bnhcrc.com.au

POST-FIRE IMPACT ASSESSMENT OF TASMANIAN SPHAGNUM BOGS

Unmanned aerial system mapping trials and method development

Morgan Harding, Darren Turner, Grant Wiliamson, Scott Nichols & David Bowman

University of Tasmania & Bushfire and Natural Hazards CRC

Version	Release history	Date
1.0	Initial release of document	22/03/2022

Publisher:
Bushfire and Natural Hazards CRC

March 2022

Citation: Harding M, Turner D, Williamson G, Nichols S & Bowman D (2022) Post-fire impact assessment of Tasmanian sphagnum bogs, Bushfire and Natural Hazards CRC, Melbourne.

Cover: : Burnt Sphangnum bog and Pencil Pine Lake Mackenzie. Source: Darren Turner,

TABLE OF CONTENTS

ACKNOWLEDGMENTS

This work was also supported by funding from Tasmanian Department of Primary Industries, Parks, Water and Environment as part of the Tasmanian Wilderness World Heritage Area Bushfire Recovery: Lake Mackenzie Rehabilitation Trials tender to the University of Tasmania. We acknowledge the field assistance of Cameron Geeves, Frank Bird, Aimee Bliss, Ruby Evans, Rosie Byers, Elliot McLaine, Sarah Cooley and Steve Harwin. We thank Scott Foyster for editorial help in preparing this report.

ABSTRACT

In the summer of 2015-2016 several large dry lightning storms ignited wildfires that burned across Western Tasmanian landscapes desiccated by the combination of severe spring drought and above average summer temperatures. Approximately 20 000 ha of the Tasmanian Wilderness World Heritage Area burnt including *Sphagnum* moss communities, or 'sphagnum bogs', and other significant areas of high conservation value Gondwanan refugia. The scale of the fires prompted the Tasmanian government to fund research in techniques to rehabilitate fire-impacted Gondwanan refugia, including sphagnum bogs, in the Lake Mackenzie area of the Northern Central Plateau. A key step in sphagnum bog restoration is the development of rapid, broad-scale, cost-effective and low impact survey techniques to identify sites in need of rehabilitation. We trialled unmanned aerial systems (UAS) with visible spectrum sensor technology to map fire extent and severity. Three sphagnum bogs were used to develop an ENVI classification workflow based on a training data set of burn severity categories and other ecological surface cover measurements to map burn severity. These maps were validated using ocular assessments of ground cover and burn severity in pre-existing permanently marked quadrats. We found poor to moderate agreement between the UAS and field fire severity with considerable variation amongst the sampled bogs. Total burnt area sphagnum bog maps were then produced by combining burnt severity categories for five bogs, including the three used for fire severity mapping, The congruence between *Sphagnum* burn extent maps with field data collected by differential Global Positioning System was found to range from substantial to poor according to Cohen's Kappa index. Multivariate analysis of the quadrat ground cover assessments showed that high grass cover was most strongly associated with poor field validation agreement (low Kappa scores), whereas acceptable field validation agreement (high Kappa scores), were associated with high cover of *Sphagnum*. A major constraint of this study was the two-year time gap between the fire and remote sensing mapping and field survey. Higher accuracy fire severity mapping and area burned mapping would be possible if imagery was acquired immediately after a fire event. In light of our findings, we provide recommendations for future UAS surveys of fire impacted sphagnum bogs, the most critical of which is acquiring remote sensing and field data in the same growing season as the fire.

BACKGROUND

2016 LAKE MACKENZIE FIRE

The Tasmanian Wilderness World Heritage Area (TWWHA) protects globally unique biodiversity values, 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. ; Harris et al. 2018). A recent example of this was the summer of 2015-2016 when several large dry lightning storms ignited numerous wildfires in remote Western Tasmania. This landscape was particularly receptive to lightning ignitions due to the low spring rainfall in 2015 and the above average summer temperature associated with the interaction of several interannual global climate modes (Bowman et al. 2019; Karoly et al. 2016). One of the most impacted areas was Lake Mackenzie where almost 14 000 ha of subalpine vegetation, including 141 ha of pencil pine (*Athrotaxis cupressoides*) forest (Bowman et al. 2019; Bowman et al. 2020) and an unknown area of *Sphagnum* moss communities (or 'sphagnum bogs'), were burnt (Figure 1). Sphagnum bogs typically exclude fire because the vegetation and organic substrate is saturated but become combustible during extreme drought conditions (Kettridge et al. 2015).

The 2016 Tasmania Wilderness Fires sparked global media interest (Marris 2016) and lead to a senate inquiry (ECRC 2016), a Tasmanian government inquiry (Press 2016) and Tasmanian Government identification of significant impacts to conservation values (DPIPWE 2017). All inquiries identified the importance of Gondwanan refugia, including sphagnum bogs, and the need to undertake research into post-fire impact assessment and restoration intervention techniques of these communities. This led to the establishment of the Lake Mackenzie Restoration Trials project undertaken by the University of Tasmania (UTAS) and funded by the Tasmania Department of Primary Industries, Parks, Water and Environment (DPIPWE).

SPHAGNUM RESTORATION

Studies in the Northern Hemisphere have advanced general peatland and *Sphagnum* post-fire restoration intervention techniques (Rochefort et al. 2003). Until recently, little research has been dedicated to trialling restoration techniques in mainland Australia (Clarkson et al. 2016). Following the widespread 2003 fires in the Australian Alps, in which significant sphagnum bogs were burnt in Namadgi and Kosciuszko National Parks (Hope, Whinam & Good 2005; Whinam et al. 2010), Whinam et al. (2010) conducted post-fire restoration experimental trials across a range of burn severities. Treatments included application of shade, rewetting, and transplantation of *Sphagnum* spp. cores into fire affected hummocks (Hope, Whinam & Good 2005; Whinam et al. 2010). Recovery of *Sphagnum* spp. observed in these trials was described as both slow and complex, however, results indicate that restoration intervention treatments, particularly shading and combined transplant and fertilizer treatments, increased recovery rates by at least twice that of untreated areas four years post-fire (Whinam et al. 2010).

Efficient and accurate targeting and monitoring of post-fire interventions is essential for effective restoration and conservation of important refugia, particularly in intractable terrain like the TWWHA (Keppel 2015). 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 is unsuitable for surveying fire severity in sphagnum bogs because of their small extent, (typically <1-2 ha), frequent obstruction by cloud cover, and complex and fine-scale vegetation mosaics (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). Additionally, digital surface models (DSM), generated from ultra-high resolution UAS imagery data, have been used for microtopographic modelling to provide detailed information about drainage and potential hydrogeological interventions for peatland restoration (De Roos et al. 2018; Hillman et al. 2021; Lucieer et al. 2014). This UAS technology may prove a valuable tool for restoration targeting and monitoring of fire impacted sphagnum bogs.

GEOGRAPHIC CONTEXT

This study is based around six burnt sphagnum bogs and two unburnt sphagnum bogs used for the sphagnum bog restoration trials that were selected from a preliminary fixed-wing manned aerial survey (Figure 1). Table 1 summarises geospatial attributes of each of the six burnt sites, and details respective quadrat and UAS survey dates.

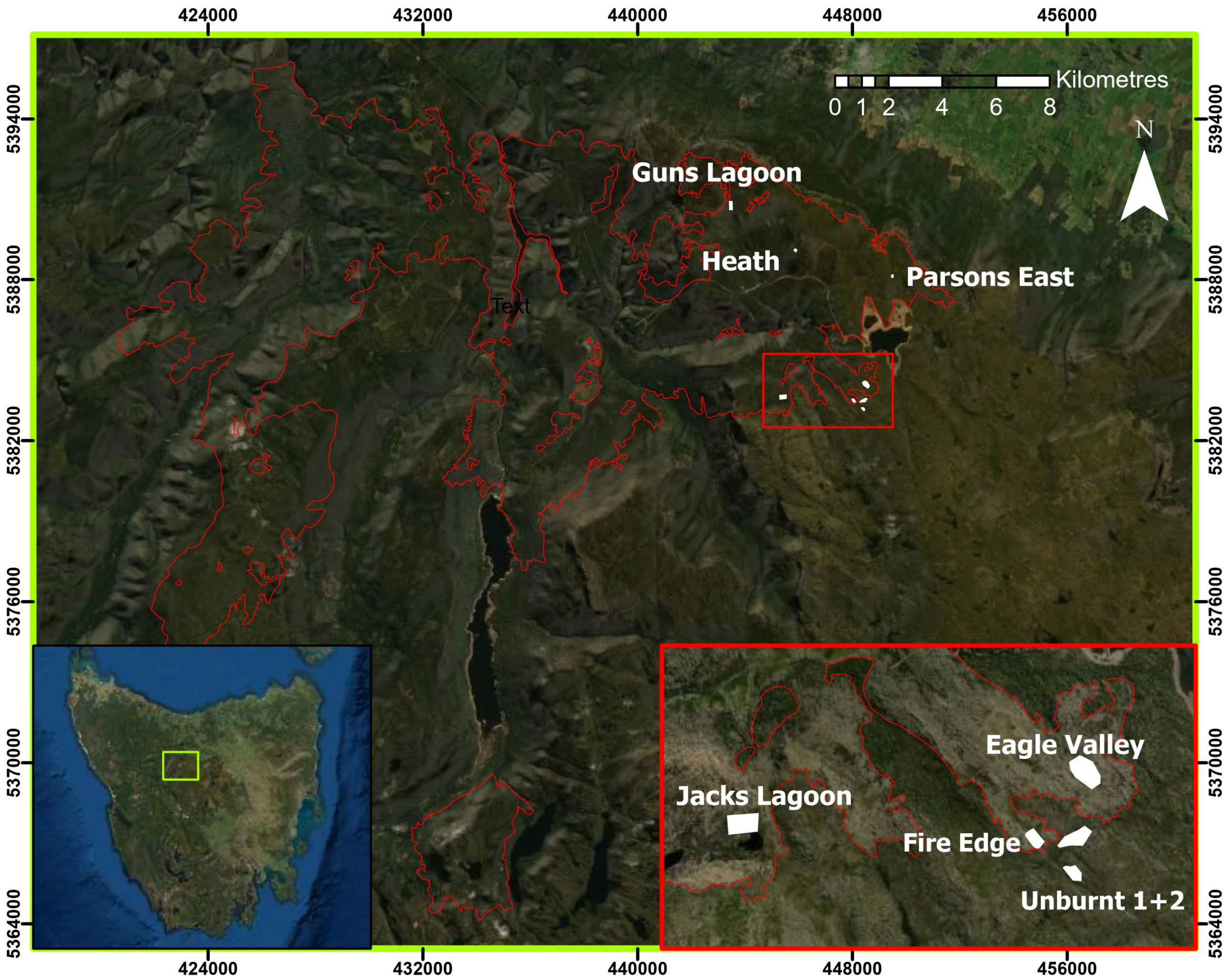


FIGURE 1: LOCATION AND NAMES OF THE 6 BURNED AND 2 UNBURNED SPHAGNUM BOGS USED IN THE LAKE MACKENZIE SPHAGNUM RESTORATION TRIALS. THE 2016 LAKE MACKENZIE FIRE BOUNDARY IS INDICATED BY THE RED POLYGON AND IS OVERLAIN ON GOOGLE EARTH IMAGERY.

TABLE 1: GEOSPATIAL ATTRIBUTES AND SURVEY DATES FOR THE SIX FIRE-IMPACTED BOGS SPHAGNUM BOG SITES STUDIED FOR THE LAKE MACKENZIE SPHAGNUM RESTORATION TRIALS.

Site	Eagle Valley	Fire Edge	Guns Lagoon	Heath Central	Jacks Lagoon	Parsons East	Unburnt 1	Unburnt 2
Site code	EV	FE	GL	HC	JL	PE	UB1	UB2
Area (ha)	1.69	0.50	3.09	0.43	1.15	0.38	2.36	2.01
Max linear path (m)	272.4	142.4	421.5	93.6	166.4	109.3	329.1	263.9
Perimeter to area ratio	0.04	0.07	0.03	0.06	0.07	0.07	0.03	0.03
Shape descriptor	Elongate	Elongate	Elongate	Globular	Globular	Elongate	Elongate	Elongate
Mean elevation (m)	2102	1246	1246	1125	1262	1192	1230	1246
Elevation range (m)	10	2	12	6	11	7	24	18

Ecological quadrat survey (mm/yy)	03/2019	10/19	02-03/20	03-04/19	11/19	03/19	03/20	03/20
UAS survey (mm/yy)	04/19	10/18	02/21	04/19	12/17	04/19	02/21	02/21
Supplementary field validation data collection (mm/yy)	03/21	03/21	03/21	03/21	03/21	03/21	NA	NA

OBJECTIVES

The primary objective of this study was to investigate the efficacy of using ultra-high resolution UAS visible spectrum imagery to map the severity and area burned of sphagnum bogs by the 2016 fires. The maps are validated against ground cover and fire severity assessments of permanent plots to identify factors affecting mapping accuracy. Based on the research we provide recommendations for future UAS surveys of fire impacted sphagnum bogs.

METHODS

FIELD SURVEY

Ocular assessments of the percentage cover of healthy, damaged and killed sphagnum (using definitions in Table 2, and summing to 100%) and the percentage cover of other lifeforms and species growing above the *Sphagnum* layer (Table 2) were conducted at the six burned bogs. Quadrats (0.5m x 0.5m) were positioned to overlay *Sphagnum* hummocks, using a stratified sampling method based on a qualitative assessment of either low (< 75% killed) or high (> 75% killed) *Sphagnum* burn severity as defined in Table 2. Each burned bog was sampled with 84 0.25 m^2 quadrats, except at Eagle Valley where an additional 18 quadrats in severely burned *Sphagnum* areas were also undertaken. In the two unburned sites with healthy *Sphagnum* cover the same cover classes were used to assess ground cover using 20 0.25m^2 quadrats that were allocated haphazardly, but with at least five metres distance from a neighbouring quadrat.

TABLE 1: GEOSPATIAL ATTRIBUTES AND SURVEY DATES FOR THE SIX FIRE-IMPACTED BOGS SPHAGNUM BOG SITES STUDIED FOR THE LAKE MACKENZIE SPHAGNUM RESTORATION TRIALS.

Cover class	Definition
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
Bryophyte	Bryophyte species other than *Sphagnum*
Gleichenia	*Gleichenia alpina*
Other fern species	Fern species other than *G. alpina*
Herbs	Miscellaneous herbaceous species
Restionaceae	Restiads, primarily *Empodisma minus*, *Sporadanthus tasmanicus,* and *Baloskion australe*
Grass	Predominately *Poa* species, some introduced fescue
Weeds	Exotic non-native species (other than fescue)
Richea	*Richea* species
Other shrub species	Miscellaneous shrub lifeforms other than *Richea* spp
Pencil pine foliage	Detached *Athrotaxis cupressoides* foliage
Dead ground vegetation	Dead foliage
Dead wood	woody debris

ANALYSIS

Data exploration and all statistical analyses were undertaken using statistical software R (R Core Team 2020). We transformed the three permanent quadrat sphagnum severity assessments (Table 2) into a categorical variable. Because assessments of percent damaged and percent killed *Sphagnum* were nearly perfectly correlated, and there was little healthy *Sphagnum* cover, the severity of *Sphagnum* impacts was classified by quartiles of percent killed (burn severity 1 – 4), with unburned quadrats assigned a burn severity class of 0. For these five severity classes, we calculated average values of the percentage of the ground cover assessments (Table 2). Box and whisker plots were produced to further explore associations of canopy cover variables between and among burn severity classes and sites (Appendix). Average cover values for all site X fire severity combinations were then ordinated using metaMDS non-metric multidimensional scaling.

UAS BASED SPHAGNUM FIRE SEVERITY AND AREA BURNED MAPPING

Fire severity mapping

Sphagnum burn severity maps were prepared for three sphagnum bogs at Lake Mackenzie: Eagle Valley, Heath Central and Parsons East (Figure 1). The methodology employed for the capture by UAS (unmanned aerial system) and orthorectification of aerial imagery in the study was based on those described in De Roos et al. (2018). Geospatial image analysis software, ENVI (https://www.l3harrisgeospatial.com/), was used to classify orthophotos into mapping units and to exclude bodies of water and areas beyond the immediate bog sites. Training data were defined by ocular examination of each orthophoto and manual selection of the target area to delineate the following fire severity and ground cover categories: healthy *Sphagnum*, damaged *Sphagnum*, killed *Sphagnum*, other vegetation, dead wood, rock, bare soil, and water. Most (c. 90%) of the training data was used in the ENVI classification workflow to produce a thematic mosaic for each site. The remainder was retained for statistical analysis of the classification performance using Cohen's Kappa scores via the confusionMatrix function in the R caret package. The fire severity maps were then compared with quadrat survey data by matching the fire severity classification for each 0.25 m2 quadrat using Pearson (r) coefficients to quantify the relationship between field quadrat cover and virtual quadrat polygon cover for *Sphagnum* condition classes, healthy (unburnt), damaged and killed.

Area burned mapping

Sphagnum area burned maps were produced by amalgamating damaged *Sphagnum* and killed *Sphagnum* classes in the burn severity maps field sites following the methods described above. These maps were validated using 490 field assessments of three broad categories of ground cover: healthy *Sphagnum*, killed *Sphagnum* and non-*Sphagnum*. These assessments were taken from within a 49cm^2 circular area that was accurately geolocated using a differential real-time kinematic GPS (differential RTK-GPS) referenced to a local base. For each burned area map the corresponding modal mapping class for each of the geolocated circular areas were compared to the field assessments using ENVI software.

FINDINGS

PERMANENT PLOTS

The ordination analysis of mean ground cover scores revealed very strong differences amongst the two unburned as well as the six burned sphagnum bog sites associated with variation in lifeform and dominant species cover (Appendix). By contrast, there was a comparatively small effect amongst *Sphagnum* spp. burn severity categories. Collectively these analyses show a very strong site effect, and a more modest effect of fire severity, on the ground cover composition, a function of pre-existing site attributes (Table 1).

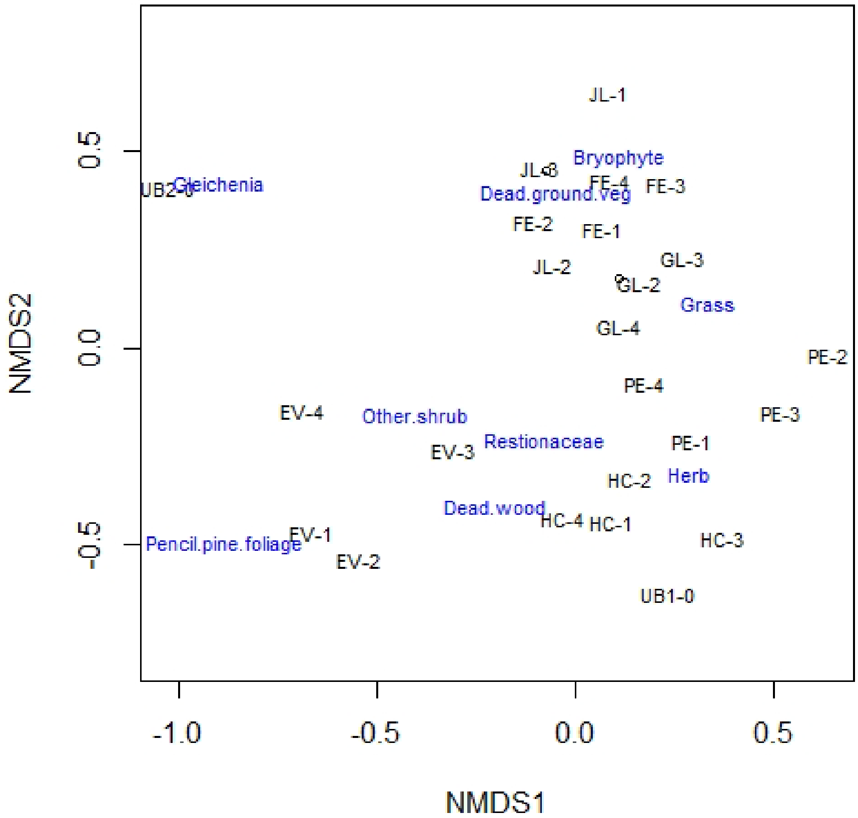


FIGURE 2: ORDINATION DISPLAYING SIMILARITY AMONGST SITES AND *SPHAGNUM* BURN SEVERITY CLASSES. THE NON-METRIC ORDINATION WAS BASED ON AVERAGED VALUES OF ALL GROUND COVER PERCENT ASSESSMENTS (TABLE 2) IN EACH BURN SEVERITY CLASS WITHIN EACH SITE. OTHER VEGETATION CLASSES MOST STRONGLY RELATED TO GRADIENTS IN THE ORDINATION SPACE ARE INDICATED IN BLUE. SITE CODES ARE PROVIDED IN TABLE 1. SPHAGNUM BURN SEVERITY CODES ARE: 0 = 0%, 1 = < 25%, 2 = 25-50%, 3 = 50-75% AND 4 > 75% KILLED.

UAS SPHAGNUM FIRE SEVERITY MAPPING

For the three study sites, the image classification using ENVI software classification performance found ‘substantial’ or ‘almost perfect’ agreement between burn severity classifications and retained testing data for all site classifications (Table 3). However, amongst the three sites, there is a variable correlation amongst mapped and field assessments of the % killed and damaged sphagnum. The Eagle Valley site showed the strongest and most consistent correlations (although not perfect) between the field and remote sensing estimates of *Sphagnum* spp. fire severity categories (Figure 3), whereas there were weak and inconsistent correlations at the other two sites (Table 4).

TABLE 3: TABLE OF COHEN'S KAPPA SCORES QUANTIFYING AGREEMENT BETWEEN *SPHAGNUM* BURN SEVERITY CLASSIFICATION DATA AND TESTING POLYGON DATA ACCORDING TO CONFUSION MATRICES FOR THREE SITES AT LAKE MACKENZIE. KAPPA SCORE INTERPRETATIONS ACCORDING TO LANDIS AND KOCH (1977) ARE PRESENTED.

Site	Cohen's Kappa score	Cohen's Kappa qualitative
Eagle Valley	0.9777	Almost perfect
Heath Central	0.9641	Almost perfect
Parsons East	0.9604	Almost perfect

TABLE 4: PEARSON (R) CORRELATION COEFFICIENTS QUANTIFYING CONGRUENCE BETWEEN FIELD QUADRAT SURVEY DATA AND VIRTUAL QUADRAT POLYGON COVER FOR *SPHAGNUM* CONDITION CLASSES: HEALTHY (UNBURNT), DAMAGED AND KILLED. ** = P-VALUE (CORRELATION NOT EQUAL TO ZERO) < 0.01.

Site	Healthy	Damaged	Killed
Eagle Valley	0.60**	0.54**	0.58**
Health Central	0.41**	0.18	0.44**
Parsons East	0.70**	0.14	0.32**

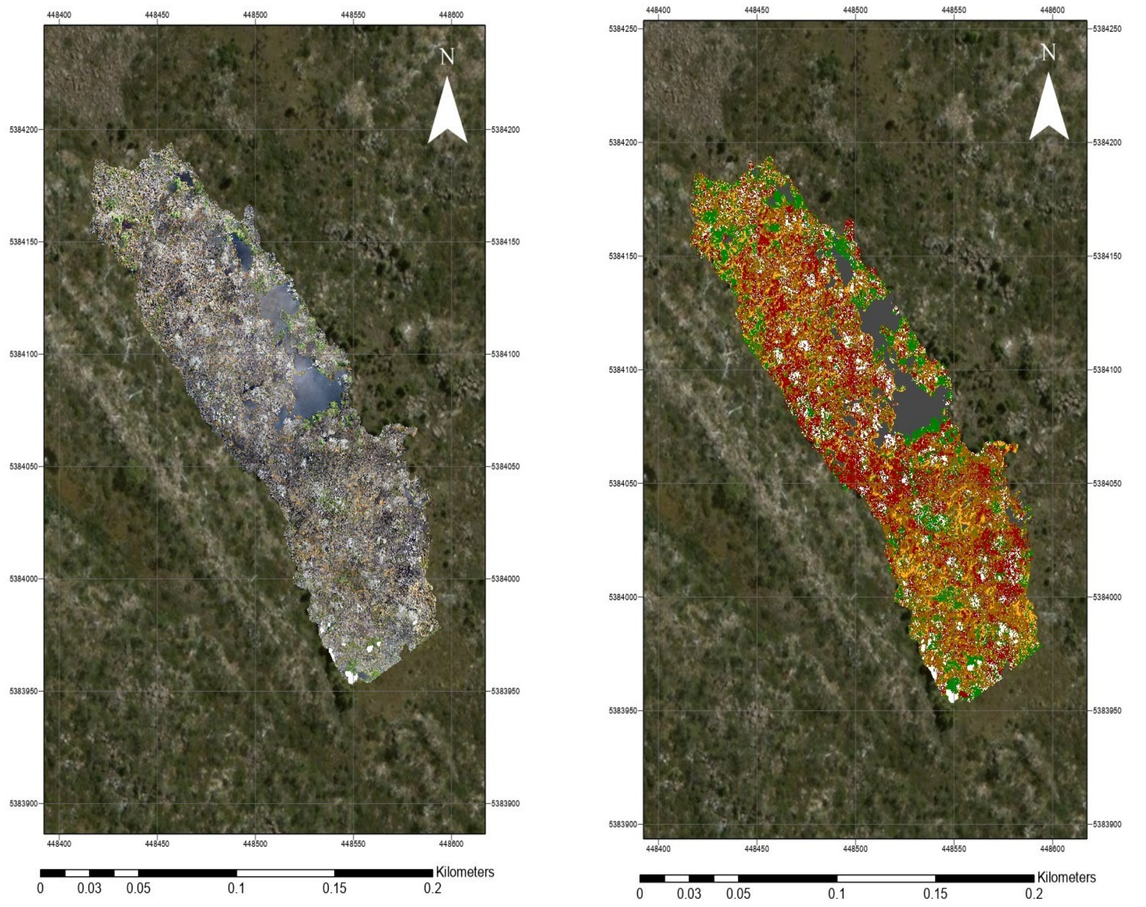


FIGURE 3: FIRE SEVERITY MAP OF EAGLE VALLEY SITE THAT HAD REASONABLE CONGRUENCE WITH FIELD DATA. PAIRED MAPS OF ORTHORECTIFIED AERIAL IMAGERY (LEFT) AND SPHAGNUM BURN SEVERITY CLASSIFICATION MAP (RIGHT) OF EAGLE VALLEY SITE OVERLAYING A GOOGLE EARTH BASE IMAGE. RIGHT MAP DISPLAYS CLASSIFICATION CLASSES: HEALTHY SPHAGNUM (ORANGE); DAMAGED SPHAGNUM (BROWN); KILLED SPHAGNUM (RED); OTHER VEGETATION (GREEN); ROCK, DEAD WOOD AND BARE SOIL (WHITE); AND WATER (GREY) GEOGRAPHIC COORDINATES AND GRID REFERENCES ARE SHOWN AT 500 METRE INTERVALS.

UAS SPHAGNUM AREA BURNED MAPPING

There was variable agreement between area burned mapping and field data collected with a differential GPS, with the strongest agreement for Eagle Valley and poorest agreement at the Parsons East sites (Figure 4). There was a strong correlation (r = 0.787) between mean percent grass cover observed on *Sphagnum* hummocks and field validation agreement for burnt sites, as measured by Kappa scores (Figure 5), suggesting at least one cause of the poor accuracy of area burned mapping relates to the post-fire regrowth of grasses.

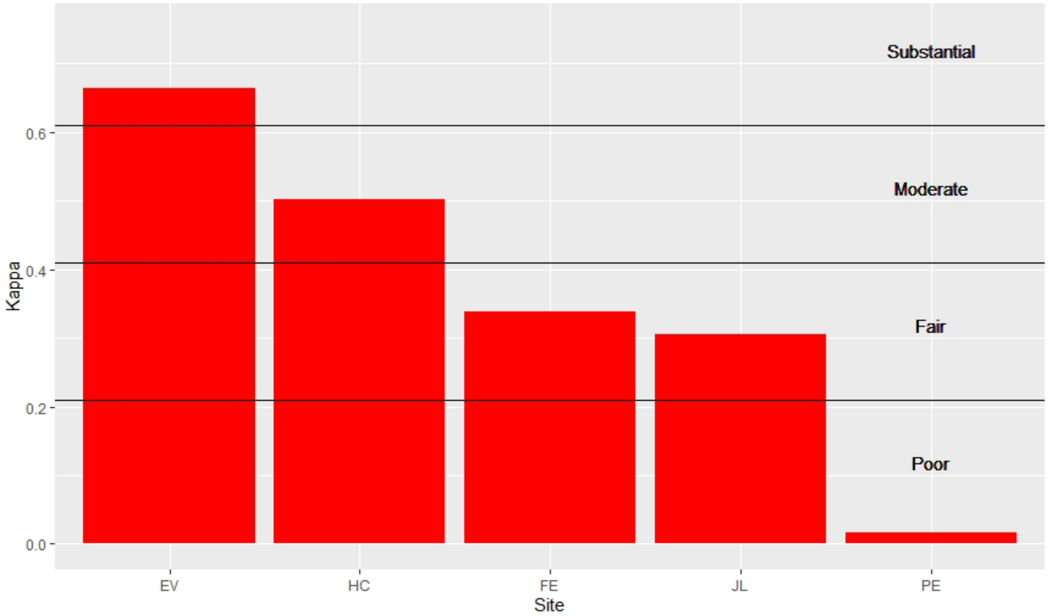


FIGURE 4: HISTOGRAM OF COHEN'S KAPPA SCORES QUANTIFYING AGREEMENT BETWEEN SPATIALLY CORRESPONDING FIELD VALIDATION DATA AND *SPHAGNUM* BURN EXTENT MAP DATA. KAPPA SCORE BENCHMARKS (LANDIS & KOCH 1977) ARE INDICATED BY *Y* CONTINUOUS INSET LINES. SITE CODES ARE PROVIDED IN TABLE 1.

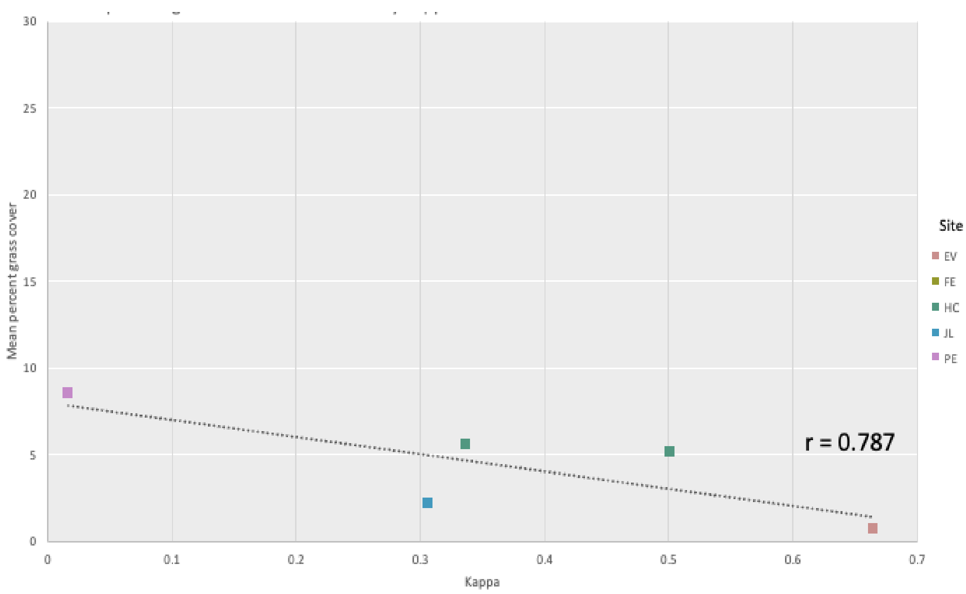


FIGURE 5: SCATTER PLOT AND CORRELATION COEFFICIENT OF MEAN PERCENT GRASS COVER AND COHEN'S KAPPA SCORES QUANTIFYING AGREEMENT BETWEEN SPHAGNUM BURN EXTENT MAPS AND FIELD VALIDATION DATA SPATIALLY REFERENCE BY DIFFERENTIAL GLOBAL POSITIONING SYSTEM. SITE CODES ARE PROVIDED IN TABLE 1.

CONCLUSION

The objective of this study was to investigate the efficacy of using ultra-high resolution UAS visible spectrum imagery as a tool for fire severity and area burned mapping in *Sphagnum* bogs. Field validation revealed that, with one exception (the Eagle Valley site), fire severity mapping had poor congruence with small (0.25 m^2) quadrats assessment of killed and damaged sphagnum cover. This poor agreement was despite the strong internal agreement of the fire severity mapping with reserved visual assessments of fire severity and ground cover categories. Likewise, field validation of combined fire severity categories into area burned did not consistently improve mapping reliability at all sites.

There are several likely reasons for the discrepancy between the UAS remote sensing classification and field assessments. First, as Figure 6 below shows there were considerable delays in the acquisition of the UAS imagery (up to two growing seasons) and the field assessment (up to three growing seasons). In the Australian Alps, Hope et al. (2005) observed rapid regrowth of and colonisation of *Sphagnum* hummocks by grasses, restiads and other bryophytes in the 18-20 months following the 2003 fires, hence it is likely the time lag between the 2016 fires and UAS imagery capture, and field assessments impacted the accuracy of fire severity and area burned mapping. This is particularly important given Tasmanian sphagnum communities are more floristically diverse than mainland communities (Whinam et al. 2010).

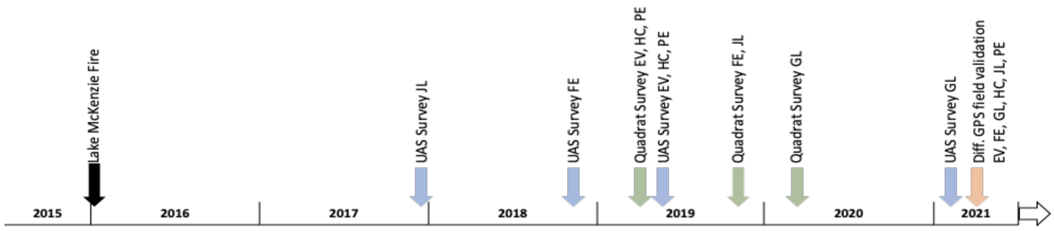


FIGURE 6 FLOW CHART AND TIMELINE OF METHODOLOGY AND DATA COLLECTION FOR THIS STUDY.

Second, and relatedly, there are substantial differences in vegetation composition amongst the bogs. Hence, the bog with the greatest sphagnum cover (Eagle Valley) was found to have the most accurate fire severity and area burned maps. By contrast, the bog with the highest grass cover (Parson East) the least.

FUTURE USE OF OUTCOMES

Considering these constraints, we recommend the following workflow for capture, classification and validation of UAS imagery for *Sphagnum* fire impact assessment (Figure 7 below). A key recommendation is acquiring UAS and field data within the same growing season as the fire event to avoid the confounding effects of post fire recovery of other plant species, particularly grass. Field validation should occur concurrently with the UAS image acquisition using differential GPS. The field assessments should be used to guide training data selection during imagery classification workflows, where 25% of these samples are retained for image classification verification.

Determining the minimum number of field assessments points required to validate maps, while minimising trampling, warrants investigation. It is possible that multi-spectral sensors, instead of the visible spectrum sensor employed for this study, could improve fire severity, and burned area mapping. However, disadvantages of this approach are the requirement for more specialised equipment (multispectral sensor) and the need to acquire field validation for individual species (Holmgren, Persson & Söderman 2008). Likewise, digital surface models (DSMs) and object-based analyses may help distinguish burnt hummocks from burnt other species occupying inter-hummock hollows and flats (De Roos et al. 2018; White et al. 2020).

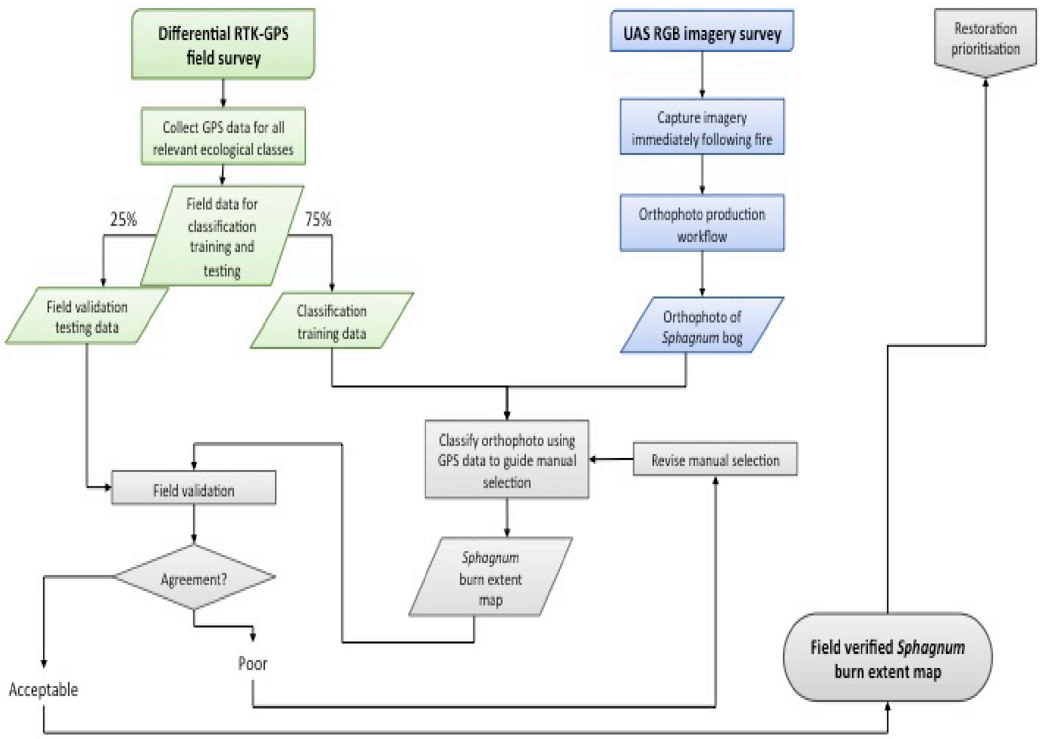


FIGURE 7: FLOW DIAGRAM OF AN IMPROVED WORKFLOW RECOMMENDED FOR FUTURE CAPTURE, CLASSIFICATION AND VALIDATION OF *SPHAGNUM* BURN IMPACT MAPS.

REFERENCES

AUSTRALIA. PARLIAMENT. SENATE. ENVIRONMENT AND COMMUNICATIONS REFERENCES COMMITTEE (ECRC). 2016. *Responses to, and lessons learnt from, the January and February 2016 bushfires in remote Tasmanian wilderness* [Online]. Environment and Communications References Committee, Commonwealth of Australia. Available: https://www.aph.gov.au [Accessed 21 March 2021].

BERGSTROM, D. M., WIENECKE, B. C., VAN DEN HOFF, J., HUGHES, L., LINDENMAYER, D. B., AINSWORTH, T. D., BAKER, C. M., BLAND, L., BOWMAN, D., BROOKS, S. T., CANADELL, J. G., CONSTABLE, A. J., DAFFORN, K. A., DEPLEDGE, M. H., DICKSON, C. R., DUKE, N. C., HELMSTEDT, K. J., HOLZ, A., JOHNSON, C. R., MCGEOCH, M. A., MELBOURNE-THOMAS, J., MORGAIN, R., NICHOLSON, E., PROBER, S. M., RAYMOND, B., RITCHIE, E. G., ROBINSON, S. A., RUTHROF, K. X., SETTERFIELD, S. A., SGRO, C. M., STARK, J. S., TRAVERS, T., TREBILCO, R., WARD, D. F. L., WARDLE, G. M., WILLIAMS, K. J., ZYLSTRA, P. J. & SHAW, J. D. 2021. Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology,* 27, 1692-1703.

BOWMAN, D. 2020. Using a natural experiment to foresee the fate of boreal carbon stores. *Global Change Biology* [Online]. [Accessed 13 August].

BOWMAN, D., BLISS, A., BOWMAN, C. J. W. & PRIOR, L. D. 2019. Fire caused demographic attrition of the Tasmanian palaeoendemic conifer Athrotaxis cupressoides. *Austral Ecology,* 44**,** 1322-1339.

CLARKSON, B., WHINAM, J., GOOD, R. & WATTS, C. 2016. Restoration of Sphagnum and restiad peatlands in Australia and New Zealand reveals similar approaches: Peatland restoration in Australasia. *Restoration Ecology,* 25**,** 301-311.

D'ACUNHA, B., LEE, S.-C. & JOHNSON, M. 2017. Ecohydrological responses to rewetting of a highly impacted raised bog ecosystem. *Ecohydrology,* 11**,** 1-12.

DE ROOS, S., TURNER, D., LUCIEER, A. & BOWMAN, D. M. J. S. 2018. Using Digital Surface Models from UAS Imagery of Fire Damaged Sphagnum Peatlands for Monitoring and Hydrological Restoration. *Drones,* 2**,** 9-16.

HARRIS, R. M. B., BEAUMONT, L. J., VANCE, T. R., TOZER, C. R., REMENYI, T. A., PERKINS-KIRKPATRICK, S. E., MITCHELL, P. J., NICOTRA, A. B., MCGREGOR, S., ANDREW, N. R., LETNIC, M., KEARNEY, M. R., WERNBERG, T., HUTLEY, L. B., CHAMBERS, L. E., FLETCHER, M. S., KEATLEY, M. R., WOODWARD, C. A., WILLIAMSON, G., DUKE, N. C. & BOWMAN, D. 2018. Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change,* 8**,** 579-587.

HOLMGREN, J., PERSSON, Å. & SÖDERMAN, U. 2008. Species identification of individual trees by combining high resolution LiDAR data with multi-spectral images. *International Journal of Remote Sensing,* 29**,** 1537-1552.

HOPE, G., WHINAM, J. & GOOD, R. 2005. Methods and preliminary results of post-fire experimental trials of restoration techniques in the peatlands of Namadgi (ACT) and Kosciuszko National Parks (NSW). *Ecological Management & Restoration,* 6**,** 214-217.

KAROLY, D. J., BLACK, M. T., GROSE, M. R. & KING, A. D. 2016. The roles of climate change and El Nino in the record low rainfall in October 2015 in Tasmania, Australia. *Bulletin of the American Meteorological Society,* 97**,** S127-S130.

KEPPEL G 2015'.The capacity of refugia for conservation planning under climate change', *Frontiers in ecology and the environment*, vol. 13, no. 2, pp. 106-112.

KETTRIDGE, N., TURETSKY, M., SHERWOOD, J., THOMPSON, D., MILLER, C., BENSCOTER, B., FLANNIGAN, M., WOTTON, M. & WADDINGTON, J. 2015. Moderate drop in water table increases peatland vulnerability to post-fire regime shift. *Scientific reports,* 5, article 8063**,** 1-4.

LUCIEER, A., TURNER, D., KING, D. H. & ROBINSON, S. A. 2014. Using an Unmanned Aerial Vehicle (UAV) to capture micro-topography of Antarctic moss beds. *International Journal of Applied Earth Observation and Geoinformation,* 27**,** 53-62.

MARRIS, E., 2016. Blazes threaten iconic trees. *Nature* 530:137-138

MCKENNA, P., ERSKINE, P. D., LECHNER, A. M. & PHINN, S. 2017. Measuring fire severity using UAV imagery in semi-arid central Queensland, Australia. *International Journal of Remote Sensing,* 38**,** 4244-4264.

PRESS, A.J., 2016. Tasmanian Wilderness World Heritage Area Bushfire and Climate Change Research Project. Tasmanian Government, Hobart

R CORE TEAM 2020. A Language and Environment for Statistical Computing. *In:* COMPUTING, R. F. F. S. (ed.). Vienna, Austria.

ROCHEFORT, L., QUINTY, F., CAMPEAU, S., JOHNSON, K. & MALTERER, T. 2003. North American approach to the restoration of Sphagnum dominated peatlands. *Wetlands Ecology and Management,* 11**,** 3-20.

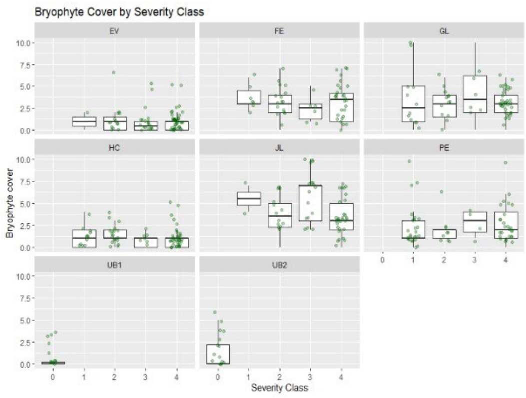
TASMANIA. DPIPWE 2017. Assessment of the ecological impacts of the 2016 Mersey Forest Complex, Nature Conservation Report, 17/05. Hobart: Natural Values Conservation Branch, Department of Primary Industries, Parks, Water and the Environment.

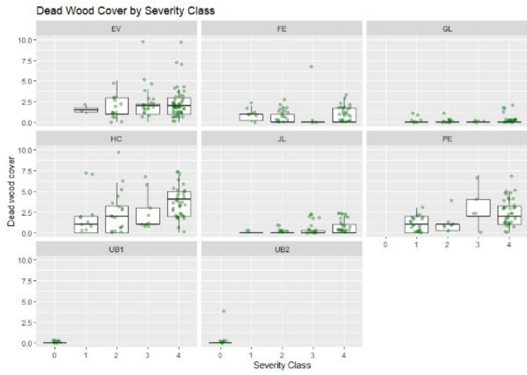
WHINAM, J., HOPE, G., GOOD, R. & WRIGHT, G. 2010. Post-fire experimental trials of vegetation restoration techniques in the peatlands of Namadgi (ACT) and Kosciuszko National Parks (NSW), Australia. *In:* HABERLE, S. G., STEVENSON, J. & PREBBLE, M. (eds.) *Altered Ecologies.* ANU Press.

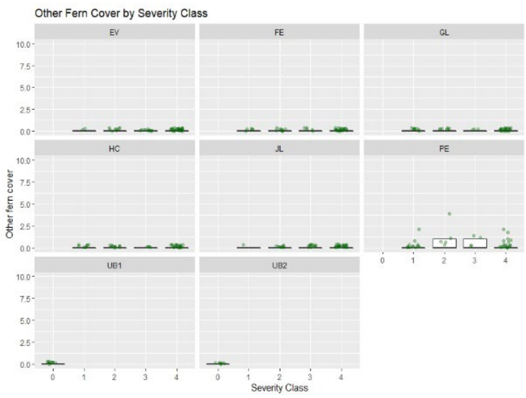
WHITE, L., MCGOVERN, M., HAYNE, S., TOUZI, R., PASHER, J. & DUFFE, J. 2020. Investigating the Potential Use of RADARSAT-2 and UAS imagery for Monitoring the Restoration of Peatlands. *Remote Sensing,* 12**,** 2383-2416.

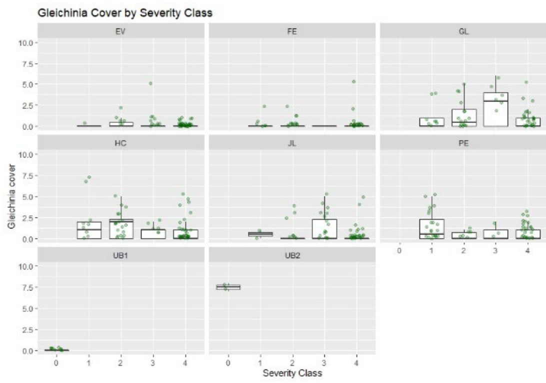
APPENDOIX

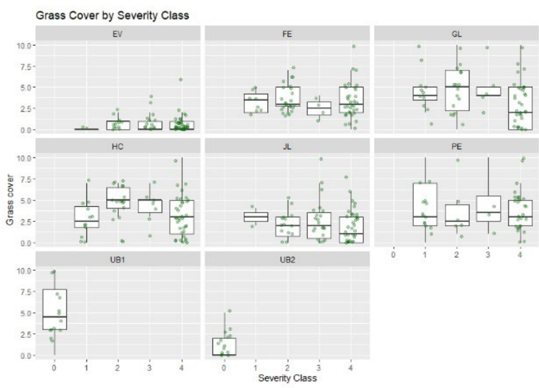
APPENDIX: BOX AND WHISKER PLOTS DISPLAYING PERCENT COVER OF GROUND COVER FOR EACH SITE BROKEN DOWN BY FIRE SEVERITY CLASSES. SITE CODES ARE EV EAGLE VALLEY; FE FIRE EDGE; GL GUNS LAGOON; HC HEATH CENTRAL; JL JACKS LAGOON; PE PARSONS EAST; UB1 UNBURNED SITE 1; UB2 UNBURNED SITE 2. SEVERITY CLASSES ARE: 0 0%; 1 <25%; 2 25-50%; 3 50-75% AND 4 >75% KILLED SPHAGNUM WITH 0.25M2 QUADRATS. BOX AND WHISKER PLOTS SHOW THE MEDIAN, THE FIRST AND THE THIRD QUARTILE (UPPER AND LOWER HINGE), THE RANGE WITH 1.5* THE IQR (WHISKERS) AND INDIVIDUAL DATA POINTS (GREEN CIRCLES). THE MEAN VALUE OF THIS DATA WAS USED IN THE ORDINATION ANALYSIS.

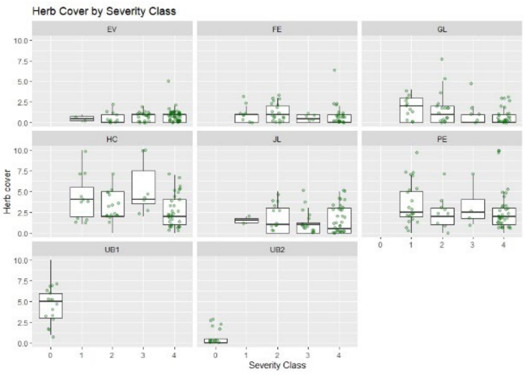


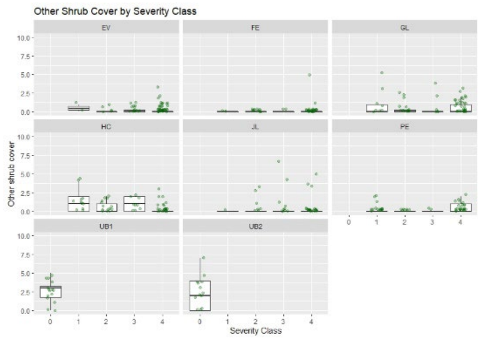


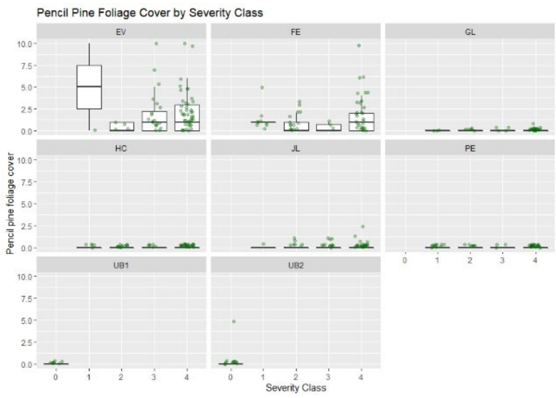


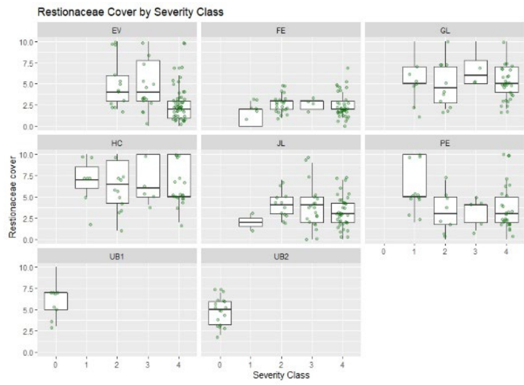


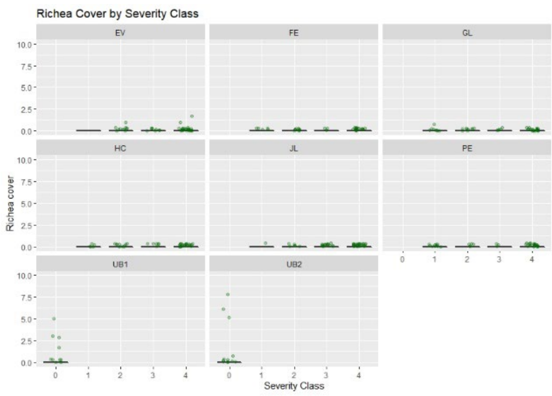


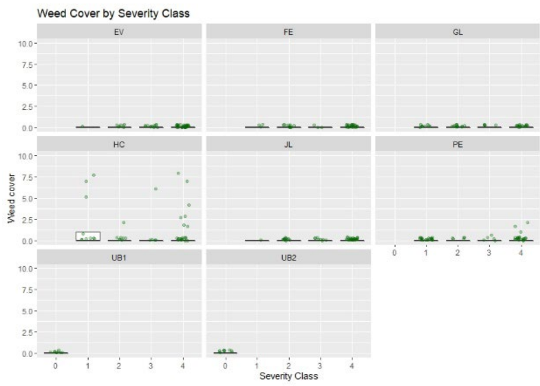

Herb Cover by Severity Class
EV
FE
GL
HC
JL
PE
UB1
UB2
Herb cover
Severity Class


Other Shrub Cover by Severity Class
EV
FE
GL
HC
JL
PE
UB1
UB2
Other shrub cover
Severity Class


Pencil Pine Foliage Cover by Severity Class
EV
FE
GL
HC
JL
PE
UB1
UB2
Pencil pine foliage cover
Severity Class


Restionaceae Cover by Severity Class
EV
FE
GL
HC
JL
PE
UB1
UB2
Restionaceae cover
Severity Class


Richea Cover by Severity Class
EV
FE
GL
HC
JL
PE
UB1
UB2
Richea cover
Severity Class


Weed Cover by Severity Class
EV
FE
GL
HC
JL
PE
UB1
UB2
Weed cover
Severity Class