NSW Biodiversity Node – Project Summary Report:

Developing a spectral library for weed species in alpine vegetation communities to monitor their distribution using remote sensing

Kerrie Tomkins, Michael Chang

Department of Environmental Sciences, Macquarie University

Author for correspondence: kerrie.tomkins@mq.edu.au and michael.chang@mq.edu.au

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Executive Summary

This project examines the potential to use remote sensing for monitoring of the distribution of several weed species in the alpine region of NSW, specifically targeting Orange Hawkweed, Mouse-ear Hawkweed and Ox-eye Daisy, as requested by NPWS. The project is based on the premise that plants absorb and reflect different amounts of different wavelengths of light in the visible and near infrared spectra, which can be plotted as spectral reflectance profiles. We aimed to determine whether the spectral profiles of the weeds were separable from the spectral profiles of other common co-occurring native plants, and if so, determine whether it was possible to detect the weeds using spectral sensors attached to a drone, and/or using high-resolution satellite imagery.

Field work was undertaken at several sites in Kosciuszko National Park (KNP) to: i) measure the hyperspectral profiles of leaves and flowers of the selected weeds and native plants using a hand-held spectroradiometer, and ii) collect surface reflectance data using a drone-mounted multispectral sensor (Parrot Sequoia). Additional satellite imagery which covered the study sites were also obtained.

The hyperspectral profiles were analysed first using the Random Forest classifier. The profiles were then down-sampled into a smaller number of spectral bands with wider spectral bandwidths defined by multispectral bands of the Sequoia and Sentinel-2 sensors (4 and 13 bands respectively). Each profile was analysed again using the Random Forest classifier. The down-sampled multispectral profiles were used to classify the drone and satellite imagery and perform a validation of the method.

The classification results based on the hyperspectral profiles of the leaves suggested an overall accuracy of 80 % when using a Random Forest classifier. Only a few species were misclassified as the weeds (including weeds not of interest to this study), such as Billy Button and St Johns Wort. When the spectral profiles of the flowers were considered as well, the classification accuracy was much greater (> 95 %).

However, the classification accuracy decreased as the spectral profiles were down-sampled. This is because the down-sampling averages out the small differences in the spectral profiles of the plants so the profiles become more similar or more generic. For example, the down-sampled results suggested that when the Sentinel-2 satellite bands were used (13), an overall accuracy of 70 % was achievable, whereas if the Sequoia bands are used (4), the overall accuracy is only around 57 %. Along with the reduction in accuracy, there was also an increase in the misclassification of the weeds as other species and an increase in the number of native species that were misclassified as the weeds.

Although the results demonstrated that the hyperspectral profiles of the collected alpine vegetation species are distinguishable from each other, several challenges were presented with using the satellite imagery and drone imagery to detect the location of the weeds. Due to the eradication program, the only hawkweeds that could be sampled were small, isolated and often obscured by other vegetation. The resolution of the satellite imagery was 2 m, but given the small and often isolated hawkweeds, centimetre-scale resolution is required for validation to avoid spectral mixing within each pixel. Use of the drone with the Sequoia sensor achieved very high resolution imagery (1-2 cm pixels), but revealed problems in calibration and image distortion.

It is possible that the problems in obtaining the drone imagery can be resolved through further work on image collection and processing. If further imagery were to be obtained, ideally use of a drone-mounted hyperspectral sensor or multispectral sensor that covers the critical bands is recommended. Based on the results of this study, collection of higher spatial and spectral resolution data would have the greatest impact on progressing the method towards use as an operational tool for weed management and eradication.

Introduction

The natural environment of the Australian Alps is an important part of both Indigenous and European Australian heritage and culture (NSW Department of Environment and Conservation 2006). The Alps are protected by a chain of national parks, the largest and most well-known of which being Kosciuszko National Park (KNP) in NSW. The alps region contains unique ecosystems, being one of the only seasonally snow-covered regions on the continent, and as such is home to a large array of rare, and unique floral and faunal species (NSW Department of Environment and Conservation 2006). The presence of noxious weeds in the KNP and surrounding areas, is of a deep concern particularly in terms of threats to the local biodiversity and health of the environment, with the potential to cause significant environmental, social, and economic impacts (Dehaan *et al.* 2007, Benson 2012, NSW OEH 2014, McConnachie *et al.* 2015, NSW OEH 2018).

The three weed species investigated in this study are members of the daisy family (Asteraceae). Orange Hawkweed (*Hieracium aurantiacum)* and Mouse-ear Hawkweed (*Hieracium pilosella*) are prohibited under the NSW Biosecurity Regulation 2017, while Ox-eye daisy (*Leucanthemum vulgare*) is a priority weed in Local Land Service regional weeds plans. Their occurrence in KNP is being targeted by multiple government agencies, including NSW National Parks and Wildlife Service (NSW Department of Primary Industries 2012). Whilst Hawkweeds are yet to reach past the early stages of establishment, they have been acknowledged to pose a major threat to ecosystems, particularly grasslands, alpine, and temperate areas (Morgan 2000, Benson 2012).

Orange Hawkweed was first discovered in the Kosciuszko National Park region in late-2003 (NSW Department of Primary Industries 2012). Listed as prohibited matter in NSW, it is internationally recognised for displacing native vegetation, and harming agricultural productivity, particularly in New Zealand, Canada, and USA (Wilson *et al.* 1997, NSW OEH 2014). Its current containment within the national park (barring two outliers discovered early-2017 in a neighbouring farm), as well as its high risk factor, makes it an ideal candidate for a targeted eradication program (Turner *et al.* 2013). Mouse-ear Hawkweed is considered the most invasive of the hawkweeds but is currently only found in one small area on the main range near Mt Twynam and Strzelecki Creek, with very few plants remaining because of the eradication program. Ox-eye daisy is a more prevalent introduced species, which is difficult to control with eradication and control programs (Benson 2012, McConnachie *et al.* 2015).

There is an urgent need to develop methods to prevent these weeds from spreading. The prevention process traditionally involves controlling and then monitoring existing infestations and scouting for additional infestations using field survey approaches (NSW Department of Primary Industries 2012). However, the demand, and urgency, to mitigate the plants distribution has led to a more diverse range of survey techniques, including sniffer dogs, volunteer programs, drones that capture visible-colour imagery, helicopter insertion surveys, and seed dispersal modelling (Williams *et al.* 2008, Hanigan and Smith 2014, Hung and Sukkarieh 2015, Cherry *et al.* 2016).

The difficulty in weed management in KNP is further increased by the exceptionally difficult topography requiring the use of charted helicopters, off-road vehicles, and off-track hiking, reducing the amount of time that can be used for searches and increasing costs (Hamilton *et al.* 2015). Time is also a major constraint as the flowering period for the hawkweeds is quite short over the summer, but makes the plants significantly easier to spot (Lass and Callihan 1997). Whereas in winter/spring, snow may cover the surface vegetation making detection of the plants impossible.

A remote sensing method that has previously been tested in KNP involves flying drones with an RGB camera over known sites to seek the orange colour value of the Orange Hawkweed flower in the image

(Hung and Sukkarieh 2015, Hamilton *et al.* 2018). However, the method relies on each plant being in flower at the same time, and can result in false-positive detection if other plants with orange coloured flowers are also flowering (Hung and Sukkarieh 2015).

A more promising remote sensing method which has been used in the agricultural sector measures plant leaf/flower reflectance at an interval of 1 nm (hyperspectral) over the spectral wavelengths of 450 nm to 2500 nm (Figure 1). In addition to providing very high resolution reflectance data which may be used to detect different plants based on their spectral profiles, the distinct advantage of this method over the RGB method is that it does not depend on the plant being in flower at the time the imagery was collected.

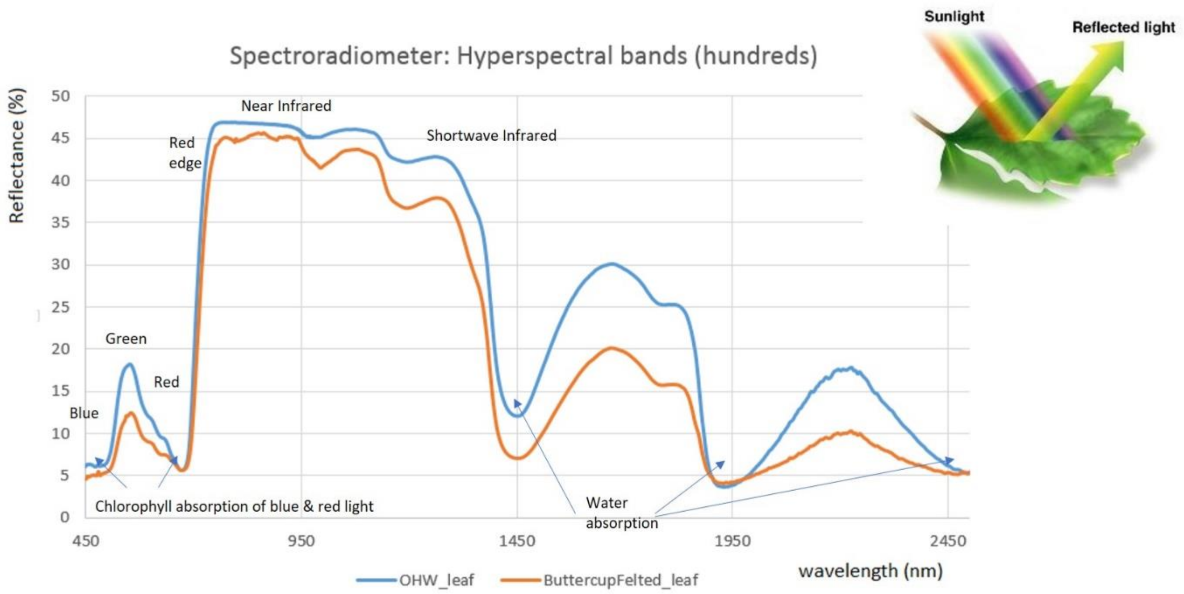

Figure 1: *Typical reflectance profile of plants showing absorption of light in the blue and red bands (450-500 nm; 625-740 nm), and reflection of light in the green (500-560 nm), Near Infrared (760-1200 nm) and Infrared bands (1200 nm +).*

Project Aims and Objectives

The aims of this project were to:

1. Develop an alpine vegetation community spectral library for the target weed species: Orange Hawkweed, Mouse-ear Hawkweed and Ox-eye Daisy, and their common co-occurring native species.
2. Determine whether the weed species have a unique spectral reflectance profile relative to the native species and evaluate whether the weeds can be accurately differentiated from the surrounding plants.
3. Depending on the results from (2), explore the available remote sensing tools to determine which products would be suitable for long-term monitoring of Orange Hawkweed, Mouse-ear Hawkweed and Ox-eye Daisy.

Study Sites

Kosciuszko National Park is located in the Snowy Mountains, NSW (latitude: 35°30’S to 37°02’S; longitude: 148°10’E to 148°52’E). Covering much of the Australian Alps Bioregion, it is the largest national park in NSW at 673,542 ha (NSW Department of Environment and Conservation 2006). Sites for this project were chosen in liaison with NSW National Parks officers, targeting areas within the park where Orange Hawkweed and Mouse-ear Hawkweed was found, or has been found previously but destroyed through the NPWS eradication program (see Figure 2). Because of the eradication program, the hawkweeds currently have a very sparse and patchy distribution with few plants remaining. This was a major limitation for this project, as ideally dense weed mats covering large areas were needed to fully test the method. One site was used to measure Ox-Eye Daisy, which is much more widespread and abundant throughout the park.

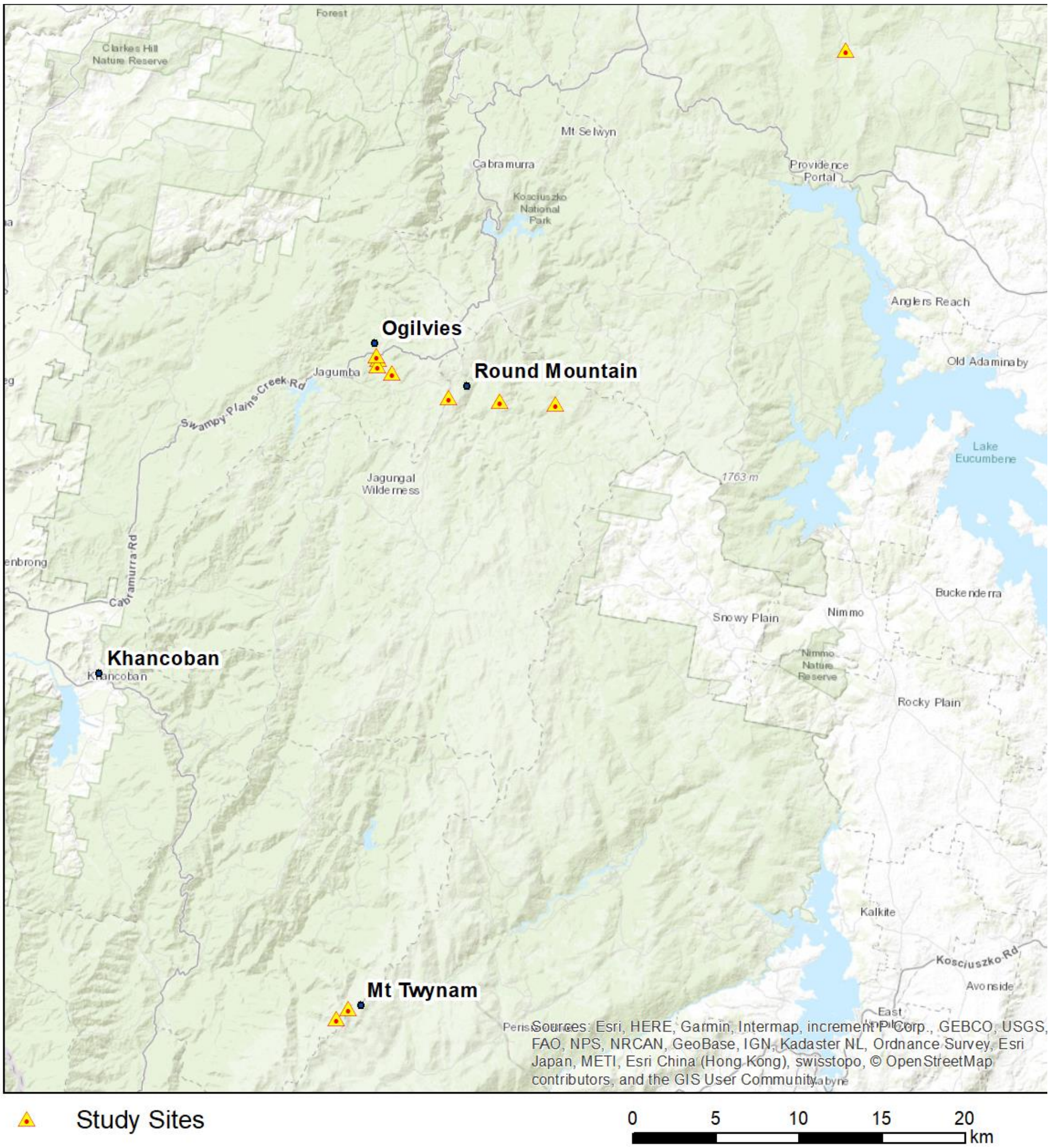

Figure 2. *Map showing the overview of the site (KNP), and the areas where the samples were collected.*

Methods

The methods consist of three stages, namely **Stage 1** – Collection of spectral profiles of the selected vegetation species and drone-based multispectral imagery; **Stage 2** – Spectral profile analysis and classification; and **Stage 3** – Identification of the weeds from drone and satellite imagery.

Stage 1: *Collection of spectral profiles and drone-based imagery*

1.1. Three field surveys were conducted in January 2017, January 2018 and January/February 2018 to determine the spectral profiles of the target weed species and dominant native vegetation occurring in the same environment. During each survey, measurements of plant leaf and flower reflectance were collected using a hand-held hyperspectral spectroradiometer, *Spectral Evolution PSR+ 3500*. Initially, during the 2017 field survey, the instrument was used with an optical lens (at a field of view of 8 degrees) held at around 1 m above ground, which measured the average reflectance of a ground field of view of 14cm. However, due to the high diversity of plants on the ground and absence of dense weed mats for sampling, we changed to using a leaf clip for the 2018 field surveys. The leaf clip directly measures the light reflected by the sample in the clip and hence gives a more reliable measurement of reflectance. Repeat measurements of 20-50 leaves and flowers of each species were undertaken where possible, to capture any within-plant variability, as well as variability associated with plant heath and growing conditions.

1.2. To capture seasonal variability in the spectral profiles of the weed species, plant samples of each weed were obtained from NPWS and kept in the physical containment laboratory (greenhouse) at Macquarie University during 2017. These were measured at frequent intervals using the spectroradiometer and leaf clip.

1.3. During the 2018 field surveys, drone-based multispectral imagery was also acquired from the Hawkweed sites using a Parrot Sequoia sensor mounted to a 3DR Solo drone. The sensor measures 4 spectral bands in green, red, red-edge and near infrared wavelengths. The drone was flown 15-30 m above the ground to achieve a pixel resolution of ~ 1 cm. Flying time was within a couple of hours of solar noon to minimise the effects of shadows and an 80-85 % overlap/sidelap was allowed between each image acquisition/pass. Processing of the data to create a calibrated mosaicked image was undertaken using the Pix4D platform.

Stage 2: *Spectral profile analysis and classification*

2.1. Analysis of the spectral profiles was undertaken through several workflows in R using pre-existing and new code specifically written for this project. The analysis involved input of the data, noise filtering of the profiles to remove errors and outliers, and calculation of the mean profiles for each species. The mean profiles were compiled into a spectral library for further analysis.

2.2. Evaluation of the separability or ‘uniqueness’ of the mean spectral profiles was undertaken using a Random Forest classifier. The Random Forest classifier is a machine learning methodology that creates a set of decision trees from a randomly selected subset of the dataset (called the training set). This is iterated a number of times, before the results are aggregated from the different decision trees to decide the final class of the test object. The output is a confusion matrix which informs of the number of times a profile was classified correctly (producers accuracy) vs the number of times that it was misclassified as another species (users accuracy). The higher the accuracy (100 %) the better the classification. Accuracies < 100 % indicate misclassifications i.e. the occurrence of false positives and false negatives.

2.3. To enable further analysis using the current multispectral satellite imagery (e.g. Sentinel-2), as well as the imagery collected by the multispectral Parrot Sequoia sensor, the hyperspectral profiles were down-sampled to simulate multispectral profiles. This involved grouping the hyperspectral bands according to the spectral bandwidths of Sentinel-2 and Parrot Sequoia and averaging the reflectance over those coarser bandwidths. Evaluation of the separability of each simulated profile was repeated using the Random Forest classifier.

Stage 3: ***Identification of the weeds from drone and satellite imagery***

3.1. To investigate the feasibility of using multispectral satellite imagery to classify and determine the distribution of the weed species, all of the currently available high resolution satellite imagery were examined to determine their suitability i.e. covered the study area, cloud-free, free of snow and preferably collected in the December-January months when field sampling was undertaken. For this part of the project, only the two species of Hawkweeds were targeted since they were a higher priority for NPWS than Ox-eye Daisy. This limited the imagery to the Main Range and areas around Round Mountain. Because of the limitations, only two high resolution satellite imagery tiles with 2 m resolution were available to be purchased. These were Pleiades-1 imagery (4 bands) acquired on 4 Jan 2018 and Worldview-2 imagery (8 bands) acquired 1 Jan 2015.

3.2. The composited multi-band images were then used to classify the weeds. Image classification was undertaken using the commonly used classifiers of Maximum Likelihood Classifier (MLC), and Spectral Angle Mapper (SAM).

Results

<u>Analysis of the hyperspectral profiles of the weeds and co-occurring native species</u>

During the three field surveys, over 75 co-occurring native and introduced species were sampled, along with the 3 weed species (see Appendix 1 for a list of species). This included both leaves and flowers where possible, to give the highest possible chance of finding differences in the spectral profiles of the plants. For some of these species however, the number of profiles collected was insufficient to establish an average profile once errors were removed. Nonetheless, over half of the species could be compiled into a spectral library and analysed.

A sub-set of these profiles for the leaves only, and flowers only, are shown in Figures 3 and 4, respectively. As expected, the profiles of the flowers are very distinctive from those of the leaves, particularly in the 450 – 800 nm range (blue, green, red and red-edge bands).

For the profiles collected using the spectroradiometer and lens, the error matrix results showed an overall classification accuracy of 71 % (Table 1). The accuracy for identifying Orange Hawkweed was 67 % to 74 % for the field samples, and 88 % to 100 % for the greenhouse samples (Table 1). The improvement in the greenhouse samples is probably due to there being no other vegetation in the background plus the change to the leaf clip in mid-2017. There were a few misclassifications, with Kangaroo grass, Ox-eye Daisy and Alpine Everlasting plants being classified as Orange Hawkweed.

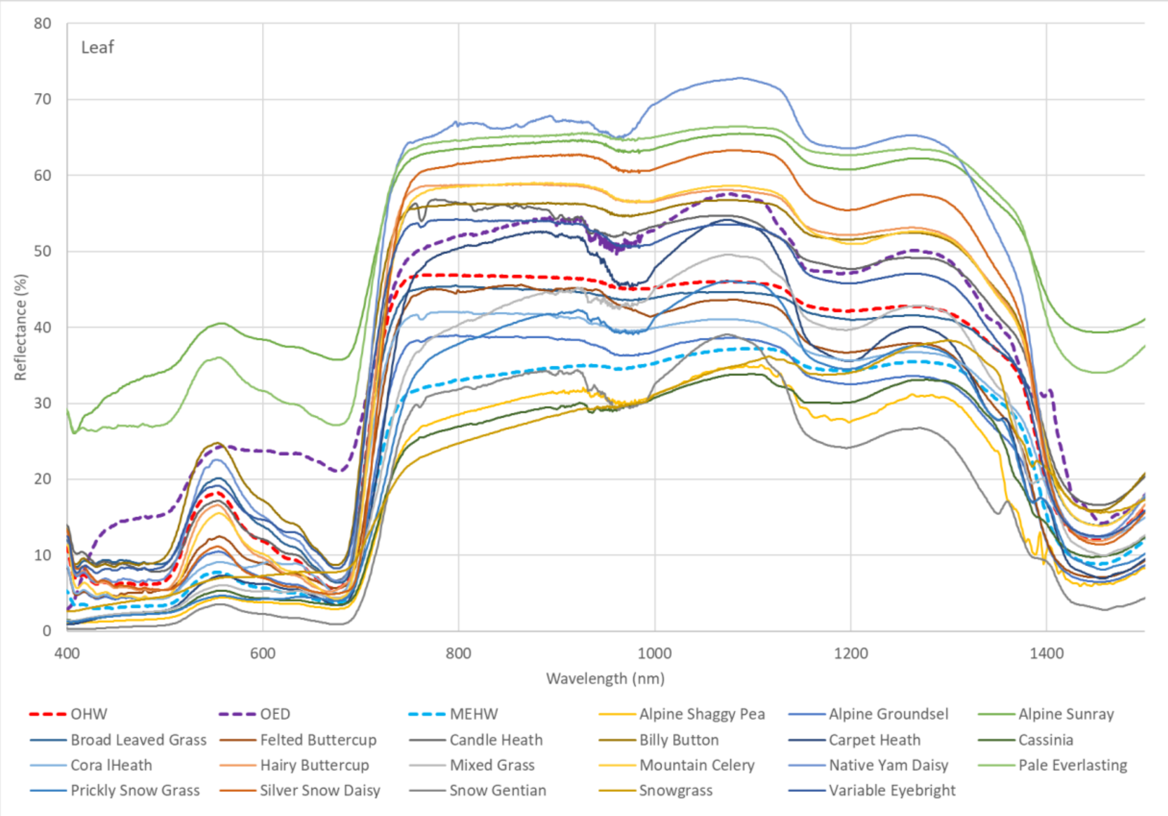

Figure 3: *Averaged spectral profiles of the leaves of Orange Hawkweed, Mouse-ear Hawkweed. Ox-eye Daisy and other common co-occurring plants sampled in the field in Kosciuszko National Park.*

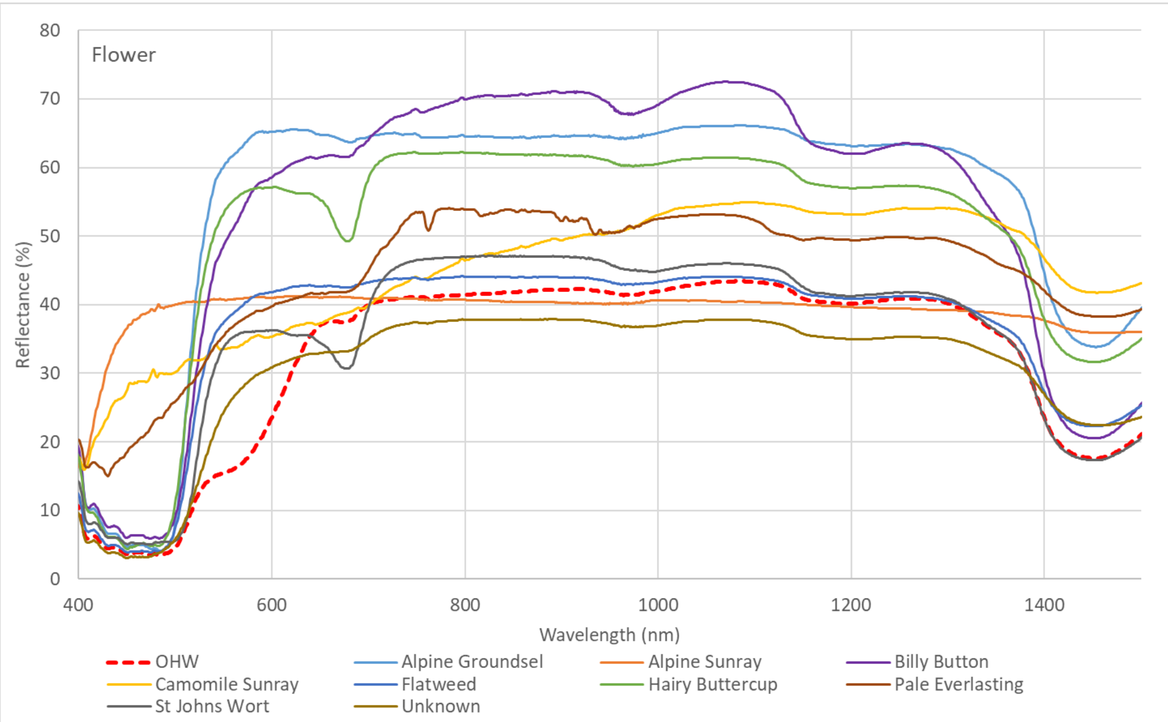

Figure 4: *Averaged spectral profiles of the flowers of Orange Hawkweed and other common co-occurring plants sampled in the field which produce similar flowers.*

Table 1: *Summary of the confusion error matrix outputs for the spectral profile data collected with the lens (plant, leaves and flowers if present). Orange Hawkweed is indicated by the red shading and Ox-eye Daisy by the purple shading*

Species	**Producer's Accuracy (%)**	**Producer's sample size**	**User's Accuracy (%)**	**User's sample size**
Alpine Daisy-bush	67	3	67	3
Alpine Grevillea	43	7	43	7
Alpine Shaggy-pea	81	16	76	17
Leafy Bossiaea	100	11	65	17
Black Sally	78	9	64	11
Sticky Cassinia	50	12	50	12
Kangaroo Grass	44	9	40	10
OHW - field flower	**67**	3	**100**	2
OHW - field plant	**74**	19	**88**	16
OHW - greenhouse flower	**100**	12	**92**	13
OHW - greenhouse plant	**88**	8	**88**	8
OED - flower	**73**	41	**77**	39
OED - plant	**48**	27	**42**	31
Alpine Everlasting - flower	83	6	83	6
Alpine Everlasting - plant	38	8	75	4
Snow Grass	73	30	88	25
Total sample size		221		221
Overall accuracy	71		71	

The classification accuracy of Ox-Eye Daisy was lower, with the plant having an accuracy of 48 %, whilst the flower was 73 % (Table 1). However, most of the misclassifications were actually the Ox-Eye Daisy plants being classified as the Ox-eye Daisy flower and visa-versa. The misclassification is probably due to the use of the lens since measurement of the flower reflectance undoubtedly included some reflectance off the leaves as well.

For the profiles collected using the leaf clip, the error matrix results showed an overall classification accuracy of 80 % for the leaves only (Table 2) and 97% for the flowers only (Table 3). For the leaves only, 64 – 83 % of the Mouse-ear Hawkweed profiles were classified correctly, while 95 % of the Orange Hawkweed profiles were classified correctly. When the Orange Hawkweed leaves were misclassified, they were detected as Mountain Celery. False detections of Orange Hawkweed leaves included Billy Button, Mouse-ear Hawkweed and an unknown species. Mouse-ear Hawkweed when misclassified, were determined as Coral Heath and St John Wort. The false detections of Mouse-ear Hawkweed included Alpine Groundsel, Sheep Sorrell, St Johns Wort and Woolly Billy Button. Of the two hawkweeds, only Orange Hawkweed was flowering at the time of sampling. 100 % of the Orange Hawkweed profiles were classified correctly as Orange Hawkweed, and only one other species, St Johns Wort was misclassified as Orange Hawkweed.

The error matrix results show that when the flowers and leaves are available, the accuracy of the detection increases significantly since both profiles can be used to identify the plant and reduce the likelihood of misclassifications. The other important output of the Random Forest classification is that it provided an indicative insight into the wavelengths where the discriminability of the weed species is maximised. For these the most useful wavelengths for spectral discrimination were found to include the bands: 400-420 nm, 440-480 nm, 510-550 nm, 570-580 nm, 640-690 nm, 710-750nm and 1300 nm.

Table 2: *Summary of the confusion error matrix outputs for the spectral profile data collected with the leaf clip - leaves only. Orange Hawkweed is indicated by the red shading and Mouse-ear Hawkweed by the blue shading*

Species	Producer's Accuracy (%)	Producer's sample size	User's Accuracy (%)	User's sample size
Alpine Groundsel leaf	100	12	67	18
Alpine Sunray leaf	100	10	83	12
Billy Button leaf	88	32	80	35
Billy Button leaf	53	19	91	11
Broad Leaved Grass	100	13	93	14
Buttercup Felted leaf	93	14	100	13
Candle Heath leaf	41	17	70	10
Carex guadichaudiana leaf	83	12	83	12
Coral Heath leaf	93	14	62	21
Dandelion leaf	67	15	77	13
Flatweed leaf	67	3	100	2
Hairy Buttercup leaf	60	5	75	4
Mixed Grass leaf	67	12	67	12
Mountain Celery leaf	92	12	73	15
MEHW leaf	**83**	24	**91**	22
MEHW leaf (Strez Crk)	**64**	11	**70**	10
Native Yam Daisy leaf	93	14	100	13
OHW leaf	**95**	22	**75**	28
Pale Everlasting leaf	91	11	83	12
Pineapple Grass	83	12	77	13
Prickly Snow Grass	80	10	80	10
Sheep Sorrell leaf	93	15	88	16
Silver Snow Daisy leaf	87	15	100	13
Silver Snow Daisy leaf	82	11	82	11
Small Star Plantain leaf	70	10	88	8
Snow Gentian leaf	100	12	100	12
Spoon Daisy leaf	73	15	85	13
St John Wort leaf	80	10	67	12
Variable Eyebright leaf	60	10	55	11
White Cover leaf	88	17	83	18
Woolly Billy Button leaf	46	13	60	10
Unknown leaf	40	5	67	3
Total sample size		427		427
Overall accuracy	80		80	

Table 3: *Summary of the confusion error matrix outputs for the spectral profile data collected with the leaf clip – flowers.*

Species	Producer's Accuracy (%)	Producer's sample size	User's Accuracy (%)	User's sample size
Alpine Groundsel flower	100	8	89	9
Alpine Sunray flower	100	12	100	12
Billy Button flower	100	15	94	16
Flatweed flower	80	5	100	4
Hairy Buttercup flower	50	2	100	1
OHW flower	**100**	20	**95**	21
St Johns Wort flower	89	9	100	8
Unknown flower	100	6	100	6
Total sample size		77		77
Overall accuracy	97		97	

Estimated accuracy of the weeds classification using simulated multispectral profiles created by down-sampling of the hyperspectral profiles

The re-sampled profiles matched to the Parrot Sequoia drone sensor (4 bands), and Sentinel-2 satellite sensor (13 bands) showed overall classification accuracies of 57 % and 70 %, respectively (Table 4), which is much lower than the accuracies achieved using the hyperspectral profiles.

For the simulated multispectral Sequoia profiles, there were several misclassifications - three unknown flower (Xsub) samples were misclassified as the OWH flower; 1-2 samples of Alpine Groundsel, Buttercup, Carex spp, Coral Heath and St Johns Wort were misclassified as Mouse-ear Hawkweed; 1-2 samples of Coral Heath, Sheep Sorrell, Silver Snow Daisy, Eyebright, Whitecover and Xsub were misclassified as Orange Hawkweed. A few Mouse-ear Hawkweed samples were misclassified as Dandelion or Hairy Buttercup, and a few Orange Hawkeed samples were misclassified as broad leaved grass, Billy Button, Pineapple grass, White Clover, Buttercup and Alpine Groundsel.

For the simulated multispectral Sentinel-2 profiles, a similar problem of misclassification occurred. One unknown flower (Xsub) sample was misclassified as an Orange Hawkweed flower; 1-3 samples of Carex spp, Coral Heath, Hairy Buttercup, St Johns Wort leaves and Xsub flower were misclassified as Mouse-ear Hawkweed; 1-2 samples of Billy Button, Buttercup, Candle Heath, Coral Heath, Dandelion, Mountain Celery, Mouse-ear Hawkweed, Variable Eyebright, and White Cover were classified as Orange Hawkweed. A few Mouse-ear Hawkweed samples were misclassified as Native Yam Daisy leaf or Orange Hawkweed leaf, and few Orange Hawkweed were misclassified as Alpine Groundsel, Billy Button and St Johns Wort.

Table 4: *Summary of the accuracy of classification using the spectral bands of the (top) Parrot Sequoia and (bottom) Sentinel-2 multispectral sensors.*

Predicted Species	MEHW leaf	OHW leaf	OHW flower	Others	Total	User's Accuracy
MEHW leaf	21	0	0	9	30	70.0%
OHW leaf	0	10	0	8	18	55.6%
OHW flower	0	0	19	5	24	79.2%
Others	3	12	1			
Total	24	22	20			
Producer's Accuracy	87.5%	45.5%	95.0%		Overall	56.8%

Predicted Species	MEHW leaf	OHW leaf	OHW flower	Others	Total	User's Accuracy
MEHW leaf	19	0	0	7	26	73.1%
OHW leaf	1	17	0	9	27	63.0%
OHW flower	0	0	20	1	21	95.2%
Others	5	5	0			
Total	24	22	20			
Producer's Accuracy	79.2%	77.3%	100.0%		Overall	69.7%

Analysis of satellite and drone-acquired remote sensing imagery to investigate whether the imagery can be used to detect the Hawkweed species

The results from the Pleiades-1 imagery and Worldview-2 imagery classifications were disappointing. Both the spectral and spatial resolutions of these two satellite imagery proved to be too coarse to accurately distinguish the vegetation down to species level, even with a 2 m pixel resolution.

This is because one of the challenges with using remote sensing imagery for vegetation assessment is that the classification assumes that every pixel contains only one species and one spectral response. Whereas in reality, spectral mixing can occur especially as pixel sizes become larger i.e. each pixel contains multiple plant species with different spectral responses hence the values for each pixel are an average of those different species. This is particularly true for the alpine vegetation communities in KNP where the on-ground diversity of native species is very high over very small areas. Furthermore, the Hawkweeds that were present during our field sampling, and hence used for validation, were small (5-10 cm rosettes), sporadic (3 or 4 plants) and dispersed amongst the native vegetation. To detect the signal of individual Hawkweed plants, satellite imagery with a much smaller resolution is required.

The drone imagery acquired by the Parrot Sequoia multispectral sensor during the field survey in Jan/Feb 2018 was more promising because of the ~1-2 cm spatial resolution (Figure 5). However, despite the high resolution, the accuracy of the classification was also very poor. All of the Orange Hawkweed pixels which are marked by the yellow sticks in Figure 5b, were identified as Buttercup, Carex spp, Mountain Celery or Woolly Billy Button.

Part of the reason for the low accuracy of the classification related to the collection of the drone data. A number of operational issues were discovered during the image calibration and mosaicking which proved to be problematic. These include:

- Sensor accuracy (radiometric calibration issues) - the sensor was calibrated using a reference calibration pad prior to each flight and through the use of a connected sunlight sensor, however errors in the calibration still occurred. For example, Figure 5a shows a trend of increasing dominance of the infrared band towards the right of the image which is due to incorrect calibration.
- Misalignment of the pixels due to inadequate overlap/sidelap - this resulted in visible tearing (Figure 6a) and wavy patination (Figure 6b).
- Geometric distortion due to the fine detail of the features in the photos - Pix4D automatically removes the distortion using a sensor catalog, however the processed outputs were still found to exhibit some distortions (Figure 6b). The apparent impact of geometric distortion could be decreased through using an increased acquisition altitude i.e 50-100 m above the ground, however this would have a detrimental impact on the pixel-size of the imagery and hence the ability to detect the small rosettes because the resolution of the imagery would be larger. Due to the geometric distortion/error in the ortho-rectified image, single frame (individual) multispectral images were also tested for classifying OHW based on the spectral response of the pixels. However, the results were still less than satisfactory and resulted in large errors.
- Incorrect ortho-rectification – offsets of several meters were evident in the processed multispectral images, but ultimately these were considered less important as they did not affect the image classification as long as known points in the image could be identified e.g. creeks, roads.

The other reason for the poor results relates to the number and characteristics of the Hawkweeds available for validation. The rosettes were often obscured by overhanging groundcover, shrubs and trees, which meant acquiring suitable remotely sensed imagery (whether oblique or nadir) that clearly identifies the weeds is a significant hurdle. Plus because of the eradication program, there were very few Hawkweeds present at the study sites to validate the imagery against. The image in Figure 5b shows a small area of ~ 40 cm x 50 cm that contains Orange Hawkweed plants but most of the vegetation is actually native plants. Ideally large areas of weed mats are needed to provide more training and validation pixels for the image classification process.

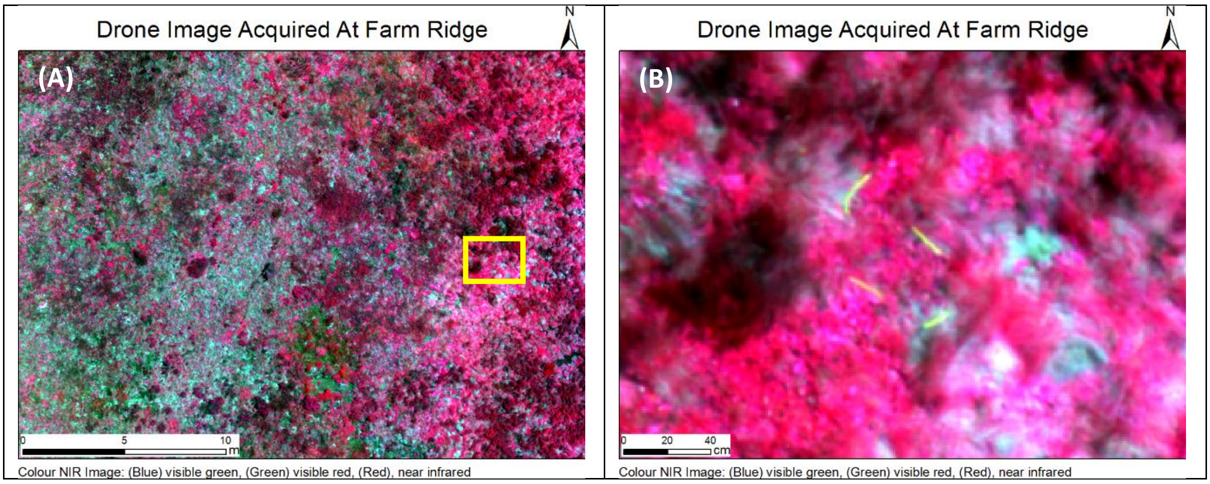

Figure 5: F*alse colour infrared image of the 4 band multispectral data by Parrot Sequoia at Farm Ridge in KNP (panel A). The zoomed-in imagery at the right (panel B) shows an area with Orange Hawkweed plants marked by the yellow sticks.*

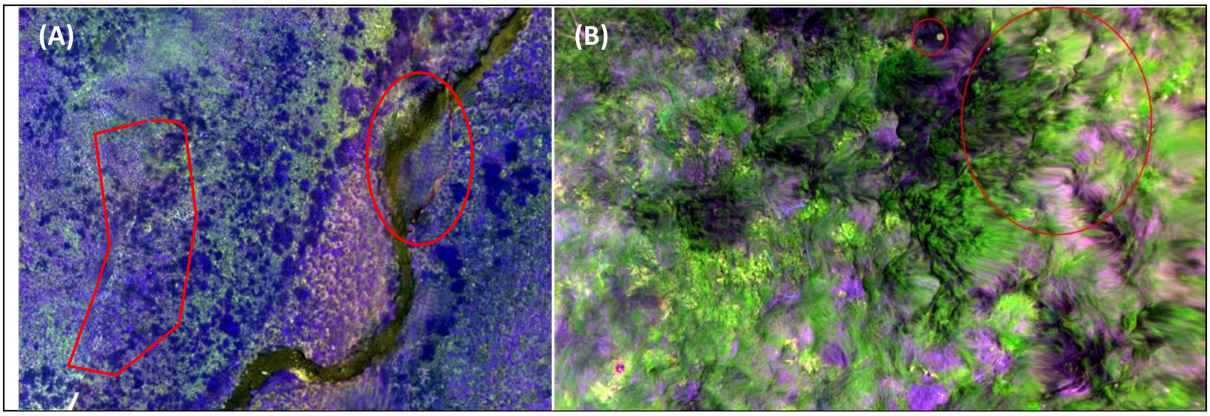

Figure 6: *(A) Tearing of the processed mosaic image acquired using 3DR Solo Drone and Parrot Sequoia sensor (processed in Pix4D). Errors were spotted in the highlighted areas. (B) Wavy patination likely caused by insufficient image overlap.*

Conclusions and Recommendations

This project collected and identified the spectral profiles of the targeted weeds and selected co-occurring native vegetation species using a handheld spectroradiometer in Kosciuszko National Park. Our analysis of the spectral profile separability using the hyperspectral profiles collected in the field showed an overall accuracy of 80 % in determining the weeds from the native species. The classification accuracy for Orange Hawkweed was increased to > 95 % when the flowers were used. A similar finding for Mouse-ear Hawkweed is also likely. Hence, an important outcome from the study is that it is hypothetically possible to map Orange Hawkweed and Mouse-ear Hawkweed based on their spectral characteristics. It may also be possible to map Ox-eye Daisy, but it would be preferable to collect new spectral profiles of the plant (leaves and flowers) using the leaf clip instead of the lens.

The re-sampled spectral profiles simulated to match the wavelengths detected by the drone-mounted Parrot Sequoia sensor (4 bands), and Sentinel-2 satellite imagery (13 bands) saw the overall classification accuracies decrease to 57 % and 70 % respectively. This is because the re-sampling to fewer wavelengths and larger band widths averages out the finer differences in the hyperspectral profiles of each species and hence decreases the separability of the profiles. As a result, there were a greater number of misclassifications using the simulated multispectral profiles compared to the hyperspectral profiles.

The current satellite imagery that covers KNP in the areas where Hawkweed has been found is limited at present in its useability for mapping the location of the weeds. While high resolution imagery is available such as Pleiades-1 and Worldview-2, the resolution was not high enough to identify the weeds where they are small, isolated or obscured by native vegetation. The imagery may be useful if dense weed-mats can be found but this needs to be validated first before a more widespread survey is undertaken.

While the classification of the drone imagery was impacted by operational issues, there is scope to resolve these issues through further investment of capital and research. For example, multiple calibration pads could be used throughout the study area to improve the radiometric calibration of the images. Use of a higher (60 - 70 %) overlap/sidelap in the imagery acquisition would minimise the geometric distortion and ortho-rectification errors when mosaicking the drone images. Alternatively, image ortho-rectification and mosaicking could be skipped if the weeds classification is only applied to individual images to identify the number of potential plants.

Much greater improvement in the classification and detection of the weeds could be achieved through investment in a scientific grade hyperspectral sensor, or a multispectral sensor which ideally covers the following bands: 400-420nm, 440-480nm, 510-550nm, 570-580nm, 640nm-690nm, 710nm-750nm and 1300nm. Use of a hyperspectral sensor would negate the need to down-sample the profiles, which has been shown in this study to result in a reduction in classification accuracy and increased likelihood of misclassification. However, to achieve this, high performance computing is also needed to run the analysis since there are tens to hundreds more bands in the hyperspectral data compared to the multispectral data. Other techniques, such as principle component analysis (PCA), could also be used to remove redundant spectral bands. It is clear that there is scope and justification for further work beyond the current project. This may be considered for a future study.

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Appendix 1.

List of co-occurring native and introduced species that were found at the sites where the three target weed species were sampled (OHW: Orange Hawkweed; OED: Ox-eye Daisy; MEHW: Mouse-ear Hawkweed)

Species	Common name	Co-occurred with:		
Aciphylla glacialis	Mountain Celery			MEHW
Asperula spp (A. scoparia and A. gunnii)	Mountain Woodruff		OED	
Astelia psychrocharis	Kosciuszko Pineapple-grass			MEHW
Baekea gunniana	Alpine Baeckea	OHW		
Bossiaea foliosa	Leafy Bossiaea	OHW		
Brachyscome decipiens	Field Daisy		OED	
Brachyscome spathulata	Spoon Daisy			MEHW
Cardamine sp	Bitter-cress	OHW		
Carex breviculmis	Short-flowered Alpine Sedge		OED	
Carex gaudichaudiana	Tufted Sedge	OHW		MEHW
Carex jackiana	Short-flowered Swamp Sedge	OHW		
Cassinia monticola	Mountain Cassinia	OHW		
Cassinia uncasta	Sticky Cassinia	OHW		
Celmisia tomentella	Silver Snow-daisy			MEHW
Chionogentias muelleriana	Snow Gentian			MEHW
Coronidium gunnianum	Pale Everlasting			MEHW
Craspedia maxgrayi	Woolly Billy-button			MEHW
Craspedia sp.	Billy-button	OHW		
Dichondra sp A.	Dichondra	OHW		
Dillwynia prostrata	Matted Parrot-pea		OED	
Epacris gunnii	Heath	OHW		
Epacris microphylla	Coral Heath			MEHW
Erigeron bellidioides	Violet Fleabane	OHW		
Erigeron spp.	Fleabane		OED	
Eucalyptus pauciflora	Snow gum		OED	
Eucalyptus stellulata	Black Sally		OED	
Euphrasia collina	Variable Eyebright			MEHW
Festuca asperula	Grass		OED	
Geranium antrorsum	Rossetted Crane's-bill		OED	
Grevillea australis	Alpine Grevillea	OHW		
Hakea macrocarpa	Dogwood Hakea		OED	
Hovea sp. aff heterophylla	Hovea sp.		OED	
Kunzea muelleri	Yellow Kunzea	OHW		
Leptorhynchos squamatus	Scaly Buttons		OED	
Leucochrysum albicans	Alpine Sunray			MEHW
Leucopogon fraseri	Leucopogon sp.		OED	
Microseris lanceolata	Native Yam Daisy	OHW		MEHW
Moss	Moss	OHW		

Olearia algida	Alpine Daisy-bush	OHW		
Olearia brevipedunculata	Daisy-bush	OHW		
Olearia myrsinoides	Silky Daisy-bush		OED	
Oreomyrrhis argentea	Silvery Carraway	OHW		
Oreomyrrhis australianum	Carraway	OHW		
Pentachondra pumila	Carpet Heath			MEHW
Plantago glacialis	Small Star Plantain			MEHW
Poa enciformis	Sword Tussock-grass	OHW		
Poa sp.	Grass	OHW		
Poa sp.	Mixed grass			MEHW
Poa spp (includes P. hookeri, P. sieberiana, P. costiniana	Snow Grass, Prickly Snow Grass		OED	MEHW
Podolobium alpestre	Alpine Shaggy-pea	OHW		
Ranunculus muelleri	Felted Buttercup			MEHW
Ranunculus sardous	Hairy Buttercup			MEHW
Ranunculus sp.	Buttercup	OHW		
Rhodanthe anthemoides	Chamomile Sunray			MEHW
Richea continentis	Candle Heath			MEHW
Rytidosperma penicillatum	Slender Wallaby-grass		OED	
Rytidosperma sp. (Danthonia sp.)	Wallaby-grass	OHW		
Senecio gunnii	Gunn's Groundsel		OED	
Senecio longipilus	Groundsel		OED	
Senecio pectinatus	Alpine Groundsel			MEHW
Stellaria pungens	Prickly Starwort	OHW		
Stylidium montanum	Alpine Triggerplant	OHW		
Tasmannia xerophila	Mountain Pepper	OHW		
Themeda australis	Kangaroo Grass		OED	
Trisetum spicatum?	Broad leaved grass - Bristle Grass?			MEHW
Veronica subtilis	Splender Speedwell	OHW		
Viola betonicifolia	Mountain Violet	OHW	OED	
Xerochrysum bracteatum	Golden Everlasting	OHW		
Xerochrysum subundulatum	Alpine Everlasting		OED	
* Acetosella vulgaris	Sheep Sorrel		OED	
* Agrostis capillaris	Brown-top Bent	OHW		
* Cerastium glomeratum	Sticky mouse-ear Chickweed	OHW		
* Hypericum perforatum	St Johns Wort	OHW		
* Hypochaeris radicata	Cat's-ear, Flatweed	OHW	OED	
* Taraxacum officinale	Dandelion	OHW		
* Trifolium repens	White Clover	OHW		

*Introduced species