a distinctive vegetation community consistent with montane peatlands and greater than 30 cm in depth of peat (Joosten and Clarke 2002).

Site characteristics were determined using the Department Finance, Services and Innovation (DFSI) (2018) digital elevation model (DEM) dataset in QGIS version 3.22.3. The mean elevation of the site is 678 m above sea level (a.s.l), ranging from 695 m in the headwaters to 660 m at the exit stream. The mean slope is 6.23%, ranging from 0.01 to 29.39%. Covering approximately 4.74 ha and with a perimeter of 1901 m, the site has three distinct sections: the upper peat forming basin; the channelised mid-section; and the lower severely channelised section (Fig. 1).

The underlying geology of the region is Permo-Triassic quartz sandstone and inter-bedded claystone (van der Beek et al. 2001; Pickett and Alder 1997). The Australia Soil Classification (ASC) (Isbell et al. 2021) classifies the soils as sapric organosols containing >0.4 m of organic materials, with seasonal water logging along the main drainage channel and increasingly sandier unconsolidated materials on the outer margins. The sampled profiles contain histic epipedons overlying a sharp transition to the underlying sandstone

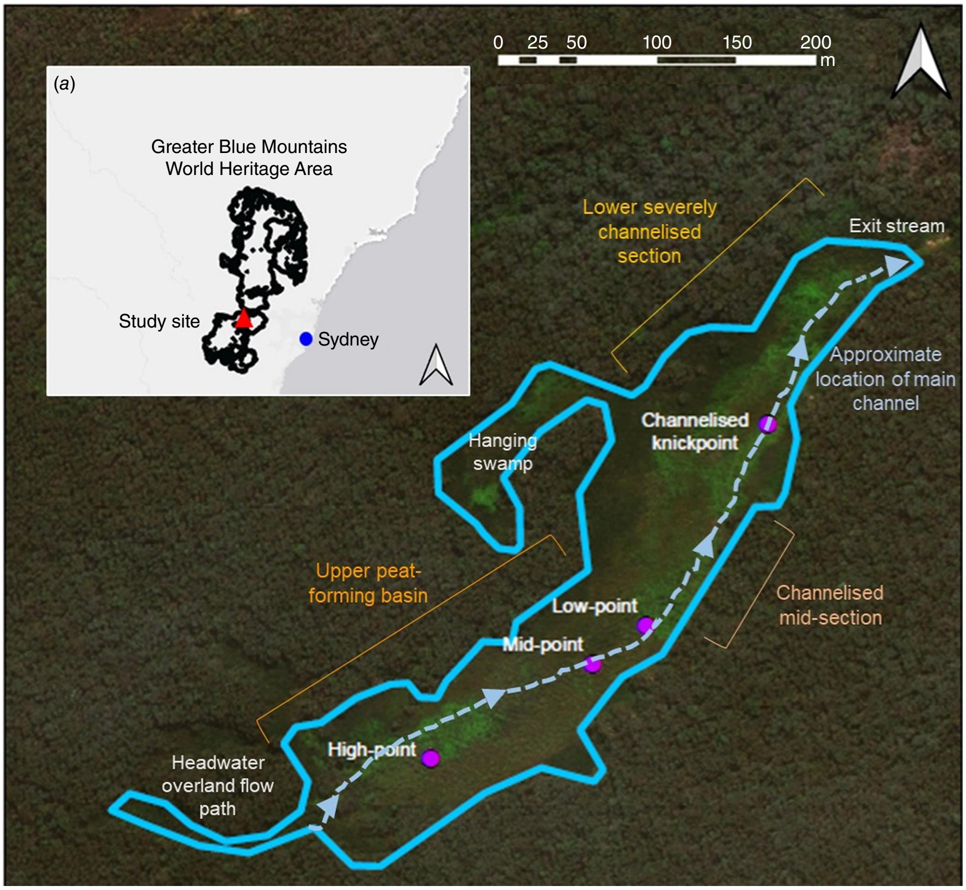

Fig. 1. Kings Tableland peatland (boundary shown in blue). Inset (*a*) highlights the location of the study site (shown with a red triangle) in the Greater Blue Mountains World Heritage Area (area outlined in black), New South Wales, west of Sydney (shown with a blue circle). The location of soil core sampling is indicated by purple circles and the direction of flow is indicated with arrows. Source: Google Satellite Imagery.

geology. This site has no permanent drainage structure, with preferential drainage lines in the upper basin, but the site is becoming increasingly channelised in the lower half of the peat-dominated area to the exit stream. The vegetation communities at the site are dominated by shrub and sedge species. Along the drainage lines, *Gymnoschoenus sphaerocephalus* (Button grass, family Cyperaceae), *Lepidosperma limicola* (Razor sedge, family Cyperaceae) and *Empodisma minus* (family Restionaceae) are prevalent. Larger shrubs, such as *Acacia ptychoclada* (family Fabaceae), and saplings of tree species including *Eucalyptus* spp. (family Myrtaceae), are common in the upper basin of the site. On the peat margin where the soil is sandier, *Schoenus apogon* (Common Bog Rush, family Cyperaceae) is present to the transition to canopy species (including *Eucalyptus* spp.).

Fire history and erosion events

A period of drought occurred across south-eastern Australia from 2017 to 2019 (Kemter *et al.* 2021; Department of Primary Industries (DPI) 2022), and high-intensity bushfire events from October 2019 to February 2020 impacted south-eastern Australia, including the Greater Blue Mountains World Heritage Area (Fryirs *et al.* 2021). The fire history and extent and severity of the 2019/2020 bushfires were assessed using QGIS version 3.22.3 based on datasets available from NSW DPE (2010; updated 2021, 2020). Observations of the impacts of the 2019/2020 fires were also taken in the field on three occasions – in March, June and November 2021 (13, 16, and 21 months post-fire event respectively).

In the period immediately following the bushfires, a significant rainfall event occurred throughout February 2020, with over four times the monthly average recorded, and above average rainfall continued across 2020 and 2021 (Kemter *et al.* 2021). Rainfall recorded by the Bureau of Meteorology (BOM) at the nearest weather station at Katoomba (Farnells Rd) was examined to determine the impacts of significant erosion events that occurred post-fire event (Bureau of Meteorology (BOM) 2022*a*).

Soil collection and analysis

Four soil cores were collected in June 2021 using polyvinyl chloride (PVC) pipes to a maximum depth of 40 cm along a transect of the peatland. The four individual cores were deemed adequate based on size of the site and the meta-analysis work of Pozza and Bishop (2019). This included three cores being collected from the high-point, mid-point and low-point of the peat-forming basin at the top half of the site, and one core being collected adjacent to a channelised knickpoint, which was eroded to bedrock in the lower half of the site (Fig. 1). Each core was eased into the ground by hand or using a mallet to the depth of the resistant layer. The cores were extracted and immediately wrapped in cling film, kept upright at all times and frozen (−18°C) prior to analysis. The depth of the peat to the bedrock or resistant layer was also estimated using a penetrating probe at each sampling location.

Cores were partially defrosted, the top layer in contact with the PVC pipe was scraped away using a scalpel, and two distinct layers were identified. The colour of each layer was determined using a Munsell Soil Color chart. A sub-sample was taken at 10 cm intervals using a scalpel to determine pH (using a Raupach soil pH kit). Two major horizons were identified based on soil visual structure, including the surface hemic layer (0–10 cm) and the lower, sapric layer (10–30 cm depending on core length and excluding the last 5 cm of the core that was impacted by the PVC pipe). Within each horizon (defined as surface (0–10 cm) and depth (10–30 cm) samples), a bulk sample was collected and thoroughly mixed prior to be being analysed by a NATA-accredited laboratory using standard methods (Rayment and Lyons 2011; Sparks *et al.* 2020) for field moisture content (% based on oven dried soil), Soil Organic Carbon (Walkley Black), Total Nitrogen, Nitrate, Nitrite, Phosphorus Retention Index (PRI), Phosphorus (Bray 1), exchangeable calcium (Ex-Ca), exchangeable potassium (Ex-K), exchangeable magnesium (Ex-Mg), exchangeable sodium (Ex-Na) and Cation Exchange Capacity (CEC).

Estimate of potential soil and carbon loss

Estimations of soil loss from within the peat boundary of Kings Tableland peatland were determined based on the modelled Revised Universal Soil Loss Equation (RUSLE) hillslope erosion for NSW dataset, which estimates soil loss ($t\,ha^{-1}\,month^{-1}$) by runoff (NSW DPE 2018). The rainfall-runoff erosivity factor in RUSLE was estimated using daily rainfall erosivity modelling for NSW and long-term rainfall records (Yang and Yu 2015). The soil erodibility factor was estimated from digital soil-mapping products and soil profile data (Yang *et al.* 2018). Slope length and steepness factor were calculated from hydrologically corrected digital elevation models (SRTM DEM-H) based on cumulative overland flow length (Yang 2015). The time series groundcover products from MODIS were used to estimate ground cover, RUSLE cover and management factor (Yang 2014). Surface manifestation of fire and erosion impacts were estimated from cover of vegetation and bare ground present at the site over time, based on the normalized difference vegetation index (NDVI) using SENTINEL-2 imagery (Copernicus Sentinel data 2018–2021).

Potential carbon loss from the system based on the estimated erosion from the period January to March 2020 (3-month period incorporating the fire–erosion events at Kings Tableland peatland) was determined. This was calculated using a conservative estimate of 12% soil carbon content based on obtained values for soil organic carbon (SOC) from the obtained cores. Approximately 20 cm of peat and organic material was estimated to have been lost from the site, and the overall depth of peat at the site was assumed to be 1 m, based on the average depth to the resistant layer at the four sampling locations.

Results

Fire history and severity

Fire history mapping from the NSW DPE (2010; updated 2021) indicates that this site has experienced four major fires since 1977, including in 2019/2020, 2015, 2001/2002 and 1977/1978. Three of these fires (2019/2020, 2001/2002 and 1977/1978) were wildfires, and the fire in 2015 was a prescribed burn. The severity of fires has varied over time, with severe and widespread impacts observed after the most recent 2019/2020 fires (Fig. 2).

The 2019/2020 bushfire event in south-eastern Australia comprised a number of high-intensity fires that burnt across the Greater Blue Mountains World Heritage Area over the period from October 2019 until February 2020, including the Gospers Mountain, Erskine Creek and Green Wattle Creek fires. An estimated 512 000 ha (or 81% of the World Heritage Area) was affected (Fryirs *et al.* 2021). Kings Tableland was impacted by the Erskine Creek fire, which started on 4 January 2020, and this event was declared finished on 9 February 2020. This fire covered an area of 22 497 ha and had a perimeter of 157 038 m (NSW DPE 2010 (updated 2021), 2020). Across this region, the Erskine Creek fire ranged from low to extreme severity, with a large area experiencing full canopy consumption (Fig. 3). Within the catchment of the Kings Tableland peatland (Fig. 3), the fire severity ranged from extreme to high (NSW DPE 2020). This resulted in the loss of the surrounding canopy, midstorey species, sedges and grasses, and the burning of the fibric layer of organic matter and peat (Fig. 4). However, fire severity information is limited because it only provides information on canopy consumption and therefore may not reflect the response of the potentially higher-moisture-content peatland environments (Fryirs *et al.* 2021).

Approximately 13 months after the fire (in March 2021), vegetation species within the swamp catchment were seen to be recovering (including sedge and shrub species).

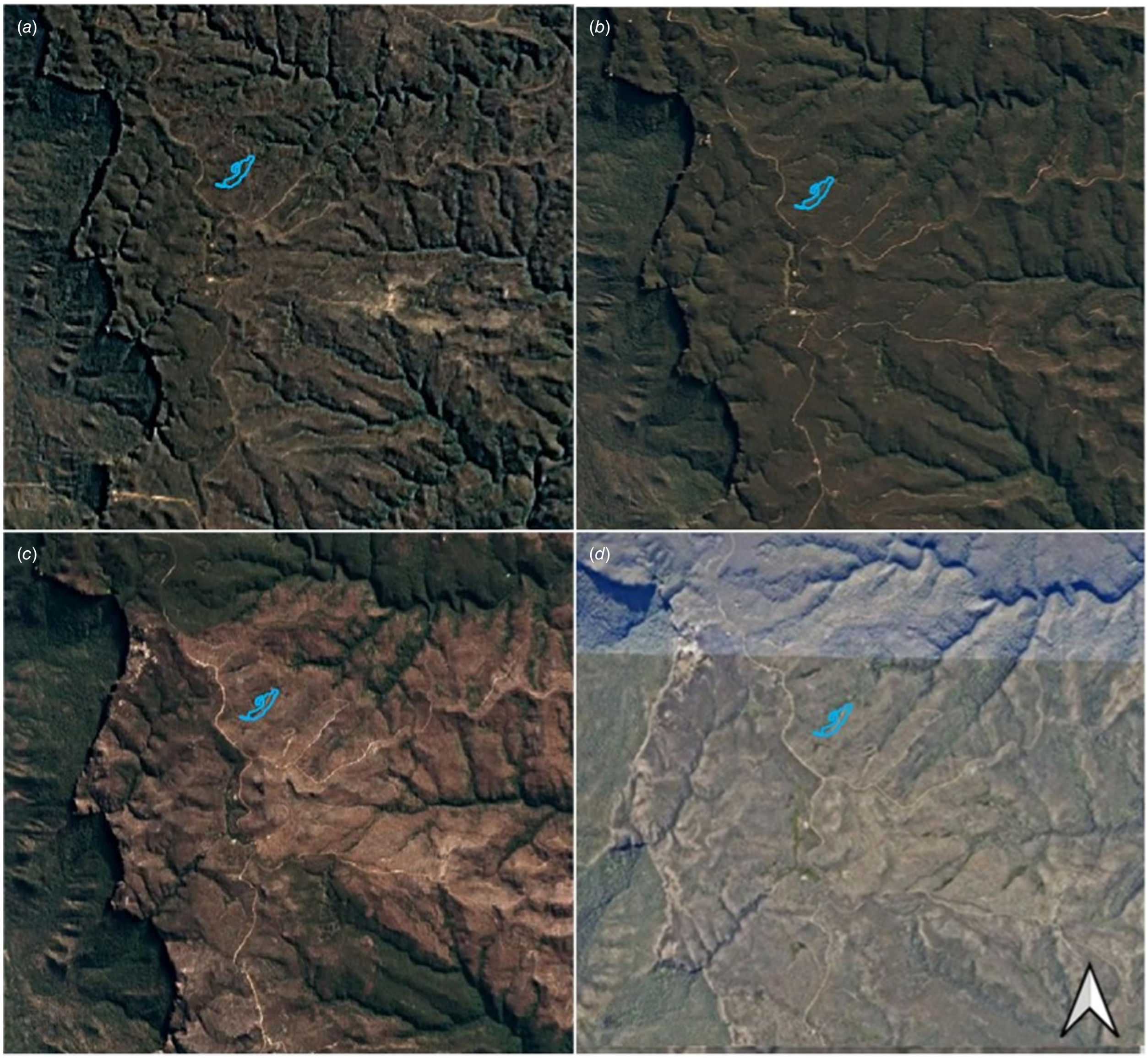

Fig. 2. Comparison of extent of fire impacts at Kings Tableland peatland (location highlighted in blue). (*a*) After moderate impact fire in surrounding region in January 2002. (*b*) Pre-fire in 2019. (*c*) Post severe fire event which occurred from January to February 2020 that had a significant impact on the site and surrounding region. (*d*) Post-fire after sampling in April 2021 when site was recovering. Source: Landsat-7 image courtesy of the U.S. Geological Survey.

Encroachment of shrub and tree species (particularly *Eucalyptus* spp. and *Acacia ptychoclada*) was observed along the drainage channels in the upper basin. Cleared areas of burnt vegetation were also prevalent, and the burnt tussocks of button grass show that approximately 20 cm of organic matter was lost from this site, predominantly in the upper basin (Fig. 4). Regrowth at the site was evident in June 2021, 16 months post fire. This included regrowth of sedge species (particularly button grass and razor sedge), and further encroachment of *Eucalyptus* species into the peat area. Recovery continued in November 2021 as regeneration occurred, but areas of bare earth were still present 21 months post-fire (Fig. 4).

Erosional events

The Blue Mountains region (and south-eastern Australia more broadly) experienced below-average rainfall and prolonged drought in the 3 years (2017–2019) leading up to the summer of 2019/2020, which fuelled the severe bushfires (Bureau of Meteorology (BOM) 2022*b*). Wetlands and peatlands that had previously been observed to maintain a high moisture content experienced increasingly dry conditions during this period (Fryirs *et al.* 2021; Ralph 2021). However, the region experienced a significant rain event in February 2020 that extinguished remaining fires and resulted in widespread runoff and erosion events (Kemter *et al.* 2021), which further

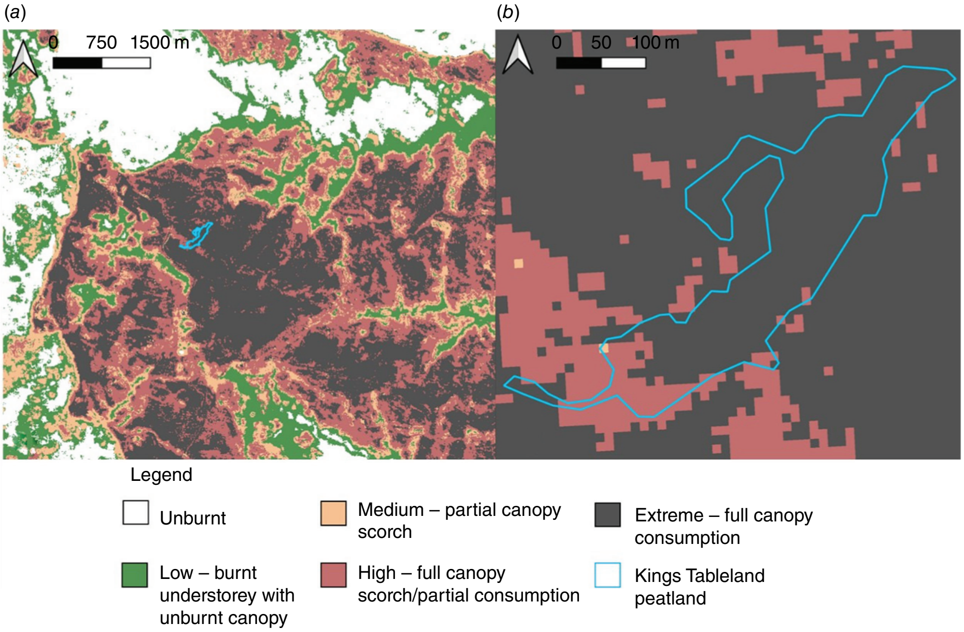

Fig. 3. (*a*) Fire extent and severity mapping from 2019/2020 for the Kings Tableland region and study site outlined in blue (*b*) Fire severity at Kings Tableland peatland, indicating that the site and surrounding area experienced predominantly extreme to high severity fire in 2019/2020. Source: Fire Extent and Severity Mapping NSW DPE 2020).

exacerbated the impacts on peatlands affected by the preceding drought and fires.

This event saw a monthly rainfall total of 701 mm in Katoomba that was almost four times higher than average February (179.1 mm) rainfall levels, with a maximum of 226 mm falling in a 24-h period on 10 February 2020, and 545.4 mm falling within the space of 1 week (from 6 to 12 February; Bureau of Meteorology (BOM) 2022*a*). Subsequently, above-average total monthly rainfall occurred in 6 out of 12 months in 2020, and this trend continued into 2021 due to La Niña conditions (Bureau of Meteorology (BOM) 2022*a*). Another significant rainfall event was also recorded during sampling in March 2021, when the monthly total rainfall was 584.8 mm and the highest daily total was 167.6 mm (Bureau of Meteorology (BOM) 2022*a*).

In March 2021, there was evidence of erosion, with sheets of coarse sands present on the exposed soil surface, and this was more prevalent across the upper basin of the site. There was also a distinct drainage channel eroded to the bedrock at the lower half of the site, which was recorded to a depth of approximately 50 cm. In November 2021, this eroded channel remained stable, and there were moderate-sized clumps of peat and organic matter present along the channel that created pools and small knickpoints, and coarse sands deposited in areas adjacent to the main channel across the site (which is in line with the formation of contemporary sand layers suggested by Cowley *et al.* (2016*a*)).

Analysis of available NDVI data from 2018 to 2021 indicates that there was a significant change in vegetation cover in response to the fire and erosion events at Kings Tableland peatland (Fig. 5). Values throughout 2018–2019 represent background vegetation cover during the drought period, and this was consistently between 0.7 and 0.9 (with values approaching one indicating high presence of green vegetation). There was a decrease in the NDVI value from October 2019 to January 2020 during the bushfire period in the Blue Mountains region. The drop in NDVI prior to the fire in the immediate peatland area in January 2020 could be attributed to smoke haze and cloud cover limiting analysis of NDVI using satellite imagery; this trend requires further investigation. Recovery of the vegetation community occurred following the fire event. A decrease in the NDVI value was then recorded for February 2020, which is in line with the significant erosion event that occurred from 10th February (Fig. 5). This suggests that there were significant areas of bare earth (value closer to zero) after this event. The NDVI value is shown to increase slowly from March 2020 due to recovery of the vegetation community. This also reflects the conditions observed in 2021, where there was a gradual increase in green vegetation cover over time from March to November 2021; however, areas of bare earth remained on the peat margins at the end of 2021 (Fig. 4).

Modelled hillslope erosion (based on the RUSLE dataset (Yang and Yu 2015; NSW DPE 2018; Yang 2020)) highlights that the greatest rainfall erosivity occurred in association with high rainfall events (Fig. 5). Hillslope erosion values were consistently between 0 and 0.5 t ha^{-1} month^{-1} from November 2018 to October 2021. However, the significant

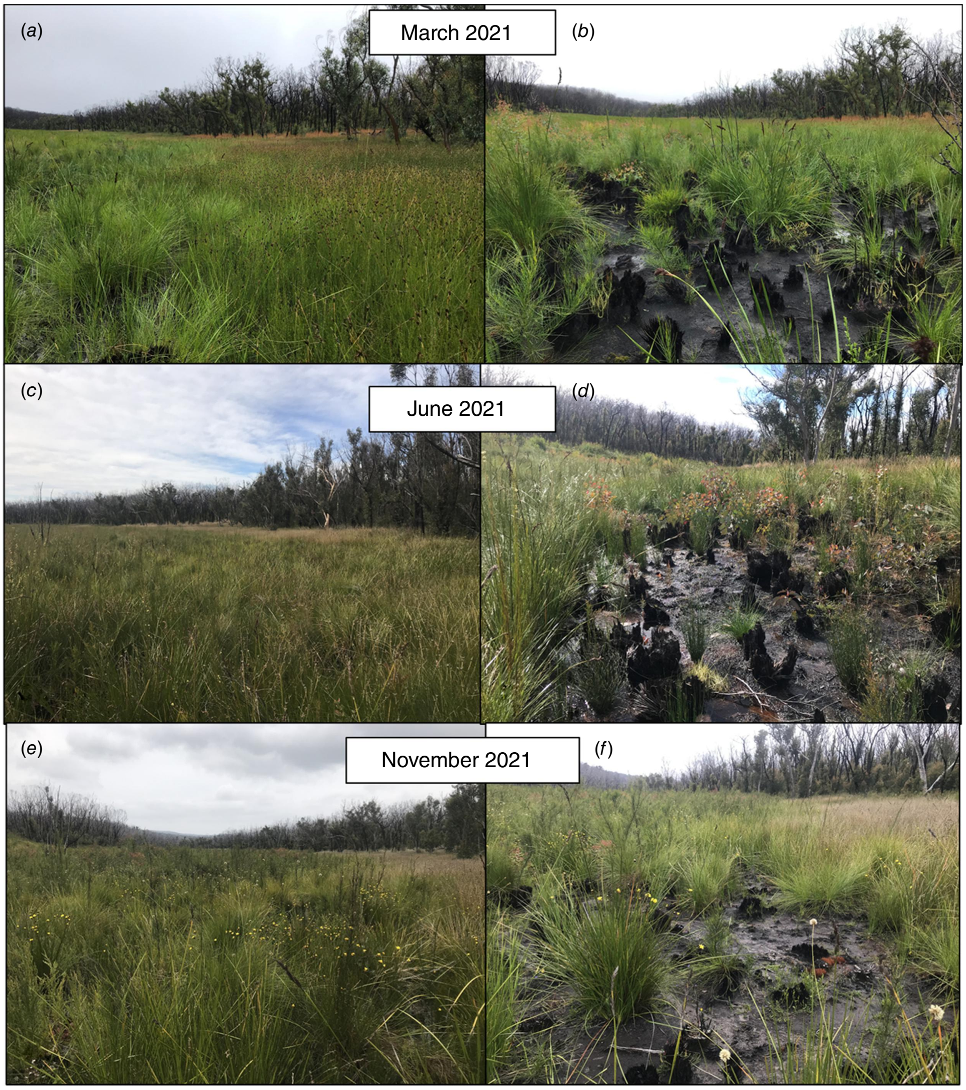

Fig. 4. Impacts of the 2019/2020 bushfires and erosion events on Kings Tableland peatland and regrowth of vegetation in (*a*) March 2021, (*c*) June 2021 and (e) November 2021. Areas of bare earth also remained present in (*b*) March, (*d*) June and (*f*) November 2021.

post-fire rainfall event in February 2020 was predicted to result in the greatest loss of 9.21 t ha^{-1} $month^{-1}$ of soil from within the peat boundary of Kings Tableland peatland. This corresponds with a high coverage of exposed soil in February 2020, with the lowest NDVI value of the monitoring period (0.23). Similarly, the high rainfall in March 2021 was estimated to have resulted in a loss of 2.30 t ha^{-1} $month^{-1}$, which was 4.7 times lower than the event in February 2020. This aligns with recovery of the vegetation community (NDVI of 0.83) to pre-fire coverage in March 2021.

Soil characteristics

The soils at the study site can be classified as a mix of organosols (with a presence of more than 0.4 m of organic materials within the upper 0.8 m) and hydrosols (seasonally or permanently saturated soils that may experience reducing conditions) (Isbell *et al.* 2021). The organosol distribution is 80% of the study site, with the edge circumference and low-lying, heavily eroded areas (coarse grain sand dominated) lacking the presence of organic materials. The underlying sandstone bedrock that exists across the site and lies exposed in the eroded channel is conglomerate mixed grain size material with 10% coarse angular grains. The overlying surface material (~0–10 cm) reflects hemic peat, being moderately decomposed with recognisable plant material present. Below this (>10 cm in depth), there is evidence of sapric peat (well-decomposed peat with some fibrous, intact organic material such as roots present). The fibric layer of the peat (top 20 cm) was not observed to be present at this site after the fire and erosion events.

The depth of the peat in the upper basin ranged from greater than 70 cm (at the high-point, which had moderate erosion)

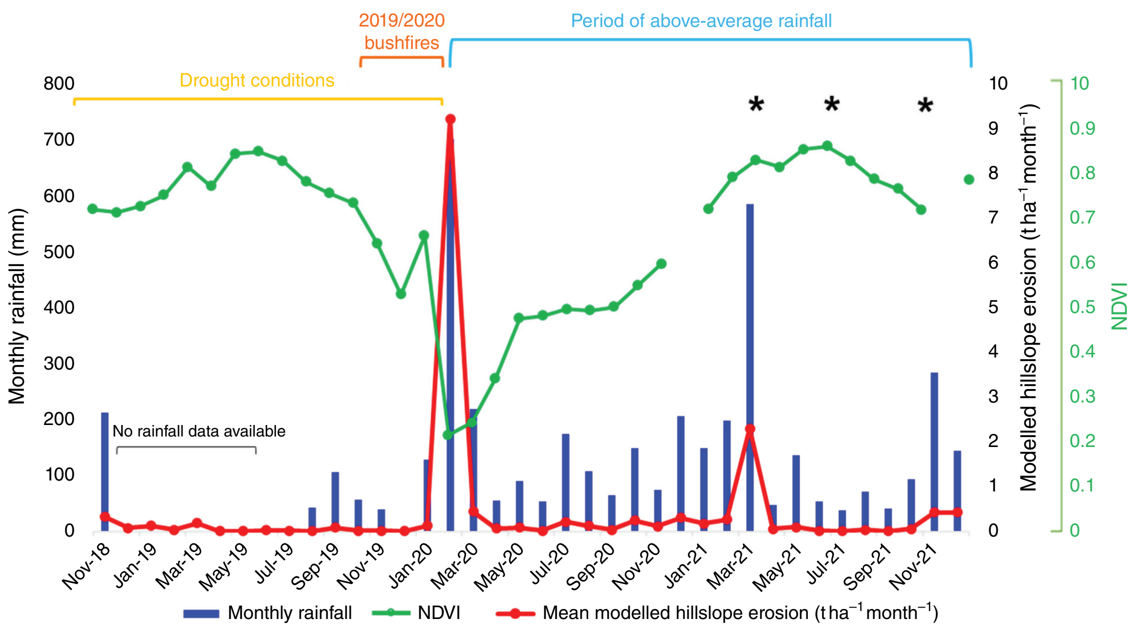

Fig. 5. Monthly total rainfall (shown in blue) from 2018 to 2021. Rainfall data were obtained from Katoomba (Farnells Rd) station (Bureau of Meteorology (BOM) 2022*a*), and no data were available for December 2018–June 2019 for this station. Modelled hillslope erosion (t ha^{-1} $month^{-1}$) based on the RUSLE calculations from the NSW DPE (2018) are shown in red. The mean normalised difference vegetation index (NDVI) data per month (from SENTINEL-2 Imagery (Copernicus Sentinel data 2018–2021)) are shown in green (no data available for December 2020 and November 2021). * refers to a sampling window of this study.

Table 1. Characteristics of soil cores from Kings Tableland peatland in June 2021.

Sample location	High-point		Mid-point		Low-point		Channelised knickpoint	
Depth (cm)	0–10	10–30	0–10	10–30	0–10	10–30	0–10	10–30
pH	5.0	5.0	4.5	5.0	5.0	5.5	4.5	4.5
Colour	5Y 3/1	5Y 2.5/1	5Y 3/1	5Y 2.5/1	5Y 3/1	5Y 2.5/1	5Y 3/1	5Y 2.5/1
Moisture (%)	63.0	52.0	65.0	64	80.0	61.0	66.0	17.0
Soil Organic Carbon (SOC)	120 000.0	120 000.0	140 000.0	150 000	270 000.0	180 000.0	66 000.0	26 000.0
Total nitrogen	6700.0	4900.0	6700.0	6900	13 000.0	7200.0	4300.0	1400.0
Nitrate	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Nitrite	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Phosphorus Retention Index (PRI)	30 600.0	22 700.0	10 900.0	26 400	17 500.0	22 900.0	220.0	330.0
Phosphorus (Bray 1)	0.9	1.0	11.0	0.6	2.0	0.9	1.0	1.0
C/N ratio	17.9	24.5	20.9	21.7	20.8	25.0	15.4	18.6
N/P ratio	7444.0	4900.0	609.0	11 500	6500.0	8000.0	4300.0	1400.0
Ex-Ca (meq/100 g)	0.3	<0.1	0.7	0.2	1.4	0.2	1.2	<0.1
Ex-K (meq/100 g)	0.2	<0.1	0.2	<0.1	0.2	<0.1	0.2	<0.1
Ex-Mg (meq/100 g)	0.2	<0.1	0.3	0.3	0.7	0.2	0.8	<0.1
Ex-Na (meq/100 g)	0.1	<0.1	0.2	<0.1	0.3	<0.1	0.1	<0.1
Cation exchange capacity (meq/100 g)	<1.0	<1.0	1.3	<1.0	2.6	<1.0	2.3	<1.0

Site locations as detailed in Fig. 1. All values are in mg kg^{-1} unless otherwise stated.

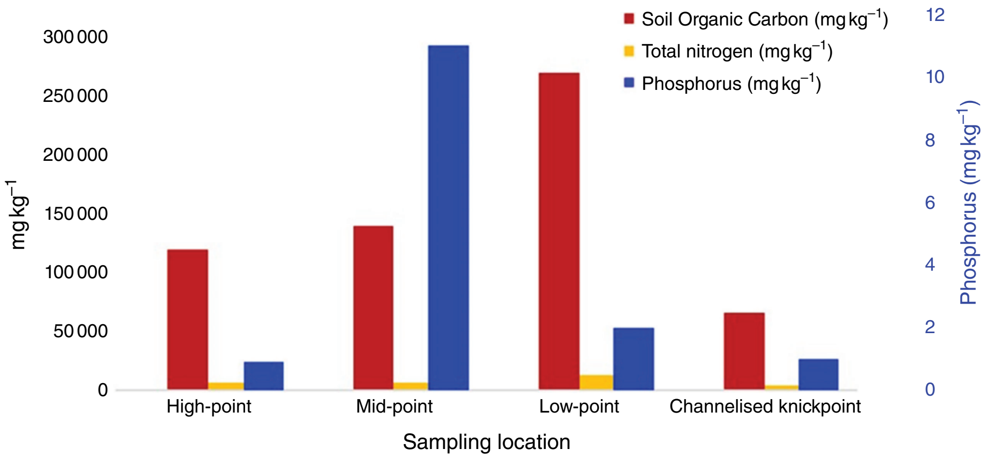

Fig. 6. Soil Organic Carbon (SOC; mg kg^{-1} of soil) shown in red in newly-exposed surface soil (0–10 cm) along the transect of Kings Tableland peatland, in addition to total nitrogen (N; mg kg^{-1}) shown in yellow, and phosphorus (P; mg kg^{-1} on secondary axis).

to over 135 cm (at the low-point, which had reduced erosion). Soils were similar in the mid-section compared with the upper basin but with reduced peat thickness due to the increase in slope. This continued in the lower channelised section (depth greater than 59 cm) and on steep slopes, with predominantly organic and coarse sands. On the surrounding margins, the soil had an increased sand content and decreasing moisture levels, which corresponded with a transition in the vegetation community.

The surface soil pH was acidic, ranging from pH 4.5 to 5.5 and 5.0 to 5.5 at depth, with only a small change in colour between the horizons (Table 1). Mean moisture content ranged from 69% in surface soil (0–10 cm) to 49% at depth (10–30 cm). Mean soil organic carbon (SOC) in surface soils for Kings Tableland peatland was 149 000 mg kg^{-1} and was highest at the low-point (270 000 mg kg^{-1}; Fig. 6), which had the least evidence of erosion present. Cation Exchange Capacity (CEC) was low in line with expectations of soil comprised of mixed organics and sands. Soluble nitrogen was below detection limits, and mean total nitrogen was 7675 mg kg^{-1} in surface soils. Phosphorus levels were also low (mean 3.73 mg kg^{-1} for 0–10 cm) across the sampling locations and with depth; however, there was an elevated outlier value in surface soil at the mid-point (11 mg kg^{-1}). The C/N and N/P ratios also reflected consistency between the hemic and sapric layers at all sampling locations.

Accounting for potential soil, carbon and nutrient loss

It is estimated that 5878 t of soil and organic material were stored within the boundary of Kings Tableland peatland prior to the bushfire and erosion event. The modelled RUSLE hillslope erosion (NSW DPE 2018) for the area of investigation over the 3-month period was a loss of 28.80 t of soil (Table 2). This equates to an estimated loss of 0.5% of soil and organic material stored at this site from January to March 2020. It is estimated that approximately 3.46 t of carbon was lost from the eroded component of soil from within the peatland boundary at this site over this 3-month period, which equates to approximately 0.73 tonnes per hectare of carbon lost from soil from the burnt area of Kings Tableland peatland during this bushfire and erosion event.

Previous research by Cowley and Fryirs (2020) suggested that peatland environments cover 4105 ha in the Blue Mountains, and it is estimated that they store approximately 3 304 546 t of carbon. Fryirs *et al.* (2021) indicated that 2139 ha of peatland were burnt during the 2019/2020 period and up to 10 cm of peat may have been lost at severely burnt sites. Based on this and characteristics of Blue Mountains peatlands from Cowley and Fryirs (2020), the potential loss of carbon from peatlands impacted by fire in 2019/2020 is estimated to be approximately 123 142 t of carbon. This equates to a potential carbon loss of 57.57 tonnes from the burnt peatland area of the Blue Mountains region during the 2019/2020 period.

Discussion

The combination of a high-intensity fire event and subsequent exposure and erosion of previously buried peat-rich organosol/hydrosol has resulted in a rapid loss of soil materials and organic carbon. The occurrence of these events over just a 3-month period has damaged this sensitive World Heritage environment. Peatlands are slow-forming accretionary systems that require extended timeframes to recover, if at all, from disturbance caused by fire and erosion events. This work exemplifies the potential for loss of organic material and carbon from peatland systems.

There is an expectation of increased prolonged droughts, severe bushfires and significant rainfall events occurring in

Table 2. Calculated loss of materials from Kings Tableland peatland in response to the bushfire and erosion events between January and March 2020.

Parameter	RUSLE loss over Jan–Mar 2020	Estimated peat areas across Greater Blue Mountains region[A]
Area (ha)	4.74	2139.00
Bulk density (g cm^{-3})	0.62	1.01
Total mass of soil lost (t)	28.80	–
SOC at 10 cm depth (%)	12.00	5.70
Δ C soil (t C)	3.46	123 142.00
Soil C loss from burnt area (t C ha^{-1})	0.73	57.57

[A]Mean bulk density (BD), soil organic carbon (SOC) and carbon stock (t C) for storage and loss of nutrients from the wider Blue Mountains region are based on Cowley and Fryirs (2020). The area of peatland burnt was identified from Fryirs *et al.* (2021).

the future (Intergovernmental Panel on Climate Change (IPCC) 2021). As a result, this may lead to further desiccation of peatlands, thereby increasing the risk of peat fires and vulnerability to erosion when high rainfall events occur – and resulting in higher exports of carbon and nutrients. Significant erosion occurred post-fire at Kings Tableland peatland in February 2020 when NDVI was lowest (Fig. 5). A second intense rainfall event occurred in March 2021, when monthly rainfall was similar to February 2020; however, the vegetation community showed signs of recovery to pre-fire cover. Erosion in March 2020 was high during this rainfall event but remained 4.7 times lower than levels seen in February 2020. This demonstrates the importance of a vegetation cover to mitigate against high rainfall and erosion events within peatlands.

The cumulative impact of drought, fire and erosion in peatlands across south-eastern Australian constitutes a significant impact on organic material loss, nutrient and carbon cycling. It is estimated that the total carbon storage in the Greater Blue Mountains is 3.3 Mt of carbon (Cowley and Fryirs 2020). During the 2019/2020 bushfire event, 3.46 t of carbon were lost from a single 4.74 ha peatland over a 3-month period from January to March 2020. The ratio of carbon loss and total burnt peatland area observed at Kings Tableland peatland was lower compared with estimates for the Greater Blue Mountains region (derived from Cowley and Fryirs (2020) and Fryirs *et al.* (2021)). This suggests that even after a severe fire and erosion event, loss of organic material and carbon was below projected expectations at this site. Previous estimates for carbon loss for the Greater Blue Mountains may therefore represent that the upper limit was not reached at Kings Tableland peatland after these fire–erosion events. However, projected estimates do not take into consideration the timeframe of this loss, which occurred only over 3 months. Because fire and erosion impacts varied among peatlands, further quantification of the loss of organic material based on ground studies is required to more accurately estimate overall carbon loss from peatlands in this region and is key to developing landscape-scale carbon budgets. Fire events can also result in continued burning of peat even after the fire event has passed (Jenkins *et al.* 2014; Qin *et al.* 2022; Santoso *et al.* 2022). In this study, the fire event was immediately followed by a significant rain event, which quelled any persistent burning and triggered erosional activities and loss of peat materials from the site.

The effects of drought, fire and erosion events are particularly concerning because peatlands are slow-forming environments. Therefore, potential recovery of peat deposits is a long process and there is the risk that damage to peatland functioning may be irreversible. Globally, peat accumulation is estimated at 1–2 mm $year^{-1}$ (Craft 2016). Therefore, the estimated loss of 20 cm at Kings Tableland peatland represents the loss of 100–200 years of organic material accumulation within a short time. As a result, peatlands in this region could in fact be losing soil materials, thereby reducing the valuable carbon sink and ecosystem services that these environments typically provide. This reflects a major problem for peatlands: as conditions become drier and warmer with increased frequency and severity of fires and intense rainfall events, the potential for peat formation may be reduced.

Conclusions

This research highlights the effects of rapid change due to drought, bushfire and erosion events on a montane peatland within a World Heritage Area, and documents the responses and recovery of a system in a state of flux. An estimated 28.80 t of soil and organic matter and 3.46 t of carbon were predicted to have been lost over a 3-month period at a single peatland in a region where peat-rich soils occur and recent fire–erosion impacts are widespread. This highlights the potential for considerable loss of organic material and carbon from peatlands in response to climate events. Australia has limited peatland areas, and due to the impacts of severe climatic events, we risk losing these slow-forming accretionary systems. Findings from this study offer an insight into the potential implications for nutrient and carbon exports and soil erosional loss from montane peatlands within Australia, and more broadly in response to climatic events and disturbance, as well as emphasising the importance of aiming to conserve these environments.

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Data availability. The data that support the findings of this study are available from the corresponding author, JKR, upon request.

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