TWWHA Bushfire Recovery: Lake Mackenzie Rehabilitation Trials

Sphagnum Trial Establishment Report

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Establishment Report for Tasmanian Wilderness World Heritage Area Bushfire Recovery: Lake Mackenzie Rehabilitation Trials: *Sphagnum*

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Cover image: Fire-affected *Sphagnum* and Pencil Pines at Eagle Valley near Lake Mackenzie, one of the study sites reported on here. Photo: Lynda Prior

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Summary

The Lake Mackenzie *Sphagnum* rehabilitation trial was set up to test whether recovery of *Sphagnum* at sites burnt by the 2016 Lake Mackenzie fire complex could be improved by three interventions: applying shadecloth, fertiliser or transplanting healthy *Sphagnum* into damaged areas.

To do this, we established a total of 544 quadrats, each 1m^2, in six burnt and two unburnt mires within 8 km of Lake Mackenzie. Positioning of quadrats was stratified according to three burn severity classes: unburnt, moderately and severely burnt, to determine how burn severity affected the response to the various treatments. We assessed the cover of healthy, damaged and killed *Sphagnum* in the central 0.25 m^2 of each quadrat. We also assessed the cover of other vegetation such as other mosses, ferns, grasses and shrubs. We then imposed six treatments: shade, fertiliser, transplant, shade + fertiliser, transplant + fertiliser, and shade + fertiliser + transplant.

This report describes the establishment of the trial, including details of the individual study mires and the methods used to impose the six treatments. It also reports the initial cover of healthy, damaged and killed *Sphagnum* and other vegetation types in relation to burn severity and site (mire). Consistent with our trial design, *Sphagnum* health was most strongly affected by burn severity, with site differences much less important. Cover of *Richea* and other shrubs was also strongly influenced by whether the quadrat had burnt or not. Initial cover of other vegetation was more affected by site differences than by burning.

As explained in this establishment report, the responses to the six treatments will be documented in a scientific publication and a final report. These will also provide management recommendations for work following future fires.

1. Lake Mackenzie Rehabilitation Trials

The Tasmanian Wilderness World Heritage Area (TWWHA) protects globally unique biodiversity, including endemic flora and fauna with origins in the supercontinent of Gondwana. Anthropogenic climate change is threatening these Tasmanian paleoendemic species directly through increased warming and drying, and indirectly by increasing the occurrence of fires ignited by dry lightning storms (Bowman et al. 2019; Bergstrom et al. 2021; Harris et al. 2018). A recent example occurred during the summer of 2015-2016. Between 13 January and 24 March 2016, lightning strikes ignited at least 639 fires throughout the state, 18 of which burnt approximately 20,000 hectares of the Tasmania Wilderness World Heritage Area (TWWHA) (Fig. 1). This landscape was particularly receptive to lightning ignitions due to the low spring rainfall in 2015 and above average summer temperatures (Figs 3 &4; Bowman et al. 2019; Karoly et al. 2016).

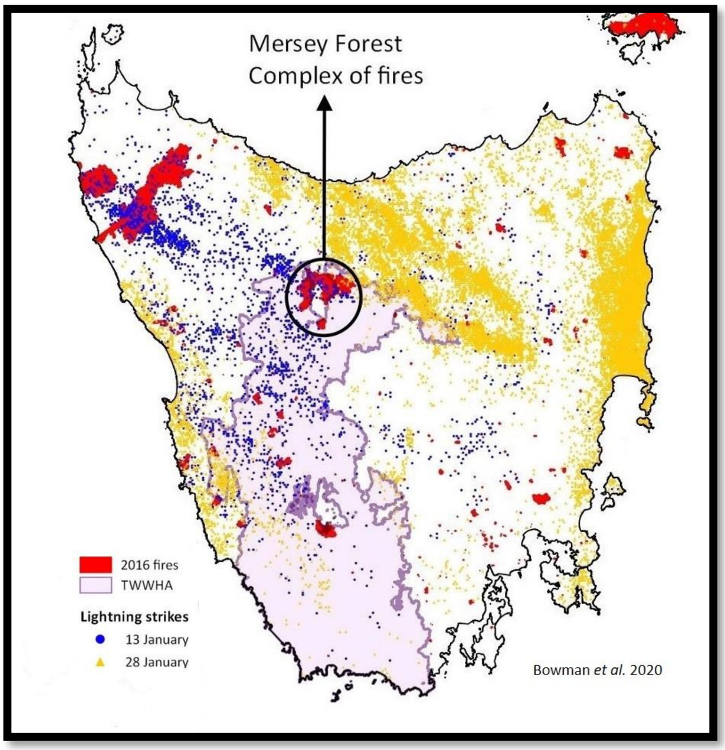

Fig. 1. Lightning strikes and subsequent fires, summer 2016 (Bowman *et al.* 2021).

One of the most severely affected areas was around Lake Mackenzie, where almost 14 000 ha of subalpine vegetation, including 141 ha of pencil pine (*Athrotaxis cupressoides*) forest and an unknown area of *Sphagnum* moss communities (or '*Sphagnum* mires') were burnt (Bowman et al. 2019; Bowman et al. 2021). *Sphagnum* mires typically exclude fire because under normal conditions, the vegetation and organic substrate are saturated, but they become combustible under extreme drought (Kettridge et al. 2015). The largest area burnt (14632 ha) within the TWWHA was by the Mersey Forest Complex fires near Lake Mackenzie (DPIPWE 2017). These fires not only burnt fire-prone pyrophilic vegetation such as *Eucalyptus* forest, but also damaged or destroyed more fire sensitive species such as *Athrotaxis* and *Sphagnum*.

The 2016 Tasmanian Wilderness Fires sparked global media interest (Marris 2016) and led to a senate enquiry (Senate ECRC 2016) and a Tasmanian government enquiry (Press 2016), with the Tasmanian Government identifying significant impacts on conservation values in the region (DPIPWE 2017). The enquiries all identified the importance of Gondwanan refugia, including *Sphagnum* mires, and the need to undertake research into post-fire impact assessment and restoration techniques of these communities. This led to the Lake Mackenzie Rehabilitation Trials, funded by the then Tasmanian Department of Primary Industries, Parks, Water and the Environment (DPIPWE) (now The Department of Natural Resources and Environment Tasmania (NRE Tas)).

Tenders were called for the *TWWHA Bushfire Recovery: Lake Mackenzie Rehabilitation Trials* Project to 'develop and trial methods for rehabilitation of pencil pine stands, *Sphagnum* peatlands and erodible soils in 2016 bushfire affected areas in Lake Mackenzie. The rehabilitation methods developed will inform assessment of risks and responses to future fire impacts on fire sensitive alpine vegetation and soils in the TWWHA and will assist with mitigating future fire impacts on the Outstanding Universal Values of the TWWHA' (Tasmanian Government Tender #1714).

The tender document specifies "the scope of work includes:
* Identify rehabilitation methods (the trials) for pencil pine stands, *Sphagnum* peatland and erodible soils in the area of Lake Mackenzie (TWWHA) impacted by the 2016 bushfires; and design a scientifically robust test of those methods.
* Establish procedures for maintenance and monitoring and develop a project plan.
* Implement the rehabilitation trials.
* Monitor, collect and analyse data from the trial rehabilitation sites.
* Produce a final report and decision tool or guide."

Funding was awarded to the University of Tasmania (UTAS) in mid-2018 to conduct the first two components of the project, and specifically "To test methods to promote recovery, rehabilitation and/or maintenance of Pencil Pine and *Sphagnum* community values in the TWWHA, where these have been damaged by fire, targeting areas burnt by the 2016 bushfires. The analysis of the trials will deliver a decision tool or guide to identifying conditions where the application of identified effective rehabilitation methods may be successful."

The UTAS researchers implemented four studies to promote recovery, rehabilitation and/or maintenance of Pencil Pine and *Sphagnum* communities:

1. A *Sphagnum* rehabilitation trial, to test whether various combinations of fertiliser, shade cloth and *Sphagnum* transplants can promote recovery of the *Sphagnum* mires burnt in the 2016 fire.
2. A trial to assess the effectiveness of interventions to restore stands of Pencil Pine (*Athrotaxis cupressoides*) damaged or destroyed by fire. These interventions included sowing seed, transplanting nursery-grown seedlings and cuttings, and use of tree guard to protect germinants and transplanted tube stock from herbivores.
3. An investigation of the potential to use unmanned aerial vehicles (drones) with visible spectrum sensor technology to map the fire severity and area of *Sphagnum* mires burned by the 2016 fires. This component has been completed and reported on by Harding et al. (2022).
4. A re-survey of adult Pencil Pines burnt in the 2016 fires to quantify delayed mortality, resprouting, and presence of juveniles, and to determine whether fire impacts can be reliably assessed as early as one year after the fire. This study built on a UTAS Honours project conducted on the same trees one year post-fire (Bliss 2017), and has been completed and published in a peer-reviewed journal (Bliss et al. 2021).

This report describes the establishment of the trial of techniques to promote rehabilitation of fire-affected *Sphagnum* mires.

2. *Sphagnum* Rehabilitation

2.1 Rehabilitation of peatlands after fire, with a focus on Australian *Sphagnum*

Studies in the northern hemisphere have advanced peatland and *Sphagnum* rehabilitation techniques, including those to promote recovery after fire (Rochefort et al. 2003; Chimner et al. 2017). Until recently, however, there have been few trials of *Sphagnum* rehabilitation techniques in Australia (Clarkson et al. 2017). In 2003, extensive fires in the Australian Alps burnt significant areas of *Sphagnum* mires in Namadgi and Kosciuszko National Parks (Hope, Whinam & Good 2005; Whinam et al. 2010). Following these fires, Whinam et al. (2010) conducted post-fire experimental rehabilitation trials across a range of burn severities. Treatments included application of shade and fertiliser, rewetting, and transplantation of healthy *Sphagnum* blocks into fire-affected hummocks (Hope, Whinam & Good 2005; Whinam et al. 2010). Recovery of *Sphagnum* observed in these trials was described as slow and complex, but results indicate that some rehabilitation interventions, particularly shading and combined transplant and fertiliser treatments, increased recovery rates to at least twice that of untreated controls during the four years post-fire (Whinam et al. 2010). Encouraged by these results, funding was provided to investigate the feasibility of using these interventions to improve post-fire recovery of *Sphagnum* in Tasmanian peatlands.

2.1.1 Peatlands

Peatlands are a type of wetland characterised by the presence of peat soil. They cover about 3% of the global land surface, but are rare in Australia (IUCN 2021). Peat is a heterogeneous mixture of decomposed plant matter that has accumulated in a water-saturated environment in the absence of oxygen (International Peatland Society 2018). It accumulates fastest where the temperature is high enough for plant growth but too low for vigorous microbial activity, which breaks down the plant material. Peat forms in mires, which can be woody (swamps) or herbaceous (marshes). Mires can be predominantly rainfed (bogs), in which case they are typically acidic and nutrient-poor, and usually dominated by sedges and shrubs and with abundant *Sphagnum* mosses, and their outflowing water is high in tannins (Wikipedia 2022). Alternatively, they can be fed by relatively mineral-rich surface or groundwater (fens), resulting in neutral to alkaline water chemistry, and are typically dominated by grasses and sedges, and often contain brown mosses and other diverse plant species (Wikipedia 2022).

Water table depth is commonly used to predict many important ecohydrological variables in peatland hydrology, ecology and biochemistry, such as run-off, saturation, redox potential, soil structure, methane emissions, carbon types and organic matter decomposition (Waddington et al. 2015).

Wetlands with peat less than 0.5 m thick are most vulnerable to high evaporative stress (Dixon et al. 2017).

Feedbacks exist that reinforce the stability of the peatland/mineral soil mosaic (Waddington et al. 2015; French et al. 2016). A high water table generally favours *Sphagnum* moss species, and promotes acidic conditions with slow decomposition of organic matter, leading to deep organic layers with very high water holding capacity and reducing surface runoff. Fire is very infrequent because waterlogged peat does not burn, leading to more accumulation of peat and greater water retention in the landscape. However, climatic drying, grazing and trampling by animals or hydrological disturbance can damage peatlands through soil compaction, increased drainage and runoff, and soil erosion. Burning can be five-fold deeper at peatland margins than in the middle, due to dense peat and low moisture content (Lukenbach et al. 2015a), so repeated fires can progressively reduce the amount of peat in the landscape. Repeated, severe fire disturbance can therefore overwhelm the stabilising influences on peatlands and convert organic to mineral soils, especially where climatic conditions are marginal (French et al. 2016).

Peatlands are valuable in providing ecosystem services such as water storage, flow regulation and run-off filtering (Good et al. 2010). Peatlands can also accumulate large amounts of carbon, which is usually stable if the sites retain their moisture (Hope and Nanson 2015). However, these carbon stores are vulnerable to fire or other disturbance.

The major factor limiting the development of *Sphagnum* peatlands in Australia is moisture availability, and in particular evapotranspiration in the driest month (Whinam et al. 2003). In south-western Tasmania, the infertile siliceous soils appear to restrict *Sphagnum*, despite suitable climate and topography (Whinam et al. 2003). Bioclimatic modelling shows marked shrinkage of the present bioclimatic space for blanket bog; such regions are at risk of progressive peat erosion and vegetation changes as a direct consequence of climate change (Gallego-Sala & Prentice 2013).

2.1.2 Effects of fire on *Sphagnum* peatlands

Fire kills *Sphagnum* and other peatland species, but it also has indirect effects (Whinam et al. 2001). Most importantly, fire can affect peatland hydrology through its effects on moisture retention and water repellency of the peat itself (Kettridge et al. 2014; Lukenbach et al. 2016; Moore et al. 2017), as well as potentially changing wetland drainage patterns. Water repellency in moss appears primarily controlled by water content, and the effect is enhanced by burning (Moore et al. 2017). Fens are more prone to erosion than bogs, because they can be sloping and with greater low hydraulic energy

(Chimner et al. 2017). Wildfire has other biophysical effects; it can change the energy balance of *Sphagnum* hollows by reducing the latent heat flux post-fire, which can greatly increase daytime surface temperatures (Kettridge et al. (2012).

There have been only a few detailed studies of fire impacts in Australian peatlands. In 2003, wildfires in the Australian Alps burnt over almost all the alpine, subalpine and montane bogs and fens, which severely damaged or destroyed *Sphagnum* hummocks and other mire plants, and dehydrated the peats, allowing the fires to burn into the peatlands (Good et al. 2010). At the time of these fires, the peat in many bogs and fens was extremely dry after 3 years of drought, which predisposed the vegetation cover and underlying peats to burning. Fire impacts varied with the intensity and rate of spread at the time the bogs and fens were burnt, but ranged from minor burning of some *Sphagnum* moss hummocks to the complete destruction of the bog and fen vegetative cover and partial burning of underlying peatbeds (Good et al. 2010). The latter resulted in the loss of the functional hydrological role of the peats and consequent loss of ecosystem services to catchment water storage, flow regulation and run-off filtering (Good et al. 2010).

The resulting changes in environmental conditions can cause changes in peatland species composition. For example, in Tasmania, conditions after fire can favour buttongrass over *Sphagnum* (Whinam et al. 2001). Light to moderate burning in northern Minnesota reduced cover of *Sphagnum* moss and dominant ericaceous shrubs, and increased the cover of pioneering mosses. This increased black spruce (*Picea mariana*) regeneration in the nutrient-poor bogs (Rowe et al. 2017).

2.1.3 Recovery after fire

Sphagnum mosses do not readily recolonise bare organic soils after fire or anthropogenic mechanical disturbance (Groeneveld et al. 2007). Hydrogeological setting affects post-fire recovery, both by influencing vegetation structure prior to wildfire and thus post-fire surface covers, and also by influencing post-fire water table positions (Lukenbach et al. 2015b). High water table positions following wildfire are critical to enable the re-establishment of keystone moss species such as *Sphagnum* (Lukenbach et al. 2015b; Chimner et al. 2017). Shade also increases regeneration of most bryophyte species (Chimner et al. 2017). Thus, in the Australian Alps, *Sphagnum* regenerates fastest where there is free-standing water and shade from bog plants such as *Carex* and *Empodisma* species (Good et al. 2010).

In a long-term study of *Sphagnum* bogs in the Australian Alps, full floristic sampling was conducted over approximately 50 years (Clarke et al. 2015). During this time, extensive wildfires partially or completely burned some of the sampled bogs. The study found a progressive increase in cover of *Sphagnum* during the last 40 to 50 years, probably reflecting recovery from grazing. Fire temporarily reduced frequency of most species but initial floristic composition was regained a decade after fire. The authors concluded that these bogs 'exhibited resilience to infrequent pulse disturbance related to fires, which appear to drive community assembly through cycles of compositional change.' A study of another fire in the Australian Alps (Bogong High Plains in north-east Victoria) showed generally greater effects (McDougall 2007). The fire reduced the cover of all peatland species. The peatlands had largely recovered floristically within three years, but recovery was slow in obligate seeders and *Sphagnum cristatum.* Although some patches of *S. cristatum* within the burnt peatlands survived the fire and some regeneration had occurred within 12 months, recovery in the next two years was very slow. The author concluded 'it is likely to be decades before the cover of *S. cristatum*… reaches pre-fire levels' (McDougall 2007).

New Zealand peatlands share many of the characteristics of Australian ones in that they are typically small and at the warmer end of the climatic envelope, with low species diversity (Whinam et al. 2003). The most common *Sphagnum* species in both countries is *S. cristatum* (Whinam et al. 2003). In southern New Zealand, post-fire *Sphagnum* recovery was mainly by slow recolonisation of fire-bared peat, rather than regrowth of fire-damaged cushion (Johnson 2001). Most re-establishment appeared to be from spores rather than from vegetative fragments, and occurred mostly in the broad wet hollow that had previously been *Sphagnum* dominated, but also less abundantly in the mixed bog type. Growth was initially slow, and 15 months after the fire the largest plants were only about 2 cm tall. These later expanded and coalesced with adjacent stems, and in the most favourable sites the largest *Sphagnum* plants were 18 cm tall cushions 6 years after the fire, and 30 cm tall after 10 years. In the mixed bog type, *Sphagnum* plants were still establishing among *Baumea* and wire rush 6 years after the fire (Johnson 2001). Also in NZ, in a *Sphagnum* –wirerush mossland, there was recovery of vegetation cover and species diversity within 4.5 years of a fire, but species composition differed (Timmins 1992). Wetter parts of the wetland were less severely burnt and recovered more quickly than drier parts.

Shade and shelter are important for *Sphagnum* recovery. For instance, in Quebec, carpets of the commonly found *Polytrichum* mosses can act as a seed trap and also a nurse plant for *Sphagnum* fragments as well as vascular plants (Groeneveld et al. 2007).

2.1.4 Post-fire rehabilitation techniques

Most techniques to facilitate peatland recovery and regeneration were initially developed to help restored sites that had been mined for peat or harvested for *Sphagnum* moss (Gorham and Rochefort 2003; Groeneveld et al. 2007; Watts et al. 2008; Chimner et al. 2017). Rehabilitation techniques developed for peat-extraction sites may be applicable in severely burned peatlands given the impacts of peat-consuming fires bear similarities to those caused by peat extraction (Chimner et al. 2017). However, it is not known how successfully the methods developed to restore northern hemisphere peatlands can be applied to Australasia, where peatlands are small, and climatic conditions marginal for peatlands (Clarkson et al. 2017).

The most important aspect of any peatland rehabilitation project is to restore landscape hydrology (Chimner et al. 2017). This requires preventing the peats from becoming hydrophobic and consequently shedding water from the site, as well as ensuring peats recover their capacity to take up surface and subsurface flows and regain their saturated state (Good et al. 2010). A major threat to damaged peatlands is gully formation, which can occur when channelised surface water creates soil or subsoil erosion, and can dewater whole valley-bottom wetland complexes (Chimner et al. 2017). Gully formation results from down-cutting (vertical lowering of the gully, which leads to deepening and widening), and head-cutting (upslope erosion, which extends the gully into headwater areas and forms gully tributaries). Gully rehabilitation should occur before erosion becomes severs, as large gullies are difficult and costly to repair. Gully rehabilitation involves stabilising the gully and modifying runoff so scouring is reduced and sediment accumulation and revegetation occur. Gullies can be blocked or filled. Blocking stops water flow by creating a series of dams or plugs that slow runoff and drainage from the peatland. Backfilling is the most effective method to raise the water table in peatlands affected by drainage ditches, and commonly involves pushing peat material from nearby surfaces into the ditch. Mineral sediment or a combination of mineral and organic sediments, or wood products, have been used to fill ditches in vegetated sites (Chimner et al. 2017).

2.1.5 Rehabilitation trials in the Australian Alps

Wildfires in the Australian Alps in 2003 burnt over almost all the alpine, subalpine and montane bogs and fens, which severely damaged or destroyed *Sphagnum* hummocks and other mire plants, and dehydrated the peats, allowing the fires to burn into the peatlands (Good et al. 2010). It was recognised there would be further losses of bog and fen communities due to post-fire runoff, leading to peat tunnelling, flowline entrenchment and consequent peat erosion unless remedial works were undertaken immediately after the fire. Earlier studies (of mire restoration and rehabilitation techniques applied to grazed and fire-damaged bogs and fens) in the Australian Alps showed that where the underlying peats of mires showed little physical damage from stock trampling and grazing they could readily regenerate a vegetative cover, and their ecosystem function recovered without any intervention (Good et al. 2010). The recovery of the *Sphagnum* component of mire vegetation was essential to this, as *Sphagnum* is the dominant contributor to the continuing accumulation of organic matter and peat formation. A rehabilitation program was developed to restore hydrological function by (i) constructing 'dams' of sterilised straw bales in flowlines to create and restore surface pools, (ii) construction of subsurface organic matter dams to slow the flow of water from the peats, and (iii) placing coir and straw-filled jute mesh 'logs' to spread surface water and trap sediments (Hope et al. 2005; Good et al. 2010). In the Australian Alps, recovery and restoration of a natural shade cover is also essential to allow widespread recovery of mire plants. In particular, *Sphagnum* regeneration requires partial shading, which is provided naturally by shrubs and taller restionaceous species (Good et al. 2010).

By applying these rehabilitation techniques, approximately 300 ha of bogs and fen ecosystems in the Australian Alps were restored to functional and stable mires following the 2003 fires (Good et al. 2010). Rehabilitation works were done on about 130 bogs and fens burnt by the fire (about 1/10 the total burnt). Monitoring and research programs were also instigated. Prior to treatment, substantial erosion was evident in sites with high water flows. The peat had been vertically incised, with channels up to 1 m or more deep, sometimes to the underlying gravels or bedrock. There was lateral erosion at the gravel/peat interface up to 2 m either side of the incised flowline. In these areas, flows were reduced through packing straw bales into the incised flowlines, and inserting straw-filled hessian bags into the undermined peatbeds. In several large drained and drying bog areas, narrow trenches were machine cut through the peats down to the underlying gravels or bedrock (1 to 2.5 m deep) in order to provide a subsurface, semi-impervious organic 'dam' to help retain subsurface inflows and thereby re-saturate the peats. These trenches were then filled with one to three rows of straw bales, which were covered with soil and planted with sods of bog vegetation (*Sphagnum*, *Carex* and *Empodisma* spp.). Sods of *Sphagnum* and *Carex* species were then generally planted into them to speed the recovery of these species and assist incorporating the organic materials into the peat complex (Good et al. 2010). This technique proved very successful, with no apparent detrimental impact on the structure, function or vegetation of the mires treated in this way.

Not all vegetation of the bogs and fens was destroyed by the 2003 fires in the Australian Alps; in some bogs, some live *Sphagnum* moss hummocks remained, and elsewhere, small patches of *Sphagnum* regenerated from within the core of hummocks (Good et al. 2010). To assist recovery at these sites, initially sterilised straw mulch was spread at a rate of 2 tonnes/ha. However, commercial shade cloth was found a better alternative, as it was lighter, easier to apply and more durable than the straw. Benefits to *Sphagnum* growth and health were noticeable within 2 years.

Fertiliser also appeared beneficial, although statistical evidence is harder to find (see Whinam et al. 2010).

2.1.6 Effect on donor sites and micropropagation of *Sphagnum*

Rehabilitation of mined, harvested or burnt peatland often involves transplanting *Sphagnum* from neighbouring healthy sites. This can affect the health of donor sites, although when done carefully the effects can be minor. A Canadian study showed careful harvesting of *Sphagnum*-dominated systems was not detrimental to the donor sites, with *Sphagnum* cover increasing with time of harvest, and recovering to that of reference sites after 10 years or more (Guêné-Nanchen et al. 2019). The authors of this study recommended minimising exposure of bare peat (without acrotelm, the living moss at the surface), and avoid sinking machinery and creating ruts. Drier donor sites could also be problematic, especially if dominated by trees, shrubs and lichens. One key recommendation is not applicable to Tasmania, i.e. that harvest should occur when soil is frozen.

The restricted occurrence of *Sphagnum* in Australasia means that it could be difficult to find enough donor material for large scale rehabilitation projects, as may be necessary after extensive wildfire. Micro-propagation offers an effective source of *Sphagnum* to reintroduce to degraded peatlands. Caporn et al. (2017) describe trials to use micropropagation techniques to produce material for rehabilitation of a degraded English blanket bog. The water table was highly variable across this landscape, ranging from high on a plateau site to very erratic or absent at many other sites where the peat layer was very thin (*e.g*. less than 10 cm) due to erosion of bare peat, which can extend down to the mineral bedrock. Three forms of micro-propagated *Sphagnum* were used: plugs, gel and beads. Typically, beads were broadcast by hand, plugs inserted individually by hand, and gel applied from a backpack sprayer or similar device delivering small-volume 'blobs'. Micropropagated *Sphagnum* was applied to bare peat, treated (re-vegetated) peat and native vegetation. In this trial, establishment of mixed-species *Sphagnum* plugs was around 99%, while *Sphagnum* gel reached a cover of 95% in two years (Caporn et al. 2017). Of the three forms of micro-propagated *Sphagnum*, plugs and gel were most able to establish and rapidly increase in cover. Bare peat was not a good surface for bead establishment. However, establishment of *Sphagnum* from beads was improved at the treated site, which had previously received the standard rehabilitation treatment of a nurse crop of young grass along with lime and fertiliser.

2.2 Lake Mackenzie *Sphagnum* rehabilitation trials

There were two facets to the *Sphagnum* rehabilitation trials at Lake Mackenzie: (1) investigating the use of small unmanned aerial systems (UAS) to identify moderately and severely damaged *Sphagnum*, and (2) testing whether recovery of fire-damaged *Sphagnum* could be improved by applying shadecloth, fertiliser or transplanting healthy *Sphagnum*.

The testing of unmanned aerial systems has been reported on by Harding et al. (2022), and is summarised very briefly here, as follows. A key step in *Sphagnum* mire restoration is to develop rapid, broad-scale, cost-effective and low impact techniques to survey to and identify sites in need of rehabilitation. Traditional on-ground mapping and monitoring of fire severity is labour-intensive and can compound fire damage through extensive trampling of already impacted areas (D'Acunha, Lee & Johnson 2017; De Roos et al. 2018). Low spatial resolution remote sensing products, such as satellite imagery and aerial photography, are unsuitable for surveying fire severity in *Sphagnum* mires because of their small extent (typically <1-2 ha), complex and fine-scale vegetation mosaics and frequent obstruction by cloud cover (De Roos et al. 2018). Small unmanned aerial systems (UAS) can capture imagery at 1-2cm resolution and have previously been used for mapping and monitoring fire severity and species compositions in other environments (De Roos et al. 2018; McKenna et al. 2017; White et al. 2020). Therefore, one component of the Lake Mackenzie project was to investigate the efficacy of using unmanned aerial systems (UAS) with visible spectrum sensor technology to map the fire severity and area of *Sphagnum* mires burned by the 2016 fires (Harding et al. 2022). This study found poor to moderate agreement between the UAS and field-assessed fire severity. Importantly, results varied between the three mires studied. There was acceptable agreement between field and remotely-sensed assessments of damage to *Sphagnum* in the mire with high *Sphagnum* cover. However, agreement was poor in areas with high grass cover, highlighting the importance of acquiring imagery immediately after fire. Further work will be required to evaluate the potential of UAS to identify areas of *Sphagnum* suitable for rehabilitation efforts if such imagery can be acquired.

The remainder of this chapter reports on the trial that aimed to test whether recovery of fire-damaged *Sphagnum* could be improved by applying shadecloth, fertiliser or transplanting healthy *Sphagnum* into sites burnt by the 2016 Lake Mackenzie fire complex.

2.2.1 Objectives

The specific objectives of this trial were to:

(1) Monitor the change in cover of healthy, damaged and killed *Sphagnum* in mires burnt in the 2016 Lake Mackenzie fires, and in two unburnt mires

(2) Test whether recovery of *Sphagnum* in moderately and severely burnt experimental quadrats was improved by applying shadecloth, fertiliser or transplanting healthy *Sphagnum*
(3) Assess changes in cover of other life forms such as other bryophytes, ferns and shrubs in relation to burn severity and applied treatments
(4) Make management recommendations for work following future fires

2.2.2 Geographic context

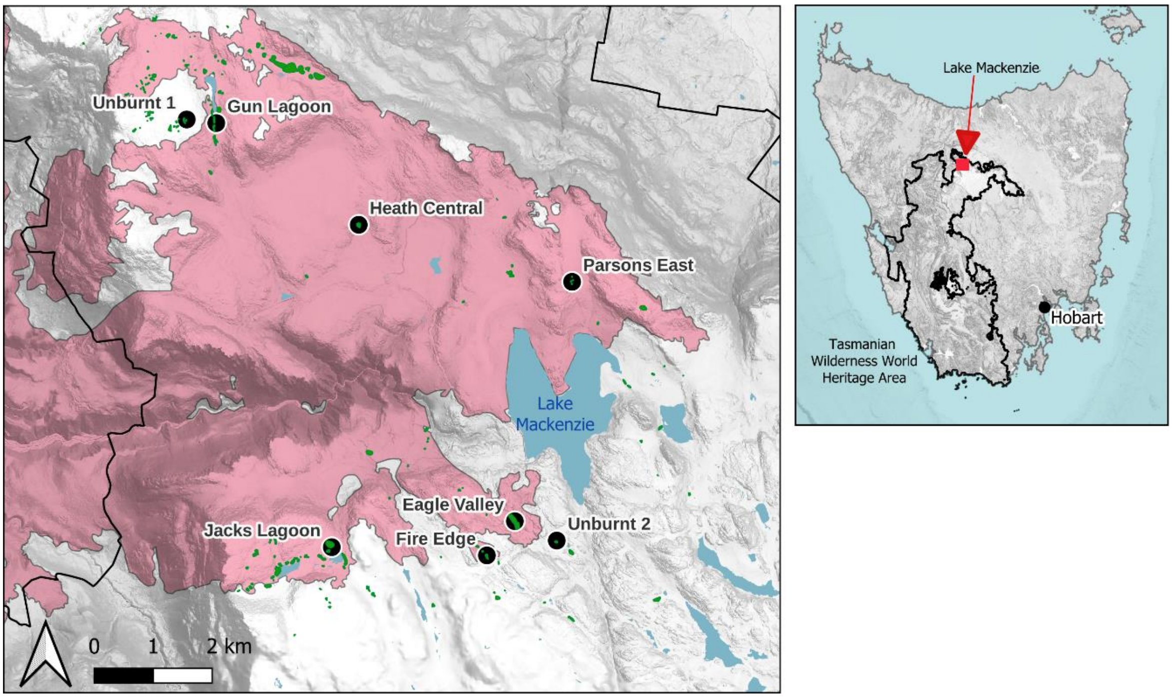

Fig. 2. Location of the six burnt and two unburnt mires used as study sites in the Lake Mackenzie *Sphagnum* restoration trials. The 2016 Lake Mackenzie fire footprint is shown in pink, with mires shown in green and the black line indicating the boundary of the TWWHA. The small map shows the study location in Tasmania.

The study sites were situated within 8 km of Lake Mackenzie ((41.67 °S, 146.37°E), an impounded lake managed by Hydro Tasmania. Lake Mackenzie is near the edge of Tasmania's Central Plateau at approximately 1200 m above sea level, in the far north of the TWHHA (Fig. 2). Mean annual precipitation is 1985 mm (Hydro Tasmania). Temperatures at Liawenee, the nearest high-elevation weather station, range from a mean monthly minimum of -1.6 °C in July to a mean monthly maximum of 19.1°C in January, with a mean annual temperature of 6.9°C (Bureau of Meteorology 2022). The area was exceptionally dry at the time of the fire, but near record rain fell during the following winter (Fig. 3). Precipitation was close to average in the lead up to the establishment of the first quadrats in autumn 2019, but was well below average in the spring and summer of 2019/20

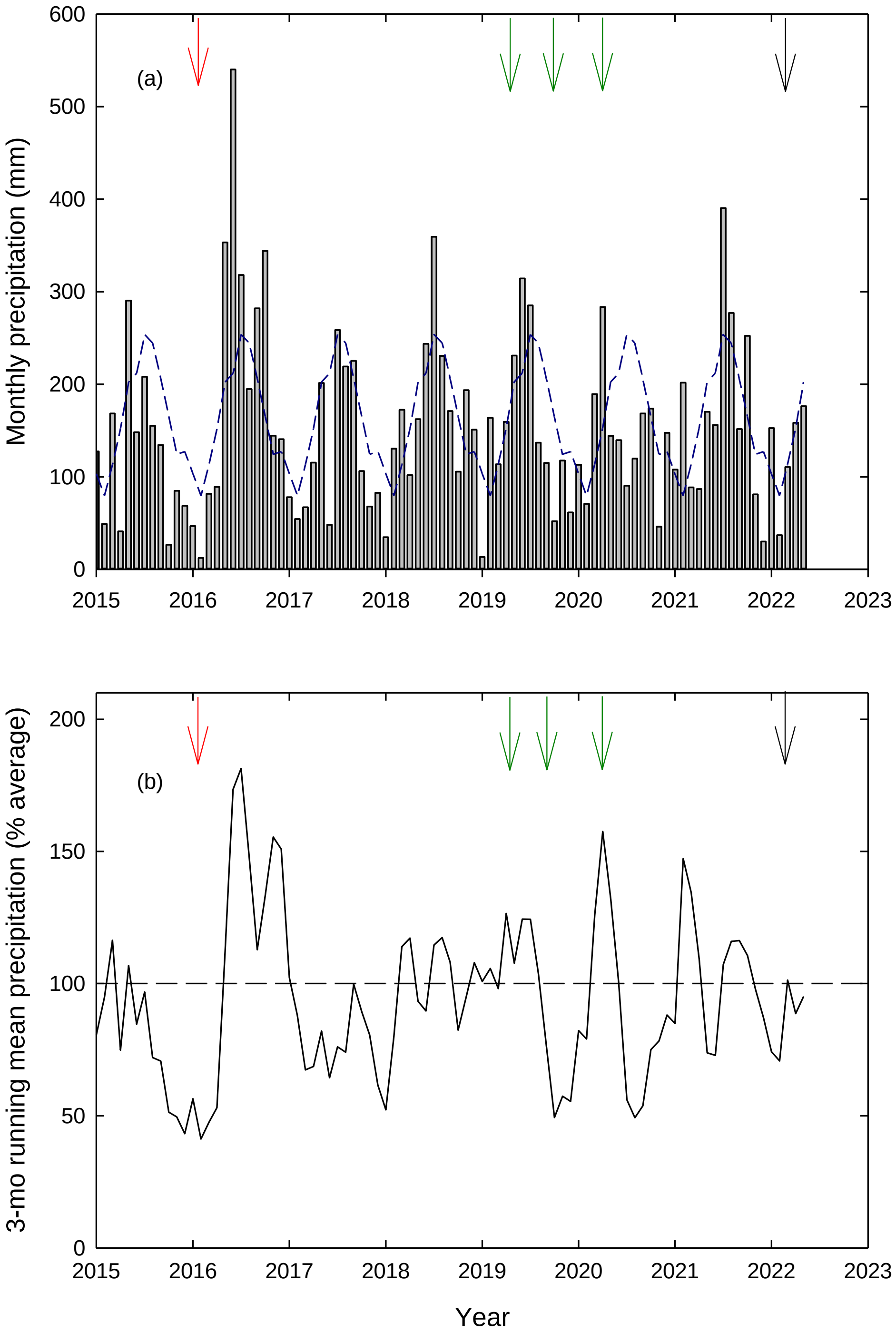

Fig. 3. (a) Precipitation at Lake Mackenzie from the lead up to the fire to the end of the trials. Monthly precipitation totals (bars) in relation to long-term averages (blue dashed lines) between January 2015 and May 2022, and (b) 3-month running average monthly precipitation as a percentage of the long-term running 3-month averages. The ticks indicate the start of the year. Note the precipitation deficiencies immediately before the fire (red arrow) and again in late 2019 and spring of 2020. Green arrows indicate establishment of *Sphagnum* study plots and the black arrow, final measurements. Precipitation data from Hydro Tasmania.

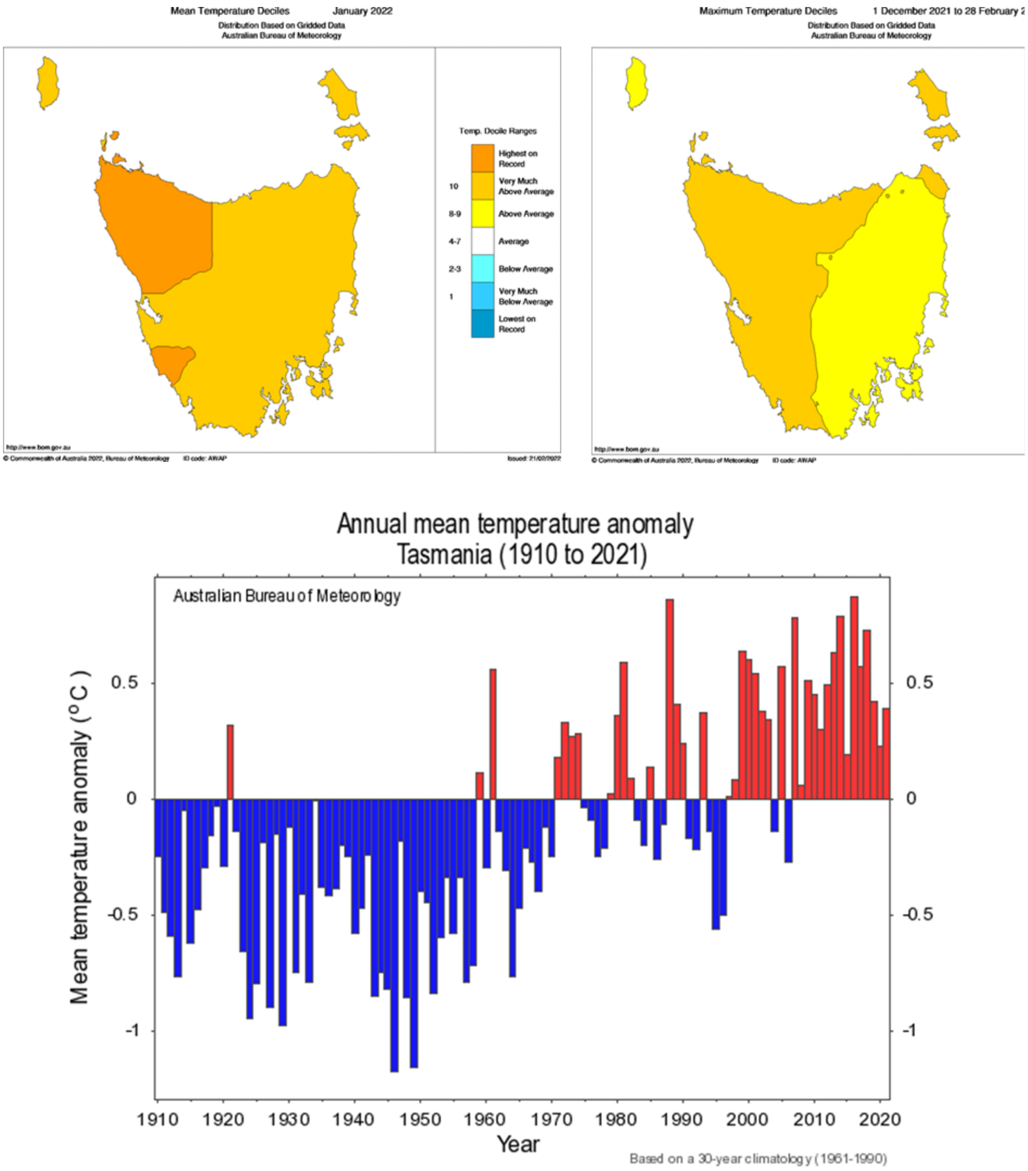

Fig. 4. Mean temperature deciles for Tasmania in January 2022, showing near-record high temperatures in our study region, and maximum temperature deciles for summer of 2021/22, showing temperatures were very much above average (Decile 10). The trend in anomalies in mean annual temperature relative to the 1961-1990 baseline, is also shown. From Bureau of Meteorology (2022)

after the second set of quadrats were established, and again in the winter and spring of 2020 after the final set of quadrats were established (Fig. 3), as well as the summer of 2021/22, immediately before the final survey. The summer of 2021/22 was also very much hotter than average across Tasmania (Fig. 4), intensifying the effects of the dry summer.

Table 1. Summary of geophysical and cover attributes for the eight *Sphagnum* mires used as study sites in the Lake Mackenzie *Sphagnum* restoration trials. All sites had a slope of <2% and a south-easterly aspect. Trial dates, and the number of quadrats at each site, are also shown. The cover of burnt and unburnt *Sphagnum* and other vegetation and free water in the whole of each mire was assessed using UAV imagery (Fig. 5). This is unlike the other cover values presented in this report, which are based on the study quadrats, and were positioned to stratify our experimental design, rather than randomly sample the mires. Geocoordinates of individual quadrats are in data repository.

Site	Eagle Valley	Fire Edge	Gun Lagoon	Heath Central	Jacks Lagoon	Parsons East	Unburnt 1	Unburnt 2
Site code	EV	FE	GL	HC	JL	PE	UB1	UB2
Easting	448493	448032	443423	445868	445405	449478	442921	449189
Northing	5384107	5383494	5390877	5389093	538665	5388124	5390877	5383725
Elevation (m)	1210	1253	1247	1132	1266	1201	1297	1170
Area (ha)	1.69	0.5	3.09	0.43	1.15	0.38	2.36	2.01
Shape	Elongate	Elongate	Elongate	Globular	Globular	Elongate	Elongate	Elongate
Cover - whole mire (%)								
Burnt *Sphagnum*	83.1	53.4	19.8	77.2	39.5	36.9	NA	NA
Unburnt *Sphagnum*	0.8	1	0	2.4	0.5	1.1	NA	NA
Burnt other	8	38.4	73	18.6	56.5	52.3	NA	NA
Unburnt other	0.4	0	0	1.8	0	6.8	NA	NA
Water	7.7	7.1	7.2	0	3.4	2.8	NA	NA
Trial summary								
Number of quadrats	84	84	84	84	84	84	20	20
Establishment Date	Mar-19	Oct-19	Feb-20	Apr-19	Nov-19	Mar-19	Mar-20	Mar-20
Remeasurement Date	Feb-22	Mar-22	Mar-22	Feb-22	Mar-22	Feb-22	Mar-22	Feb-22
Summer growing seasons	3	3	2	3	3	3	2	2

The eight study sites were selected from imagery collected using a fixed-wing manned aircraft. and included six burnt and two unburnt *Sphagnum* mires (Fig. 2). The extent of *Sphagnum* cover and the area burnt in each mire was subsequently evaluated using high resolution imagery acquired from an unmanned aerial vehicle (UAV) (Harding et al. 2022). The UAV imagery captured all *Sphagnum* patches within a contiguous area of the mire, and included a narrow buffer of non-*Sphagnum* vegetation (> 1 m). Subsequently a geographic information system was used to create a polygon to define the perimeter of the mire, following vegetation boundaries where possible (noting this boundary sometimes arbitrarily segmented homogeneous tracts of non-*Sphagnum* vegetation) and ensuring that all *Sphagnum* patches apparent on the imagery were included. Analysis of the mapping based on the UAV imagery showed that 20-84% of the area of the six burnt mires had been covered in *Sphagnum* before the fire, and that more than 90% of the *Sphagnum* cover had been burned by the 2019 fire (Table 1; Fig. 5; Appendix 1). The unburned mires had approximately 10% (Unburnt 1) and 5% (Unburnt 2) *Sphagnum* cover.

Reconnaissance of the study area commenced in late 2018, research permits were approved in February 2019 and the first quadrats were established in March 2019. Most research sites were accessed on foot from trails starting at the end of the Lake Mackenzie Road (E448431, S5385756). Key geospatial attributes of the study sites and survey dates are summarised in Table 1.

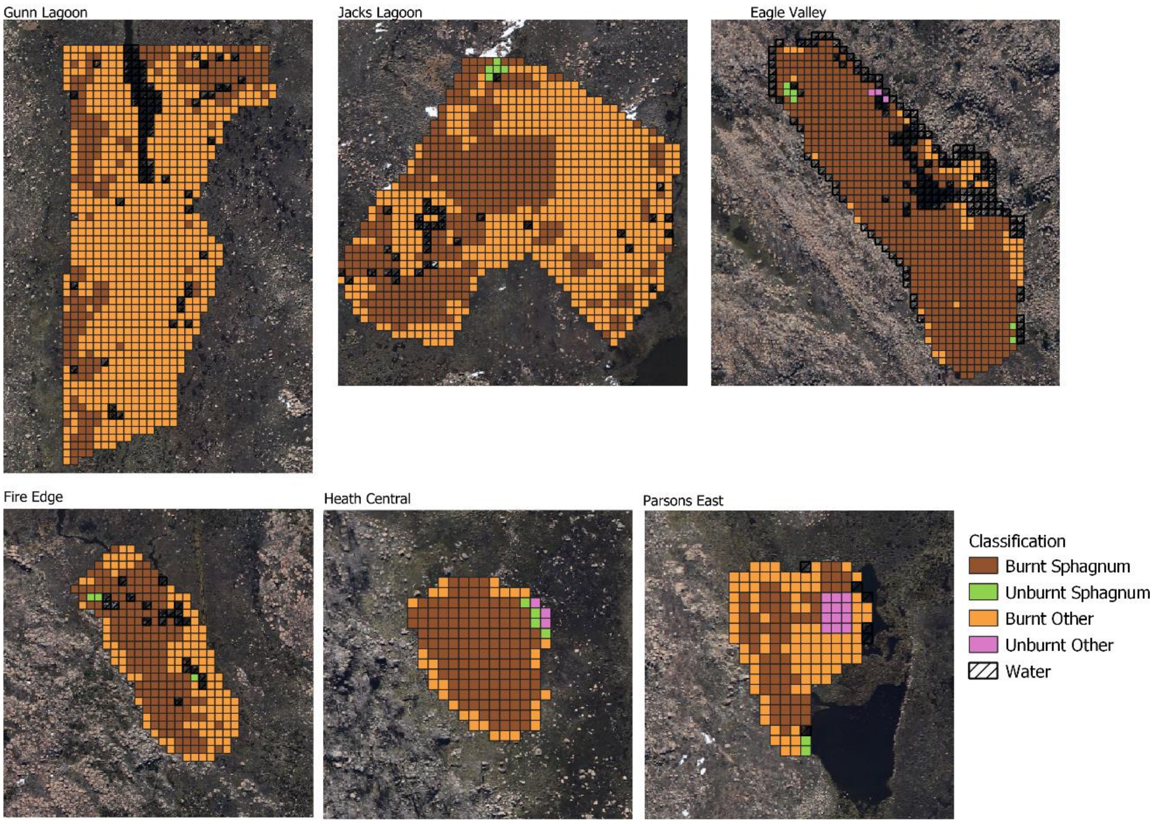

Fig. 5. UAV images of each burnt mire showing areas classed as burnt *Sphagnum*, unburnt *Sphagnum*, burnt other vegetation, unburnt other vegetation and free water. The areas of each are summarised in Table 1. The UAV imagery for Eagle Valley, Heath Central and (c) Parsons East is shown in Fig. 6. Validation of these assessments shown in Appendix 1.

2.2.3 Description of the study mires

Eagle Valley

Eagle Valley is a shallow depression sprinkled with small pools connected by a small creek (Fig. 6a). It is found approximately 400 metres from the Blue Peaks Track, and contains substantial stands of *Athrotaxis cupressoides* and large *Sphagnum* mires, most of which were severely fire damaged. Surrounding slopes are rocky, with stands of pencil pine and eucalypts, interspersed with bare rock and scrub. This was one of the areas most damaged by the 2016 wildfires, and part of the studies reported by Bowman et al. (2019) and Bliss et al. (2021). At this site, fire killed 59% of the live stems (Bowman et al. 2019). Soil core samples were collected here with "peat" depths of up to 3 metres found before striking glacial clays. Eagle Valley is at an elevation of 1210 m, is roughly rectangular, 250 metres x 75 metres, and drains to the south east. *Richea* shrubs were well established among the *Sphagnum*. Low, steep slopes are found to the west and east with small eucalypts and *Orites* shrubs scattered among dolerite boulders. The south-east fire boundary is 300 metres beyond this site. Of all the study sites, Eagle Valley was arguably the place of greatest natural beauty and the 2019 fire appears to be more damaging here, certainly aesthetically.

Fire Edge

Fire Edge is the only site found within sight of a well-travelled path (the Blue Peaks Track), and is within 50 metres of the southern fire boundary, at an elevation of 1253 metres. Situated at the end of an approximately 350 metre long catchment of pools and streams, the Fire Edge mire drains to the southeast into a small unnamed tributary which flows through Unburnt 2 and then on to the Fisher River, 1.5 kilometres to the east. Running the length of the study area is a stand of large pencil pines, only a few of which appear to have survived the fire. The vegetation of the surrounding rocky slopes includes *Orites* and *Richea* and small eucalypts.

Gun Lagoon

Gun Lagoon is a 750 metre long, narrow, permanent water body situated at the far north-west of the Central Plateau, at an elevation of 1247 metres. *Sphagnum* mires are found at various positions around the lake. This study's quadrats are located at the far southern end, where the lagoon drains into Gun Lagoon Creek. The site is accessed via a 3 kilometre long walk following the creek upstream from Lake Mackenzie Road. The study area is sheltered to the west by steep, dolerite boulder-strewn slopes rising to 1300 metres, with more gentle slopes to the east. Surrounding vegetation is dominated by low shrubs such as *Richea scoparia* and *Orites revoluta*, with taller trees such as eucalypts and pencil pines absent. Gun Lagoon is close to the north-west fire boundary, and all of the area within at least 150 metres of the lagoon appeared burnt, while a relatively large region on the plateau above escaped the fire.

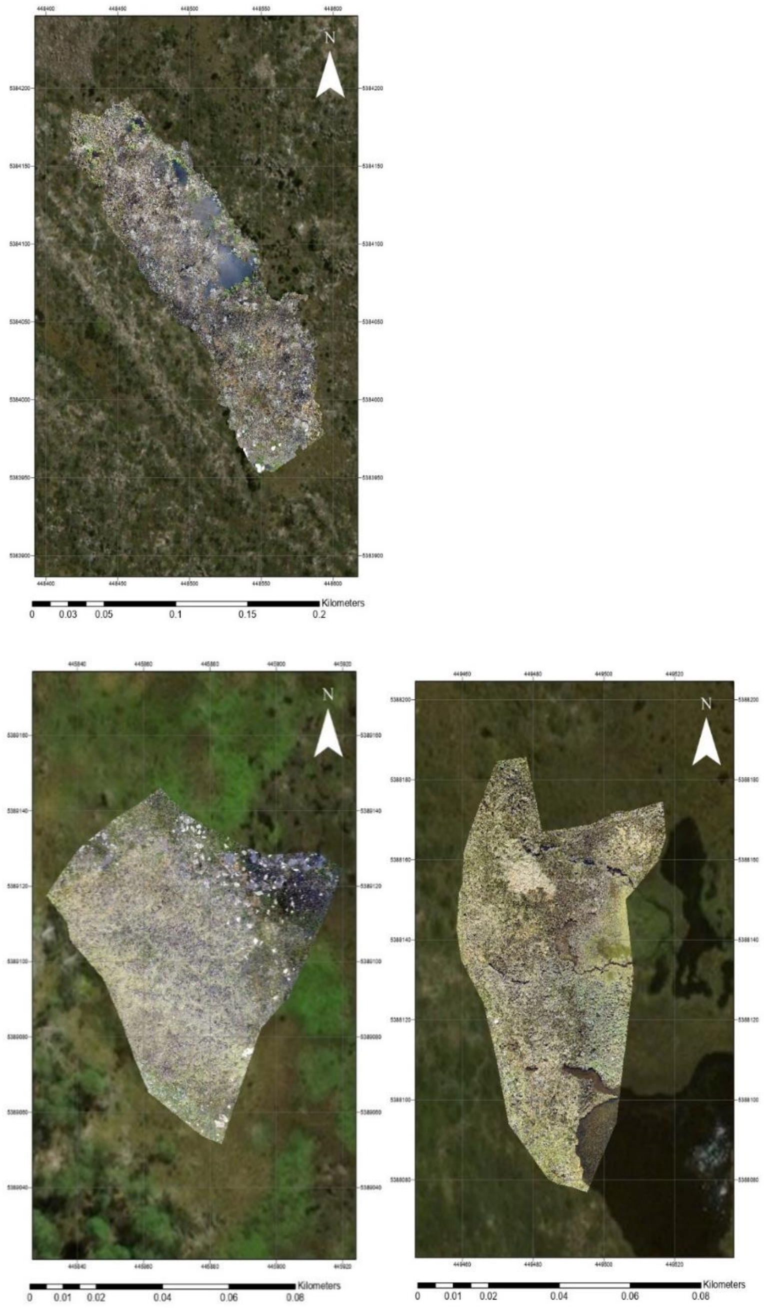

Fig. 6. Examples of UAV imagery of three study mires: (a) Eagle Valley, (b) Heath Central and (c) Parsons East. These were used for the assessments of fire damage and *Sphagnum* cover in Fig. 5 and Table 1.

Heath Central

Heath Central is 1050 metres north of the Lake Mackenzie Road, accessed via a footbridge over the Hydro canal. Heath Central is the lowest elevation site at 1132 metres, and, as with all other sites the land does rise to the west, and drainage is to the south-east (Fig. 6b). Superficially it appears to be the driest of the study sites – aside from a few small pools and an ephemeral creek to the east there is little obvious water, with the nearest substantial water body being Yeates Lagoon 1350 metres to the south-east. Heath Central is the most isolated of the mapped *Sphagnum* mires, with no other within two kilometres and even further to the nearest observed pencil pine. Other distinguishing features include a stand of relatively large eucalypts within 30 metres and a substantial covering of grasses, including the introduced Tall Fescue, over the burnt *Sphagnum* mounds.

Jacks Lagoon

Jacks Lagoon is 3.7 kilometres south-west of Lake Mackenzie. Access is from the end of the Parsons Fall Canal Road and a 2.2 kilometre walk via Ritters Plain and Jacks Creek. Elevation at the lagoon is 1266 metres. While the topography does slope up to the west, this is a relatively gentle incline, unlike the steep slopes found west of most other burnt sites. Extensive *Sphagnum* mires are found around both Jacks Lagoon and nearby Last Lagoon - all of this study's quadrats are located in an area 150-200 metres NW of Jacks Lagoon. A copse of pencil pines, some of which survived the fire, is at the northern edge of the study site, otherwise trees are absent from the area which is dominated by low shrubs of *Orites* and *Richea*, with some *Diselma archeri* near the lagoon.

Parsons East

Parsons East is situated 200 metres east of the Parsons Track, as it appears on maps, although it is difficult to find on the ground. Access is via a 2.5 kilometre walk north from the Lake Mackenzie dam wall. The most compact of the study sites in area, all quadrats are situated within 60 metres north-west of a large permanent pond, at the southern end of a one kilometre long catchment of pools, mires and streams (Fig. 6c). Elevation is 1201 metres. While a steep, 30 metre high hill of dolerite rising immediately to the west would appear to shelter this site, the topography in fact creates unusual wind turbulence, observed on the final visit, explaining why this was the only site where the shadecloth treatments were significantly disrupted. Low shrubs of *Orites* and *Richea* surround the area, and while stands of pencil pine and eucalypt are found 400 metres away, there are no trees closer to the site.

Unburnt 1 and 2

Two unburnt sites were chosen 10 kilometres apart, to sample the subtle geographic variability across the broader Lake Mackenzie study region. Unburnt 1 is atop a plateau, situated in the far north-west at an elevation of 1297 metres, approximately 500 metres west of the burnt Gun Lagoon site. Unburnt 2 is in a 200-250 metre diameter circular depression, located in the far south east at an elevation of 1170 metres, and is approximately 900 metres south east of Eagle Valley. The surrounding vegetation of Unburnt 1 is dominated by low shrubs of *Orites* and *Richea* with no larger trees within sight. *Orites* and *Richea* are also present at Unburnt 2, while Eucalypts and Pencil pines are widespread nearby. Within the study quadrats the assessed vegetation also differed: Unburnt 1 was the only site at which *Gleichenia alpina* was not present, whereas Unburnt 2 contained an abundance of this fern.

Restionaceous species and grasses were found at both sites, but were much more prevalent at Unburnt 1. There is less apparent standing water and no obvious drainage at Unburnt 1, whereas a network of larger ponds drains in a south-east direction from Unburnt 2.

2.2.4 Establishment of study quadrats

We used a stratified study design, in which we assigned six treatments, including an untreated control, to quadrats in areas burnt at moderate severity (visually assessed as < 75% *Sphagnum* killed) or high severity (≥ 75% killed) in each of the six burned mires (Table 1). We also applied four of these treatments to quadrats in the two unburnt mires. Examples of healthy *Sphagnum* in unburnt quadrats, damaged *Sphagnum* in moderate severity quadrats and killed *Sphagnum* in severely burnt quadrats are shown in Fig. 7. At each burnt mire, seven replicates of six treatments were assigned to quadrats in areas burnt at low and high severity (Table 2). Thus, at each burnt mire we established a total of 84 quadrats, allocated evenly between areas burnt at moderate severity and high severity. We also established 20 quadrats in each of two unburned mires. These were located haphazardly, but at least 5 m distant from any neighbouring quadrat. We applied five replicates of four treatments to quadrats in both unburned mires (Table 2). In total, 544 permanent quadrats were established to assess the initial vegetation cover in the various mires and severity classes, and measure how it changed with time. Our focus was on the *Sphagnum*, but we also measured cover of other vegetation and biophysical variables (Appendix 2). The details of these measurements, and of the applied treatments, are described below.

Table 2: Study design showing the total number of study quadrats according to treatments and burn classes (shaded treatments shown in grey).

Burn Class	Control	Fertiliser	Transplant & Fertiliser	Shade	Shade & Fertiliser	Shade & Transplant & Fertiliser	TOTAL
Unburnt	10	10	-	10	10	-	40
Moderate	42	42	42	42	42	42	252
Severe	42	42	42	42	42	42	252
TOTAL	94	94	84	94	94	84	544

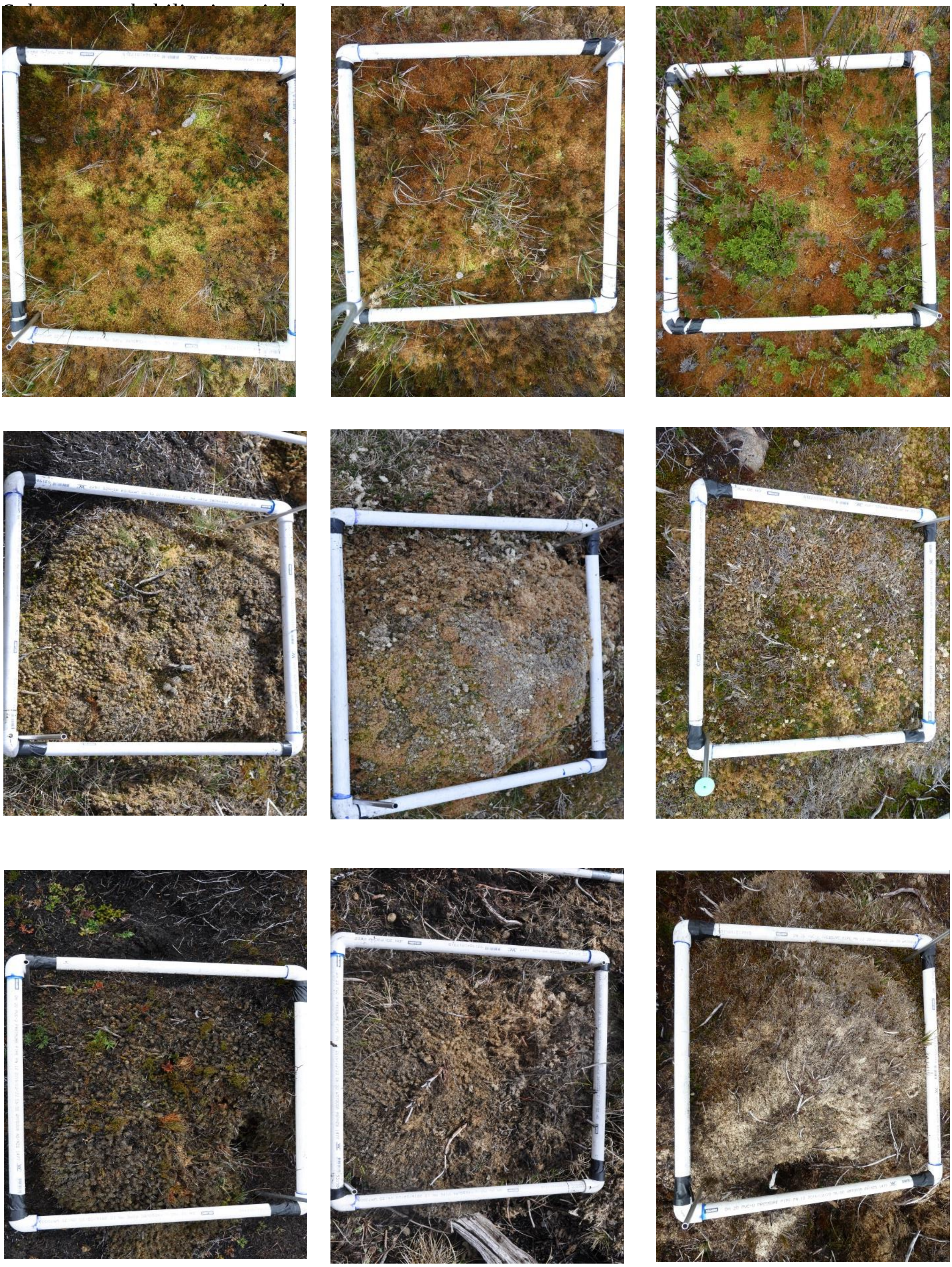

Fig. 7. Examples of healthy *Sphagnum* in unburnt quadrats (top row), damaged *Sphagnum* in moderately burnt quadrats (middle row), and killed *Sphagnum* in severely burnt quadrats (bottom row). Appendix 3 illustrates assessments of *Sphagnum* cover. (Photos: Scott Nichols)

Table 3. Cover variables assessed in the quadrats at burnt and unburnt *Sphagnum* mires in the Lake Mackenzie trials.

Cover variable	Definition
	Sphagnum
Killed *Sphagnum*	Deeply combusted foliage with no evidence of life
Damaged *Sphagnum*	Living but with burned foliage
Healthy *Sphagnum*	Free of any killed or damaged foliage
Outer - healthy	Healthy *Sphagnum* in the outer quadrat
	Other cover
Richea	*Richea* species
Shrubs -other	Shrubs other than *Richea* species
Restionaceae	Restiads, primarily *Empodisma minus*, *Sporadanthus tasmanicus*, and *Baloskion*
Grass	Predominantly *Poa* species, some introduced fescue
Herbs	Miscellaneous herbaceous species
Gleichenia	*Gleichenia alpina*
Ferns -other	Fern species other than *G. alpina*
Bryophytes - other	Bryophyte species other than *Sphagnum*
Threatened species	
Weeds	Exotic species (other than fescue)
Dead wood	Woody debris
Pencil pine foliage	Detached *Athrotaxis cupressoides* foliage

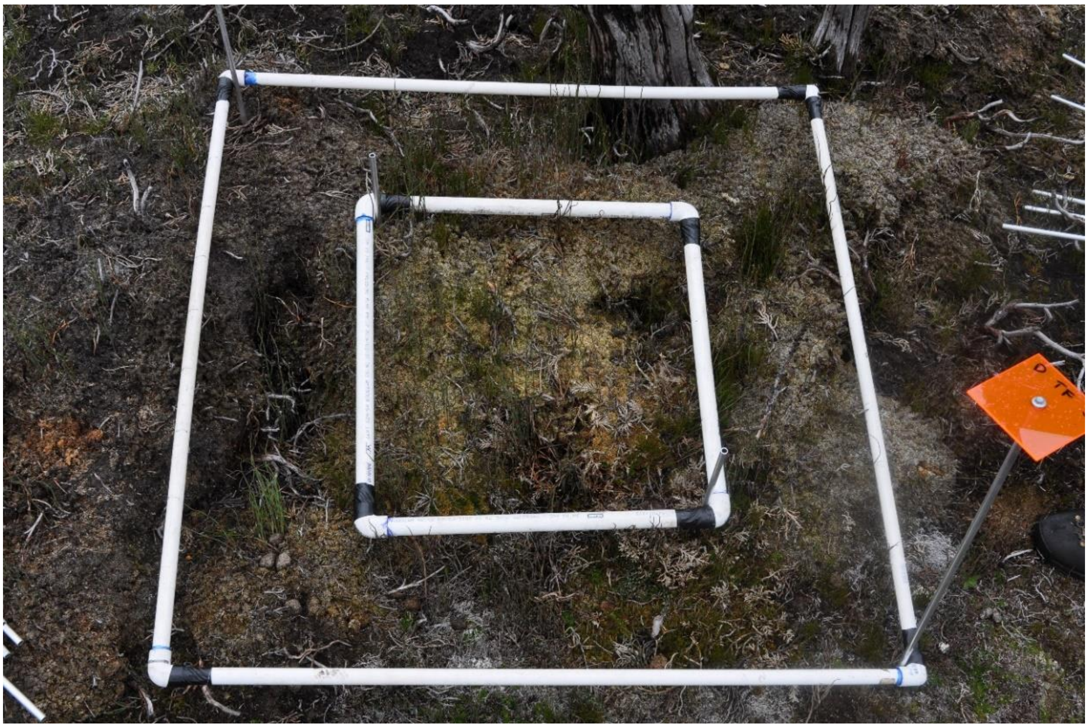

Fig. 8. Plot EVDTF6 showing outer and inner quadrats (PVC tubing removed after vegetation assessments and application of treatments). (Photo: Scott Nichols)

2.2.5 Field assessment of cover

Quadrats (1 m x 1 m) were positioned to overlay *Sphagnum* hummocks. Our focus was on the *Sphagnum*, but we also measured cover of other biophysical variables (Table 3; Appendix 2). Cover was assessed on the central 0.5 m x 0.5 m (0.25 m^2), with the outer quadrat constituting a buffer (Fig. 8). Within each quadrat, we visually assessed the percentage cover of healthy, damaged, and killed *Sphagnum*. Healthy *Sphagnum* was alive, with no apparent fire damage. Damaged *Sphagnum* was singed at the surface, but with evidence of life. Killed *Sphagnum* was deeply combusted, with no evidence of life. We also recorded the cover of healthy *Sphagnum* in the outer quadrat. Examples of this assessment of the quadrats are shown in Appendix 3.

We then visually assessed the percentage cover of other lifeforms and species growing above the *Sphagnum* layer in the inner 0.25 m^2 quadrat. Pencil pines (alive and dead) were counted within a 5 m radius of the quadrat centre. We also counted the number of marsupial scats present in each quadrat as an indication of herbivory.

2.2.6 Initial vegetation cover of study quadrats

Total *Sphagnum* cover in individual study quadrats ranged from 70-100% (average 97%), although in the burnt sites, much was damaged or killed. Moderate burn severity quadrats had on average 41% killed, 51% damaged and 4% healthy *Sphagnum* cover, and there was 15% cover of healthy *Sphagnum* in the outer quadrat (Fig. 9). By comparison, severely burnt quadrats averaged 97% killed, 0.6% damaged and 0.05% healthy *Sphagnum* cover, with 2.5% healthy *Sphagnum* in the outer quadrat.

Restionaceae and grasses were major vegetation types across most mires, and other bryophytes and herbs were important at several (Table 4). In two quadrats we observed *Senecio* plants that were possibly exotic species, although we are uncertain about species identity. Some of the grasses at Heath Central could have been the introduced Tall Fescue, but again we were uncertain of their identity. No threatened species were observed. The most obvious effect of burning on species other than *Sphagnum* was that burnt quadrats had very little cover of *Richea* or other shrubs (Table 4). Most cover variables were more strongly correlated with site than burning. The most striking difference in vegetation composition amongst the sites was that *Gleichenia* cover averaged 35% in quadrats at one unburnt site, but it was <2% at all other sites. Live pencil pines were found only at Eagle Valley and Unburnt 2, while dead pencil pines were also found at Fire Edge.

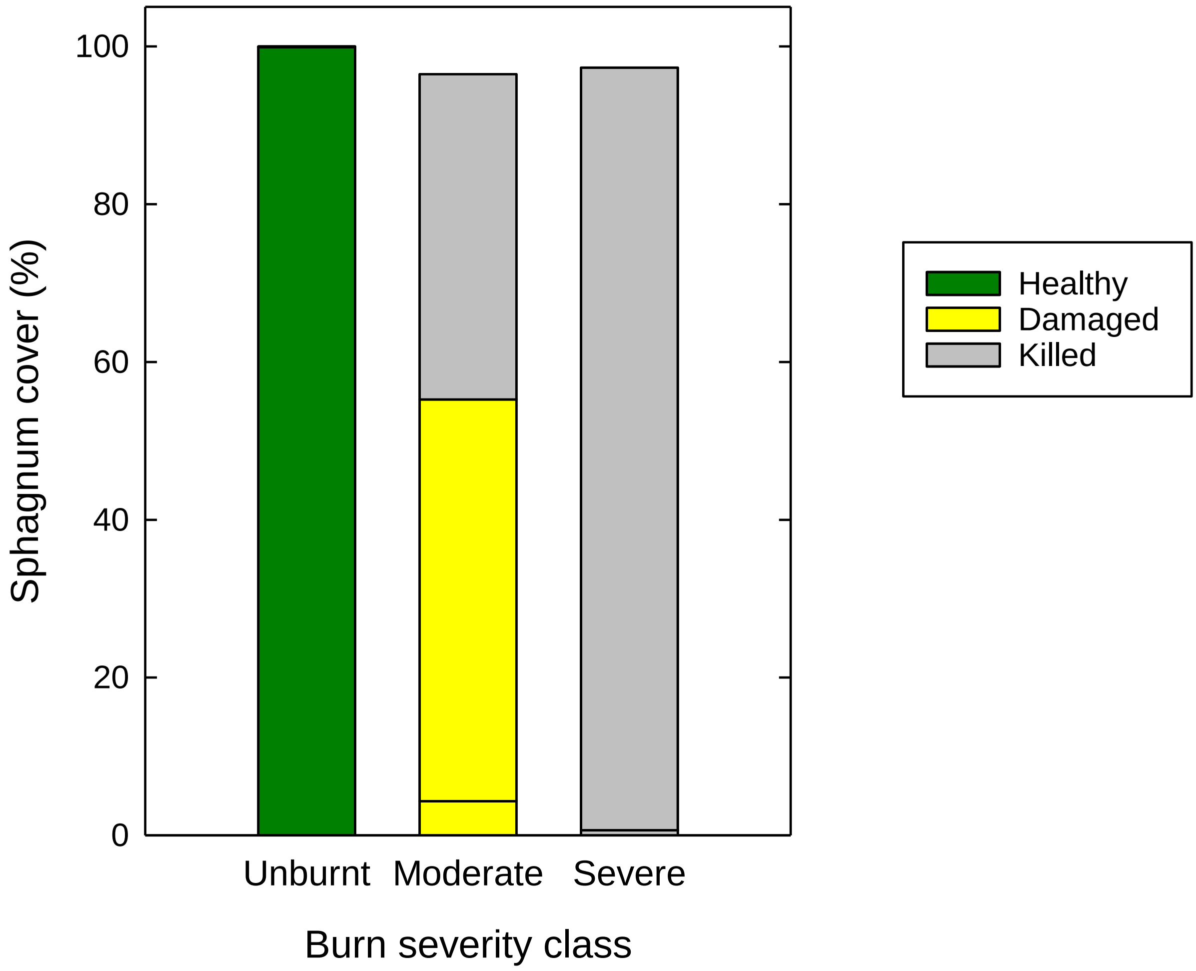

Fig. 9. Cover of healthy, damaged and killed *Sphagnum* at the time quadrats were established, in relation to burn severity class.

Table 4. (i) Average initial cover of the three *Sphagnum* health classes in the inner quadrat, and healthy *Sphagnum* in the outer quadrat (ii) other cover variables and (iii) counts of scats in the study quadrats at all eight mires. *Sphagnum* cover variables were most closely related to quadrat Burn Class (Table 5). Shrub cover (both *Richea* and other) was strongly associated with whether the quadrat had burnt or not, but other variables were most strongly related to Site differences (which include differences between burnt and unburnt sites, as well as differences amongst sites unrelated to burning). See Table 5 for details

	Eagle Valley	Fire Edge	Gun Lagoon	Heath Central	Jacks Lagoon	Parsons East	Unburnt 1	Unburnt 2
Site code	EV	FE	GL	HC	JL	PE	UB1	UB2
Quadrats (n)	84	84	84	84	84	84	20	20
Sphagnum cover in study quadrats (%)								
Killed	76	67	69	69	75	57	0	0
Damaged	17	28	29	27	22	32	0	0
Healthy	3	0	2	3	0	4	100	100
Outer -healthy	5	17	7	4	15	7	76	79
Other cover in study quadrats (%)								
Richea	0.02	0	0.01	0	0	0	1.4	2.9
Shrubs- other	0.2	0.1	0.6	0.7	0.4	0.3	6.1	7.1
Restionaceae	7.5	3.3	9.0	11.6	4.7	11.0	15.8	5.9
Grasses	0.8	5.5	5.4	6.5	2.2	8.5	7.3	1.0
Herbs	0.9	0.7	2.6	6.2	1.6	5.7	8.6	0.6
Gleichenia	0.2	0.2	1.3	1.6	0.8	1.1	0	34.7
Ferns- other	0	0	0	0	0	0.2	0	0
Bryophytes - other	0.8	7.0	5.0	1.7	8.1	5.2	0.7	1.4
Threatened species	0	0	0	0	0	0	0	0
Weeds	0	0	0	0	0	0.1	0	0
Wood Dead	2.2	0.8	0.1	3.4	0.4	2.1	0	0.2
Athrotaxis foliage	4.0	1.8	0	0	0.1	0	0	0.3
Counts of *Athrotaxis* trees and scats								
Live *Athrotaxis*	0.1	0	0	0	0	0	0	0.1
Dead *Athrotaxis*	2.0	2.9	0	0	0	0	0	0
Scats	1.2	2.7	0.9	1.0	0.8	0.8	1.3	2.1

Table 5. Comparison of generalised linear models describing initial cover and counts in the study quadrats. The delta AICc values are shown for the four models tested for each vegetation variable: predictor variables compared were burnt *vs* unburnt, burn class (unburnt, moderate or severe), site or the intercept only model. The best models for each vegetation variable are shown in yellow, other good models are shown in orange, and models that are not as good, but that are better than simply using an overall average (the intercept only model) are shown in green.

	Model			
Vegetation variable	Burnt *vs* unburnt	Burn Class (unburnt, moderate or severe)	Site	Intercept only
		Sphagnum cover		
Killed	879	**0**	868	1046
Damaged	892	**0**	887	923
Healthy	105	**0**	60	1928
Outer -healthy	111	**0**	61	605
		Other cover		
Richea	**0.2**	2.2	**0**	88
Shrubs- other	**0**	2.0	7.2	175
Restionaceae	86	82	**0**	89
Grasses	112	107	**0**	110
Herbs	84	85	**0**	84
Gleichenia	424	424	**0**	626
Ferns- other	49	51	**0**	48
Bryophytes - other	74	76	**0**	83
Threatened species	na	Not detected		
Exotic species	na	Detected at only one site		
Wood Dead	145	140	**0**	157
Athrotaxis foliage	89	90	**0**	90
		Counts		
Live *Athrotaxis*	6.3	2.5	**0**	8.2
Dead *Athrotaxis*	351	355	**0**	368
Scats	57	45	**0**	77

Models with delta AICc <2 are regarded as having substantial support, those with delta AIC between 4 and 7 have considerably less support, while those with delta AICc> 10 have essentially no support, relative to the best model in the candidate set (Burnham and Anderson 2001). Values should only be compared within rows.

2.2.7 Imposition of experimental treatments

After measuring the initial vegetation characteristics of our study quadrats, we imposed the experimental treatments, which consisted of various combinations of three interventions: shade, fertiliser and transplants. These have been shown to promote post-fire recovery of *Sphagnum* in the Australian Alps (Clarkson et al. 2017; Whinam et al. 2010). The three interventions were combined in an incomplete factorial design to give a total of six treatments, as follows (Table 2). There were four possible combinations of shade and fertiliser, and we applied these four treatments to all burnt and unburnt sites. However, we minimised the number of quadrats receiving *Sphagnum* transplants because of the likely adverse effects on donor sites. Therefore, we did not transplant *Sphagnum* into unburnt quadrats, and we did not use all possible combinations of fertiliser and shade with the transplants. Expert advice suggested that all transplants should receive fertiliser, so we omitted the treatments without fertiliser. Thus, only two transplant treatments were applied (Transplant + Fertiliser and Transplant + Fertiliser + Shade), and then to only the burnt sites. The applied treatments are summarised in Table 2.

Shade

Fig. 10. Shadecloth applied at quadrat EVDS3 (Photo: Scott Nichols)

Unlike Whinam et al. (2010), who applied shadecloth in large continuous sheets up to 20 m long, we used 1 m x 1 m shadecloth squares in order to maximise replication by targeting small areas, which also reduced material waste and allowed materials to be carried long distance. Shadecloth squares were constructed off site from beige 70% block out shadecloth material. Squares of 1200 x 1200 mm were cut, the four edges folded and creased at 100 mm and held together by 20mm stainless steel eyelets at each corner, forming a total shade square of 1m^2 (Fig. 10). Lightweight 10mm diameter aluminium stakes provided secure anchors against high winds. The outer quadrat aluminium marker stakes, plus two additional corner stakes were thread through the eyelets and into the ground surface, then cinched and fixed securely with plastic cable ties. Approximately 132 of these were checked for secureness after one year, which revealed no significant damage from wind or animals (3 of 132 needed resecuring). At the completion of the trial it was found that only 20 of 272 shadecloth treatments were disturbed, 14 of these at one site (Parsons East).

Fertiliser

Fertiliser was used in all multi-factorial treatments because it was considered to improve recovery of *Sphagnum* after fire in the Australian Alps (Whinam et al. 2010). Fertiliser treatment is inexpensive, simple to apply, and low doses are considered to have minimal adverse effects on the sensitive montane environment. We applied slow-release fertiliser (Scott's Osmocote Native Gardens; Bella Vista, NSW) at a rate of 80 g m^{-2}, as recommended after consultation with the Royal Tasmania Botanical Gardens. Fertiliser was evenly distributed by hand over the entire 1m^2 quadrat.

All plant types were monitored in the experimental quadrats to test for possible proliferation of undesirable plants following addition of fertiliser.

Transplants

Sphagnum transplants potentially offer a way of re-establishing *Sphagnum* into sites where fire is so intense it is lethal to the *Sphagnum* (Whinam et al. 2010). *Sphagnum* transplants were therefore included in our trial.

Transplant techniques were modelled on those described by Whinam et al. (2010). Transplant material was sourced from remnant healthy patches within each mire, typically within 200 m of the receiving quadrat (Fig. 11). Blocks (20 x 20 x 20 cm) of live *Sphagnum* and underlying dead and humified material were cut using a bread knife and relocated to a cavity cut from the centre of the burnt quadrat (Fig. 12). Donor site locations were recorded to enable future monitoring of recovery rates (Fig. 13). After two years, these sites appear to be recovering well (Appendix 4).

Fig. 11. Healthy transplant material (Photo: Scott Nichols)

Fig. 12. Healthy transplanted *Sphagnum* at quadrat PEDTSF4 (Photo: Scott Nichols)

Fig. 13. Examples of donor sites, which have been revisited to visually assess recovery (see Appendix 4). (Photo: Scott Nichols)

2.2.8 Resurvey and removal of equipment

All quadrats were resurveyed in February and March 2022, and the results will be presented in the final report. The resurvey visually assessed *Sphagnum* cover (healthy, damaged and killed) in all quadrats. As for the initial survey, this was done in the inner 0.25 m^2. In addition, we assessed cover of other bryophytes, *Gleichenia*, other ferns, Restionaceae, grasses, herbs, *Richea* and other shrubs, and counted scats.

2.2.9. Equipment remaining in the field

Most equipment was removed following the resurvey. All shade cloth was removed from all sites, as were the coloured discs and longer outer pegs. Everything was removed from the furthest sites, namely Gun Lagoon, Jacks Lagoon, Unburnt 1.

However, as agreed by the study's Technical Committee, the quadrats at Eagle Valley, Parsons East, Heath Central, Fire Edge and Unburnt 2 are still marked by two short inner pegs and a cattle tag, which will allow future monitoring of *Sphagnum* health.
Remaining: At each quadrat at Eagle Valley, Parsons East, Heath Central, Fire Edge and Unburnt 2 (a total of 374 quadrats) are two short inner pegs with a cattle tag label secured.

2.2.10. Data analyses

We investigated differences in initial cover of *Sphagnum* and other vegetation in relation to burn severity class and site using Excel and the statistical software R (R Core Team 2020). Our statistical approach uses generalised linear modelling, multi-model inference and model selection based on Akaike's information criterion (AIC), which balances model bias and simplicity (Burnham and Anderson 2001). This approach has important advantages over traditional hypothesis testing based on frequentist statistics, especially in avoiding many of the problems associated with backward or forward variable selection in regression analysis.

We compared generalised linear equations containing the terms burnt (burnt vs unburnt), burn severity class (unburnt, moderate, severe) and site, to evaluate the strongest influences on the various types of cover. Changes in the cover of *Sphagnum* and other vegetation, between establishment of quadrats and the final measurements, will be analysed in relation to our applied treatments and burn severity, using site as a random effect to account for spatial correlation in the data.

2.3 Communication and Data Records

The findings from this project will be communicated directly to staff from the NRE Tasmania and other interested parties through a series of meetings and workshops. Meetings of the TWWHA Lake Mackenzie Project Committee and the Bushfire Research Group have been scheduled, at which these results will be presented.

The results of the trial have been analysed, and a manuscript is being prepared for publication in an appropriate peer-reviewed international journal.

A decision support tool, based on this study, is being developed to help guide future *Sphagnum* rehabilitation efforts.

All data and metadata files, including descriptions of methods, have been uploaded to a repository housed by the University of Tasmania's Institutional Research Data Portal These will also be provided to NRE Tasmania.

2.4 Recommendations for future work

Ongoing monitoring is important to assess the speed and completeness of the recovery of the burnt *Sphagnum*. While most equipment was removed following the resurvey (see 2.2.8), as agreed by the study's Technical Committee, the quadrats at Eagle Valley, Parsons East, Heath Central, Fire Edge and Unburnt 2 are still marked by two short inner pegs and a cattle tag, which will allow future monitoring of *Sphagnum* health. Ideally, these quadrats will be assessed every two years over the next decade, but at a minimum, after 5 and 10 years. Should this not be intended, we recommend removing all remaining pegs and tags within 2 years. The methods we describe above should be adapted for future re-surveys.

2.4.1 Recommendations for next re-survey

The assessment methods described above should be repeated for future resurveys. At every quadrat at Eagle Valley, Parsons East, Heath Central, Fire Edge and Unburnt 2 (a total of 374 quadrats) are two short aluminium inner pegs with a coloured and numbered "livestock ear tag" secured. Each colour and number combination coincides with a site/burn class/treatment/replicate code; e.g. yellow tag 99 at Eagle Valley is EV D S 1, as recorded in the master data sheet. Every plot has unique GPS coordinates, that will lead to within a few metres of each plot. The inner pegs protrude approximately

10cms above surface level (as of 2022), so may require some searching if many years have passed since last visit.

Equipment List for Resurvey:

- Quadrat grid made of 4 x 0.5m lengths of 20 mm PVC tube and 4 elbows
- Camera
- Hand-held GPS unit (eg Garmin Etrex 10 used for this study) preloaded with GPS coordinates
- Topographic map of area
- Maps of plot numbers/coordinates at each site to assist with relocating and check off progress
- Scoresheets (ideally on waterproof paper)
- Clipboards, pencils
- Metal detector – to find inner aluminium pegs if plots are heavily overgrown

Time and personnel requirements:

The Lake Mackenzie region should be considered a remote alpine environment, despite the proximity of road and Hydro infrastructure. The weather is extremely variable and presents the greatest risk to any field work. The field team should be equipped with appropriate clothing and safety equipment for working several kilometres from a vehicle in a remote alpine environment.

All sites are within 2 hours walk of Lake Mackenzie Road, mostly off track. This can be arduous, and fog can quickly reduce visibility from greater than 1km to less than 20 metres - maps, compass and GPS are essential as well as appropriate clothing and emergency communications such as EPIRB, satellite phone and/or “spot tracker” (mobile phone service is extremely limited and unreliable).

Allow approximately 8 - 10 hrs per site including 4 hrs walking and rest time.

Two people are recommended for this task, one to assess and one to scribe and photograph; while the scribe can assist with estimates, for consistency we chose not to alternate roles.

2.4.2 Future research

It is recommended that any future research or rehabilitation should be implemented much sooner than the 3 years that elapsed between the 2016 fire and the commencement of this study, to minimise the establishment of competing species before treated *Sphagnum* is given time to recover. This will also minimise further damage to damaged *Sphagnum* from drought stress or high ultraviolet light levels.

Future studies should include a treatment of transplant without fertiliser, some assessment of hydrological conditions within and near treatment plots, and be conducted over a longer period, say 5 years or more.

Further investigations of the potential to use transplants in severely affected areas are warranted, given the lack of recovery without intervention. A key problem to overcome is that of water repellency, so hydrological treatments need to be tested to encourage survival and growth of transplanted *Sphagnum*. Micropropagation should also be considered, to minimise the harvest of *Sphagnum* from healthy populations.

We recommend greenhouse experiments be conducted, as they are much simpler logistically. For example, they could be used to investigate (i) the water repellency problem, (ii) whether low doses of fertiliser, with a lower N:P ratio, could be beneficial for *S. cristatum*, and (iii) micropropagation techniques and their success in relation to soil water availability.

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4. Appendices

Appendix 1. Validation of mapping of burnt mires using experimental quadrats

We checked the location of the burnt study quadrats in relation to the vegetation classification based on the mapping. This was used to validate our mapping, given that at the burnt mires, all quadrats were placed in vegetation identified in the field as burnt *Sphagnum*.

This showed that 89.5% of quadrats were in vegetation that was correctly classified.

Mapping classification	Number of quadrats	Relative frequency (%)
Burnt *Sphagnum*	433	89.5
Burnt other	47	9.7
Free water	4	0.8
Unburnt *Sphagnum*	0	0
Unburnt other	0	0

Inspection of the maps showed that the 10.5% of points incorrectly classified were located very close to areas classed as burnt *Sphagnum*, and the discrepancy was due to the coarser scale of the vegetation mapping (5x 5 m grid, compared with 1 x 1 m quadrats) and possibly to slight inaccuracies in the hand-held GPS.

Appendix 2. Data sheet for quadrat assessments.

Site	**Quadrat ID**	
Coordinates (UTM)		
Date	**Photo #**	
		% Cover
Sphagnum	Unburnt	
	Damaged	
	Killed	
Mosses	Other	
Ferns	*Gleichenia*	
Ferns	Other	
Restionaceae	(*spp*.)	
Herbs	(*spp*.)	
Grasses	(*spp*.)	
Shrubs	*Richea*	
Shrubs	Other	
Dead Wood	Dead	
Dead ground cover veg	Dead	
Weeds	(species)	
Threatened species	(species)	
***Athrotaxis* foliage**		
Outer 1m2 Healthy *Sphagnum*		
		Count
Scats		
Live *Athro* > 1.5 m w/i 5 m		
Dead *Athro* > 1.5 m w/i 5 m		
Comments:		

Appendix 3. Scoring *Sphagnum* Health

Sphagnum health was assessed visually and based on a combination of apparent colour, structure and moisture content of foliage. A 0.5m x 0.5m quadrat grid made of 20 mm diameter PVC pipe was laid over the plot and *Sphagnum* area coverage and health was estimated to the nearest 5% (although an intermediate score was occasionally given). Healthy *Sphagnum* appeared green, yellow or orange, hydrated and maintaining typical structure of tightly clustered capitula or heads (Figs A3 (a), (b), (c)). Killed *Sphagnum* appeared grey, white or brown, was obviously desiccated, capitula crumbling and the mound structurally breaking down (Figs A3(g), (h), (i)). Damaged *Sphagnum* was more challenging, time consuming and ambiguous to assess than Killed or Healthy, with a combination of all these characteristics in varying stages found within any plot (Figs A3(d), (e), (f)). (Photos: Scott Nichols)

Fig A3(a). Healthy *Sphagnum* (UB1S2), assessed as 100% Healthy.

Fig A3(b). Healthy *Sphagnum* before treatment (UB2C7), assessed as 100% Healthy.

Fig A3(c). Healthy *Sphagnum* before treatment (UB1S5), assessed as 100% Healthy.

Fig A3(d) Damaged *Sphagnum* before treatment (FEDC7), assessed as 50% Damaged, 40% Killed (and 10% Void).

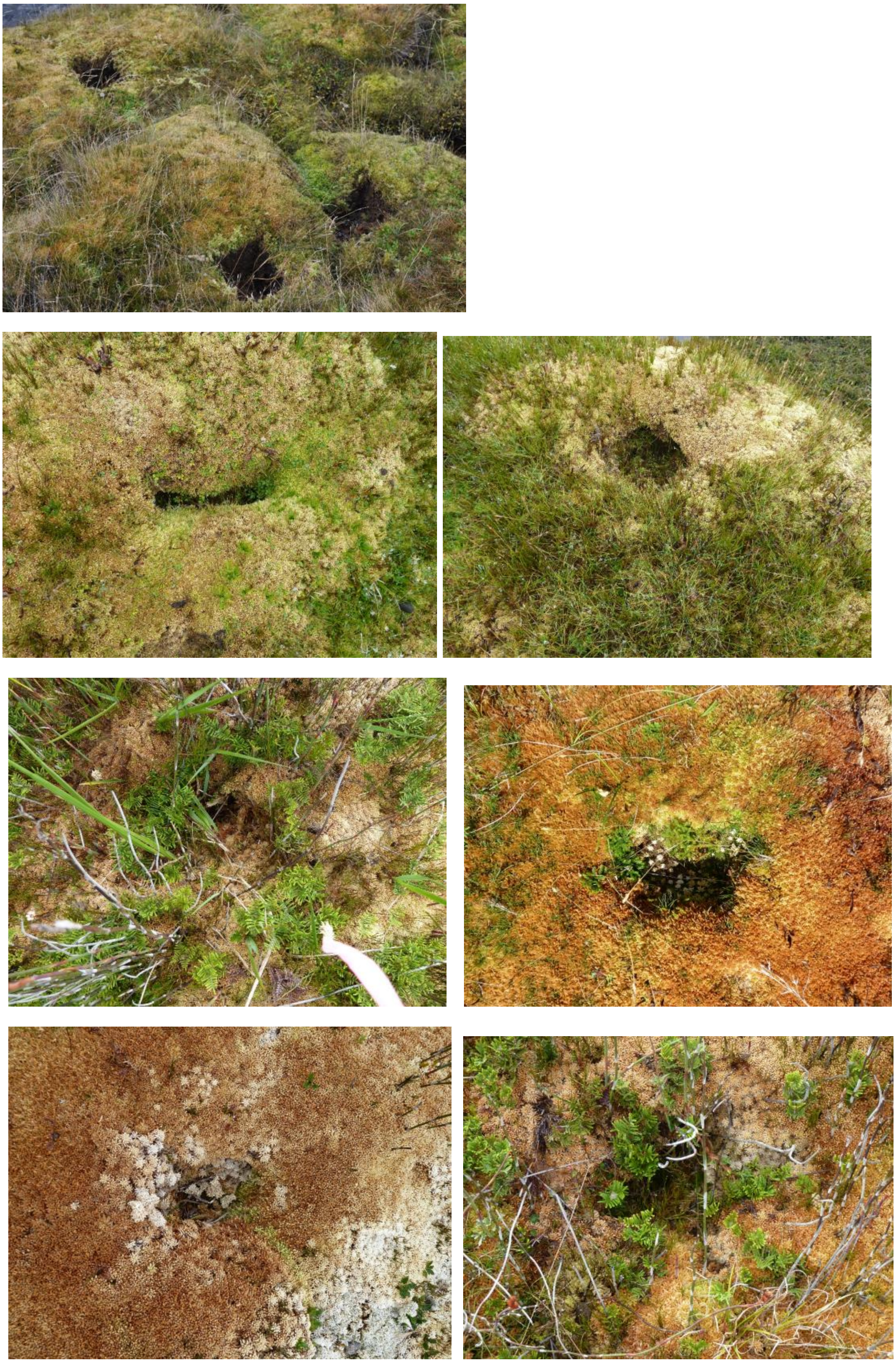
Fig3(e). Damaged *Sphagnum* before treatment (FEDSF4), assessed as 50% Damaged, 35% Killed (and 15% Void).

Fig A3(f). Damaged *Sphagnum* before treatment (GLDSF2), assessed as 10% Healthy, 65% Damaged, 25% Killed.

Fig A3(g). Killed *Sphagnum* before treatment (EVKC2), assessed as 90% Killed (10% Void).

Fig A3(h). Killed *Sphagnum* before treatment (FEKF6), assessed as 100% Killed.

Fig A3(i). Killed *Sphagnum* before treatment (JLKTF2), assessed as 95% Killed and 5% Void.



Appendix 4. Recovery of *Sphagnum* donor sites. Donor site immediately after harvest of *Sphagnum* (top), and below, similar sites after 2 summers. (Photos: Scott Nichols)

Appendix 5. Budget and resources*

Quadrat costs

Materials $6.65 per square / with drone markers $9.80 per square
Shade cloth (70% beige) $360 per 3.65 x 50m (1200 x 1200 per shade square), total 125 squares - **$2.80 per square**

Corner stakes -aluminium extrusion $9 per 6.5m length 10mm diameter (4 x 0.6 m = 2.4 m per square) **- $3.30 per square**

Cable ties $12.90 packet of 500 (min 4 per shade square) **- 10c per square**

Eyelets 12mm stainless steel **-** $5.60 per packet of 50 (4 per shade square) **- 45c per square**

Plot markers (drone) $2,200 - (1728 squares) **$1.28 per maker plate (2 per plot)**

Hex head screws 35mm 500 box $75.00 (2 per marker stake) **- 30c per square marker**

Labour 12 squares per hour (to prepare shadecloth in advance)

Field installation costs

20 squares per hour 1-2 person (no survey) + field traverse

4 squares per hour 1-2 person (with survey) + field traverse

Field removal costs

60 squares per hour 1-2 person (no survey) + field traverse

6 squares per hour 1-2 person (with survey) + field traverse

Additional resources required

Helicopter $2,637 per hour including standard insurance, additional organisation-specific insurance may be stipulated

Permits submission and approval process

Drone surveys

Data management

*Indicative costs based on the Lake Mackenzie trial conducted in 2019-20

Photo by Scott Nichols