Northern Inland Weeds Advisory Committee

Integrated Aerial Surveillance Innovative Project

Feasibility Report

NSW GOVERNMENT | Department of Primary Industries

NEW SOUTH WALES WEEDS ACTION PROGRAM

Prepared for NSW Department of Primary Industries
by
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in association with
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RM Consulting Group.

June 2015

CONTENTS

ABBREVIATIONS

ACFR	Australian Centre for Field Robotics
BIS	Biosecurity Information System
CASA	Civil Aviation Safety Authority
CBA	Cost Benefit Analysis
DECCWA	Dept. of Environment , Climate Change and Water
ISP	NSW Invasive Species Plan 2008-2015
LCA	Local Control Authority
LLS	Local Land Services (North West and Northern Tablelands)
LMA	Landholder Management Agreement
MoU	Memorandum of Understanding
NEWA	New England Weeds Authority (Walcha, Armidale Dumaresq, Uralla & Guyra Shires)
NIWAC	Northern Inland Weeds Advisory Committee
NWAC	Noxious Weeds Advisory Committee
NSW DPI	NSW Department of Primary Industries
RMCG	RM Consulting Group
RP	Remotely Piloted
RWS	Regional Weeds Strategy
UAV	Unmanned aerial vehicle
WAP	NSW Weed Action Program

1. EXECUTIVE SUMMARY

This feasibility study outlines the methods used and demonstrates the results of an investigation into the potential use of Unmanned Aerial Vehicles (UAVs) as an aerial surveillance tool for mapping and classification of vegetation as part of local control authorities' regional inspection programs for invasive weed species.

The study was co-ordinated by the Northern Inland Weeds Advisory Committee's (NIWAC) as part of a NSW Department of Primary Industries (DPI) Innovative Project 2013-2015.

Field work was conducted by The University of Sydney's (USYD) Australian Centre for Field Robotics (ACFR). Low altitude aerial images were collected for the invasive weed species, Tropical Soda Apple, Alligator Weed, Serrated Tussock and Water Hyacinth using a hexacopter UAV to calculate the optimum altitude to achieve the highest classification accuracy for the four weeds. This altitude information would ultimately help determine the flight duration and hence area covered during any one flight.

The aerial imagery was then used to train and evaluate the weed classification algorithms. It was demonstrated that these classification algorithms were able to correctly classify the four weeds.

Following on from the field work and weed classification analysis, RM Consulting Group (RMCG) was commissioned by NIWAC to undertake an economic assessment of the use of UAVs and weed classification analysis as part of the trial of the technology.

This analysis showed that under specific scenarios UAV technology and weed classification analysis can be used by weed managers in a cost-effective way. This was demonstrated in the following scenarios of the study:

- Small block assessments can be undertaken using UAV technology at a similar order of magnitude cost to current practice.
- Large block assessments (250 hectares) using hand held UAVs appear to be more expensive than current practice largely due to the larger scale of the area producing higher data collection and weed classification analysis costs.
- Riparian water assessments using UAVs appear to be significantly more cost effective than current practice, due to the labour-intensity of current manual inspection and the ability to use a fly-over approach to help delimit the area requiring manual visits.
- High risk pathways have somewhat limited use for UAVs, as highways are no-fly zones and the use of hand held UAVs for other pathways do not appear to produce significant time savings. However, the use of manned fly-overs and potentially regional UAVs appears to be similarly cost effective compared to current practice.

The cost-effectiveness of UAVs in weed management is, unsurprisingly, affected by the cost of using the technology, which will reduce over time, and the technology will also find a number of other practical uses for Government and private business, thus making it commercially more viable, and valuable for day-to-day operations.

This is a very important point, not only because technological advancement may reduce the cost of data collection and analysis over time, but also because there may prove to be a number of different uses for the data by both Government and private business.

For example, if landholders could use the data for crop management or business planning, they may be willing to co-fund data collection with weed management agencies. Similarly, there may be many uses of aerial photography data across agencies and tiers of Government, leading to opportunities for cost-sharing among Government departments and other entities in the future.

Furthermore, technological advancement in camera resolution may result in cost-effective state-wide data collection for multiple purposes.

If so, it is conceivable that annual data collection and weed identification analysis across a region or even the state could become standard practice over time. In such a scenario, where weed officers are collecting data using UAVs in a cost effective manner and uploading the data to the ACFR server, the identification and control of weeds could become far more coordinated and effective than is currently possible. The benefits to Government, landholders and the community of such an outcome are likely to be significant.

This innovative study, an Australian first, has found that the use of UAVs and image classification algorithms to accurately detect weeds in a rural landscape could be employed cost effectively as part of regional inspection programs.

With further development to operationalise the technology, the study suggests that UAVs could play an important role in early detection of outbreaks of high-risk new and emerging invasive weed species, to complement existing field inspection methods.

Where a rapid response is required for a new incursion, the smaller hand held UAV has potential to reduce the time required to locate the spread of the incursion and subsequent treatment of the area.

In looking to the future, there may be opportunity to build on these findings to explore the merits of applying the technology at multiple scales:

a) A Local Land Services (LLS) regional fly over capturing data for multiple uses by a number of organisations – eg farm management, feral animals and weed management.

b) A fly over on a sub-regional scale, similar to (a) but on a smaller scale.

c) A fly over of riparian areas in an LLS region.

In the interim these results suggest that further work on the technical effectiveness of the technology can be approached by placing into operation low-cost UAVs for weed officers and testing out the data passing to the ACFR and automated classification.

2. INTRODUCTION

In recent times the establishment of Weeds of National Significance such as Serrated Tussock together with new weed incursions of Tropical Soda Apple, Alligator Weed, and Water Hyacinth have occurred within the Northern Inland Weeds Advisory Committee (NIWAC) region, often occurring in inaccessible and remote areas resulting in considerable costs and utilisation of resources to carry out initial surveillance, mapping and recording.

It has been recognised for some time that to progress weed management and control techniques that we must look to continually improve our methods of weed surveillance in an innovative and cost effective manner.

This project is the culmination of the Northern Inland Weeds Advisory Committee's successful regional grant submission to the NSW Department of Primary Industries (DPI) New Innovative Projects for Weeds 2013 – 2015. It takes the regional inspection program to the next level by way of this feasibility study and cost benefit analysis of integrating new technology including unmanned aerial vehicles (UAVs), thermal imaging and a proven existing mapping system for the detection and surveillance of high risk invasive weed species.

The purpose of the project is to establish the cost effectiveness, early detection and monitoring of invasive weed species as an alternative to the more conventional methods of on-ground inspection programs.

The project explores the feasibility of using unmanned aerial vehicles being deployed to explore whether they could add value to local and remote area sensing and surveillance activities.

Central to the success of this project has been the engagement of the Australian Centre for Field Robotics (AFCR) faculty of the University of Sydney (USYD) in the study of the four different weed species detection using low altitude unmanned aerial vehicles and aerial imaging.

Consultants RM Consulting Group were engaged to carry out a Cost-Benefit Analysis (CBA) comparing the costs and benefits of incorporating the technology into a regional inspection program.

It is envisaged that the feasibility study will lead to further research and development, including field testing of UAVs for applications identified as beneficial in the Cost Benefit Analysis.

The total project budget was $220,000 comprising $44,000 of contributions from member Local Control Authorities (LCAs) of NIWAC and grant funding of $176,000 from the NSW Department of Primary Industries Innovative Project funding, over the 2 year project period (2013-2015).

Appendix 1 provides details of the project tasks, outcomes and project costs by project year.

The final report was submitted to the NSW DPI at the completion of the two year project in June 2015.

Tropical Soda Apple

Serrated Tussock

Water Hyacinth

Alligator Weed

Photo 1: Nominated weeds for this study.

3. PROJECT PARTNERS

The success of this project has been very much dependent upon the following partners:

Northern Inland Weeds Advisory Committee	(NIWAC)
New England Weeds Authority (Lead Agency)	(NEWA)
Northern Tablelands Local Land Services	(NT LLS)
University of Sydney	(USYD)
University of New England	(UNE)
NSW Department of Primary Industries	(NSW DPI)

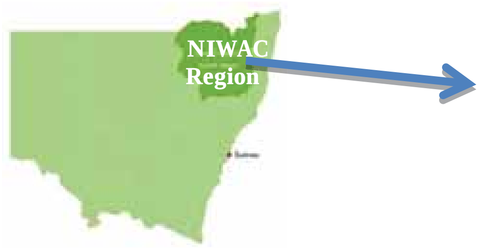
To facilitate the continuity of the project the Project Team met with the project partners on a regular basis and held a regional workshop (Refer **Appendix 2: Workshop in Armidale**) in June 2014.

4. REPORT

Weed management in NSW is a significant issue costing NSW $1.8 billion[1] annually in control and lost production.

Weeds not only affect the economy but have significant impacts on productivity, agricultural sustainability, amenity values and affect biodiversity amongst other impacts. In response weed management activities are essential and must be undertaken to mitigate these impacts, requiring the investment of new technologies, time and resources.

NIWAC is the lead organisation for weed management in the New England and North West regions, comprising key stakeholders from Tenterfield in the north, south through the New England to Tamworth and the Liverpool plains, and extending west to Gunnedah, Narrabri and Moree.



Map 1: NIWAC Region
(showing Local Government boundaries)

As we know weeds know no boundaries and whilst we have seen significant improvements in the advances of chemicals and other control methods, the matter of on-ground inspections has changed little over the past decade.

1 The Economic Cost of Weeds in NSW – Graingrowers Research Rep

With the advancement of technologies in particular UAVs, it is important that we continually look to improve our methods of weed surveillance and detection so as to be both innovative, practical and cost effective.

The NIWAC innovative pilot project looks at taking the regional inspection program to the next level by way of integrating new technology through the adaptation of UAVs, thermal imaging and a proven existing mapping system for the detection and surveillance of high risk invasive weed species

The project comprises two major components;

a) A **feasibility study** outlining recommendations on the integration of unmanned aerial vehicles, thermal imaging and mapping in the NIWAC region.

b) A **cost-benefit analysis** of the implementation of the recommendations of the feasibility study within the NIWAC region.

In summary, the objectives of the study include:

1. To have an in-depth understanding of current UAV applications to on-ground surveillance of pest weed species.
2. To investigate and determine the accuracy of the classification algorithms on different weed species at different altitude settings to determine the optimal settings for future data collection operations.
3. To perform a cost benefit analysis comparing the use of unmanned aerial vehicle surveillance, maintenance and operational costs against the conventional methods of utilising on-ground surveillance and aerial inspections by manned helicopter.
4. To explore the operational requirements and the technical and legal implications of the use of deploying unmanned aerial vehicles in surveillance and monitoring of pest weed species, with results being able to be integrated into existing mapping systems.

The deliverables of this project will include the following as per the **Workplan Summary** included in **Appendix 3**.

a) A detailed report to the NSW Department of Primary Industries on the results of the Northern Inland Weeds Advisory Committee Integrated Aerial Surveillance Innovative Pilot Project.

b) An independent report on the cost-benefit analysis of the feasibility study into the integrated aerial innovative pilot project to the NSW Department of Primary Industries.

The outcomes of this project were achieved through the following three stage activities:

- **Stage 1 – Field trials**
- **Stage 2 – Weed classification**
- **Stage 3 – Cost Benefit Analysis**

4.1 Stage One - Field Trials

Field Trials were performed at four different sites to collect images of different weed species using an UAV hexacopter, at different altitude settings of 10, 20 and 30 metres to determine optimal settings for future data collection operations.

The weed species and locations included:

1. Tropical Soda Apple - Macleay Valley
2. Alligator Weed – Garvin, near Stroud
3. Serrated Tussock – near Armidale
4. Water Hyacinth – Gingham wetlands near Moree

Methodology

There were two stages used in the methodology, being data collection and data pre-processing. In the data collection a hexacopter with a camera to take images was deployed.

In the imaging pre-processing stage, the images were divided into different groups according to their altitude settings.

With an altitude estimate per image, the images were then grouped into different altitude brackets for further analysis.

The field trials conducted to collect aerial images of the four subject weed species at different altitudes were successfully completed.

The data pre-processing stage by grouping images of different altitudes was followed by weed/non weed patch extraction for further classification analysis as part of Stage 2.

Refer Appendix 4: for further details on low altitude aerial images – data collection.

It was found that the aerial image collection process of the four abovementioned weeds at different altitudes could be successfully achieved with the optimum altitude being summarised in the table below.

Weed Type	Survey Altitude (m)	Pixel Size (mm)	Classification Accuracy (%)
Water hyacinth	30	7.8	90.0
Serrated tussock	20	5.2	90.7
Tropical soda apple	10	2.6	72.2
Alligator weed*	20	5.2	86.8

Table 1: Optimal Altitude Settings

*Results for Alligator weed were from previous experiment. The Alligator weed sites in this trial dod not contain sufficient numberfor the study.

4.2 Stage Two: Weed Classification

Stage One was followed by the USYD weed detection and classification software being used to establish if the weeds could be identified from the imagery collected.

The classification methodology used the collected images to evaluate the weed classifier with featured learning (algorithms) applied to generate the filter bank followed by pooling to summarise the image statistics before passing to a texton based linear classifier for the nominated weeds.

The USYD Research team achieved acceptable classification results for the four subject weed species, with Tropical Soda Apple the most difficult to classify.

Results showed that classification accuracy was highly dependent on how distinguishable the weed was from the surrounding plants. The ideal time to survey the weeds would be when they are most distinguishable from neighboring plants ie during flowering season.

It was demonstrated that image classification algorithms are able to correctly classify weeds of interest from remote sensing data collected from small UAVs.

Photo 2: The University of Sydney's Hexacopter used in the trial work.

The weed trial study established the required UAV survey altitude (and the corresponding image resolution), and the classifier window size (the size of the bounding box within an image that is used for training and testing the classifier) to achieve acceptable classification performance.

The following describes the results of the classification analysis in respect of the four nominated weeds as provided by USYD.

4.2.1 Water Hyacinth

Results showed that the classification accuracy improved with larger window sizes. This may be because water hyacinth grows in large patches at this site. A larger window size increases the area of observation, which leads to more consistent colour and texture features. This consistency in turn leads to higher classification accuracies.

Further, it was found that the accuracy did not change significantly with increasing altitude.

The algorithm was able to distinguish water hyacinth from other classes at different altitudes with F1 scores (a measure of the tests accuracy that considers both precision and recall) of greater than 90%. The main reason is that this data is amenable to classification; most of the green area was infested by water hyacinth.

Photo 3: Aerial photo of water Hyacinth

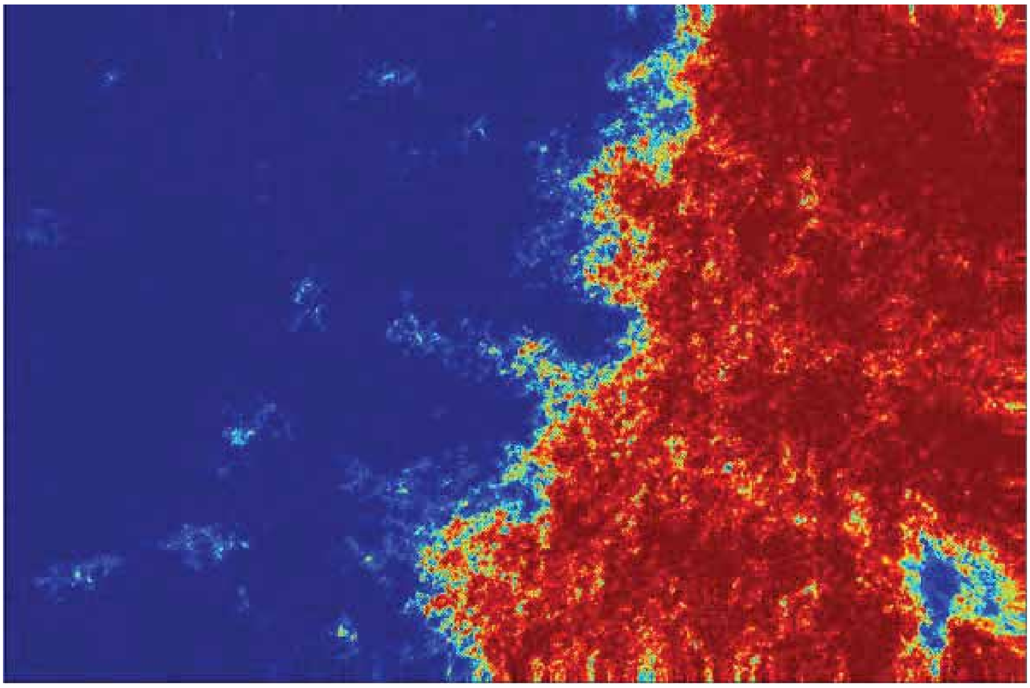


Figure 1. Algorithm prediction on water hyacinth, red indicates high probability and blue indicates low probability

4.2.2 Serrated Tussock

The classification accuracy improved with increasing window size up to the dimension that most of the serrated tussock plants can be fully observed. The classification accuracy reduced slightly with increasing altitude as fewer details of the serrated tussock plant could be resolved.

Photo 4: Aerial photo of serrated tussock

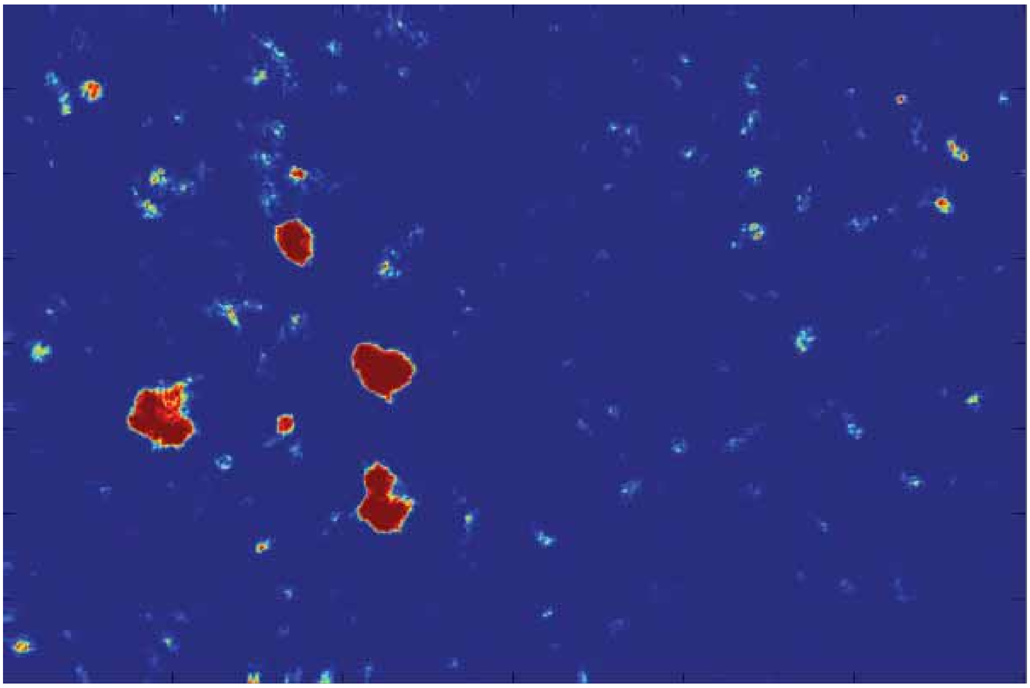


Figure 2: Algorithm prediction on serrated tussock, red indicates high probability and blue indicates low probability

4.2.3 Tropical Soda Apple

The results showed that the window size did not affect the classification performance significantly. Further, the results showed that the altitude had a significant impact on the classification accuracy; the best results were obtained at 10 metres.

Only images collected below 10 metres had enough resolution to see the prickly leaves. It was hypothesized that the ability to resolve this distinctive feature aids classification performance. It becomes increasingly difficult to resolve the distinctive leaves of the Tropical Soda Apple from above 10 metres.

The classification results showed that the classifier did not perform as well as for the other weed species. The reason was that the current feature bank is populated with mostly colour and texture filters. While these cues were useful for Water Hyacinth and Serrated Tussock, they were not enough to describe the subtle differences between Tropical Soda Apple and other plants of similar appearance.

Further developments of a specialist classifier to incorporate the extra shape information of the leaves similar to the work on flower classification can potentially improve the classifier performance.

4.2.4 Alligator Weed

The size of the dataset was too small for meaningful algorithm evaluation. It was too difficult to sample training and evaluation data without any overlaps. Additional data is required in future trials for meaningful performance assessment.

However USYD have conducted alligator weed trials previously with Victorian DPI using the same platform at Dandenong, Victoria. The previous results showed that the algorithm was able to classify alligator weed from the aerial images with 80% accuracy.

4.2.5 Conclusion

For area infestations such as Water Hyacinth, the classification algorithm is less sensitive to the altitude setting and more sensitive to the window size setting. The large window size allows a large area of observation, and the more consistent colour and texture features leads to higher classification accuracies.

For the classification of individual plants, such as Serrated Tussock and Tropical Soda Apple, both the window size and altitude settings are important. The altitude dictates the amount of detail that can be resolved in the images, which is important because certain species can appear similar without those details. It can also be important if additional features which describe the specified properties of the plants (such as leaf shape and spikes of Tropical Soda Apple) is incorporated. The windows size should be selected according to the physical size of the target plants; it should be large enough to include the entire plant but not too large to introduce noise from the neighbouring plants.

The results showed that classification accuracy depended highly on how distinguishable the weed was from its surroundings. Thus, the survey strategy is as important as the classification algorithm.

There are three strategies that can be applied to maximise the distinction between the weeds and its surroundings. The first (and potentially best) approach is to time the survey to coincide with seasonal changes that maximise the difference in appearance, for example during flowering season. Secondly the survey can be performed at lower altitudes to obtain more detail at the cost of lower coverage. The third approach is to use sensors with higher resolution to obtain the same amount of detail at higher altitudes.

One disadvantage of flying at higher altitudes is that the observations become more sensitive to the vehicle's motion. Any perturbations in the platform pose at higher altitudes will cause large displacements in the sensor's orientation and may cause motion blur. Therefore to obtain the same amount of detail at higher altitudes will require a higher resolution sensor and a more stable vehicle.

The requirements for each weed species and the expected accuracies are summarised in the table below.

It was found that the aerial image collection process of the four abovementioned weeds at different altitudes could be successfully achieved with the optimum altitude being summarised in the table below.

Weed Type	Survey Altitude (m)	Pixel Size (mm)	Classification Accuracy (%)
Water hyacinth	30	7.8	90.0
Serrated tussock	20	5.2	90.7
Tropical soda apple	10	2.6	72.2
Alligator weed*	20	5.2	86.8

Table 2: Optimal Altitude settings

*Results for Alligator Weed were from previous experiment. The Alligator Weed sites in this trial did not contain sufficient number for the study.

Note that for the classification system to work, it is critical to collect a set of image examples of the target weeds to train the classifier. In this preliminary study it was demonstrated the classifier working in a particular environmental setting. To extend this to a robust system will require additional training examples of the weed at different growth stages and from a wide variety of environmental settings (e.g images collected in different weather conditions and backgrounds).

A detailed report on the methodology and findings on the weed classifications are detailed in Appendix 5.

4.2.6 Data Analysis

In addition to collecting data with a UAV, the data must also be analysed, stored and disseminated.

The analysis of data is best suited to staff with an understanding of the theory and practice of remote sensing and/or with domain expertise in weed species. For example, these skill-sets are required in training the classification algorithm. The most likely scenario is that for automatic classification the skillsets and software developed at the USYD would be used.

Manual classification involves an expert operator to sift through the many images collected.
This would happen after data has been collected and geo-referenced. It cannot happen during flight as the algorithms required to accurately match the images to the topography for geo-referencing requires significant computational requirements. During flight manual detection can provide an overall understanding of the extent of weed activity.
The storage of data and dissemination of data products generated by the analysis is an Information Technology (IT) function that may be satisfied by skill-sets available through existing IT or system administration staff.

4.2.7 Outsourcing

There are three options available:

1. To outsource the entire operation to the USYD or like organisation who will conduct the remote sensing capture (UAV or manned), tuning/training of the algorithm, and the reporting.

2. To outsource the remote sensing operation to a third party (UAV or manned), the data collected is then provided to the USYD for automatic detection, or kept internal for manual detection.

3. To conduct the UAV trials internally and manned flights externally through the ACFR or third party. The data collected is then provided to the USYD for automatic detection, or kept internal for manual detection.

4.2.8 Integration to Mapping system/s WeedTr@cer – NSW Biosecurity Information System (BIS)

After the classification process has been completed (assuming automatic classification) data can be extracted in either paper, xml or Microsoft Excel ® format or directly to software on a computer or tablet:

a) **Paper** documentation that provides the location of weeds detected, type of weed, and classification accuracy.

b) **XML or Excel data format** that can be easily interfaced to mapping software such as WeedTr@cer (currently in operation throughout the NIWAC region) which then displays the results and is field ready.

Tr@ceR Mobile Mapping can accommodate all of the above formats however using paper documentation would not be recommended due to inefficiencies in manual processing.

From within Tr@ceR there is a “Data Import Function” that allows for importing of both XML and Excel formats, weed infestation data in point format and path travelled during the inspection process.

The data file schema requirements for import into Weeds Tr@ceR software are as follows:

FieldName - Data Type
Date/time - date/time
Weed - String (100)
Lattitude - double
Longitude - double
Classification Accuracy % - integer
Survey Altitude - integer
Project - string (100)

This information then is overlaid on the Weed Tr@ceR ® mapping screen and allows for the generation of the following:

- Notice of Entry Letters
- Inspection Recording and Inspection Letter
- Re-inspection Notices

This information can then be made readily available for reporting and data integration (compliant with NSW DPI Weeds Metadata Standard 1.0) into the NSW DPI Biosecurity Information System (BIS).

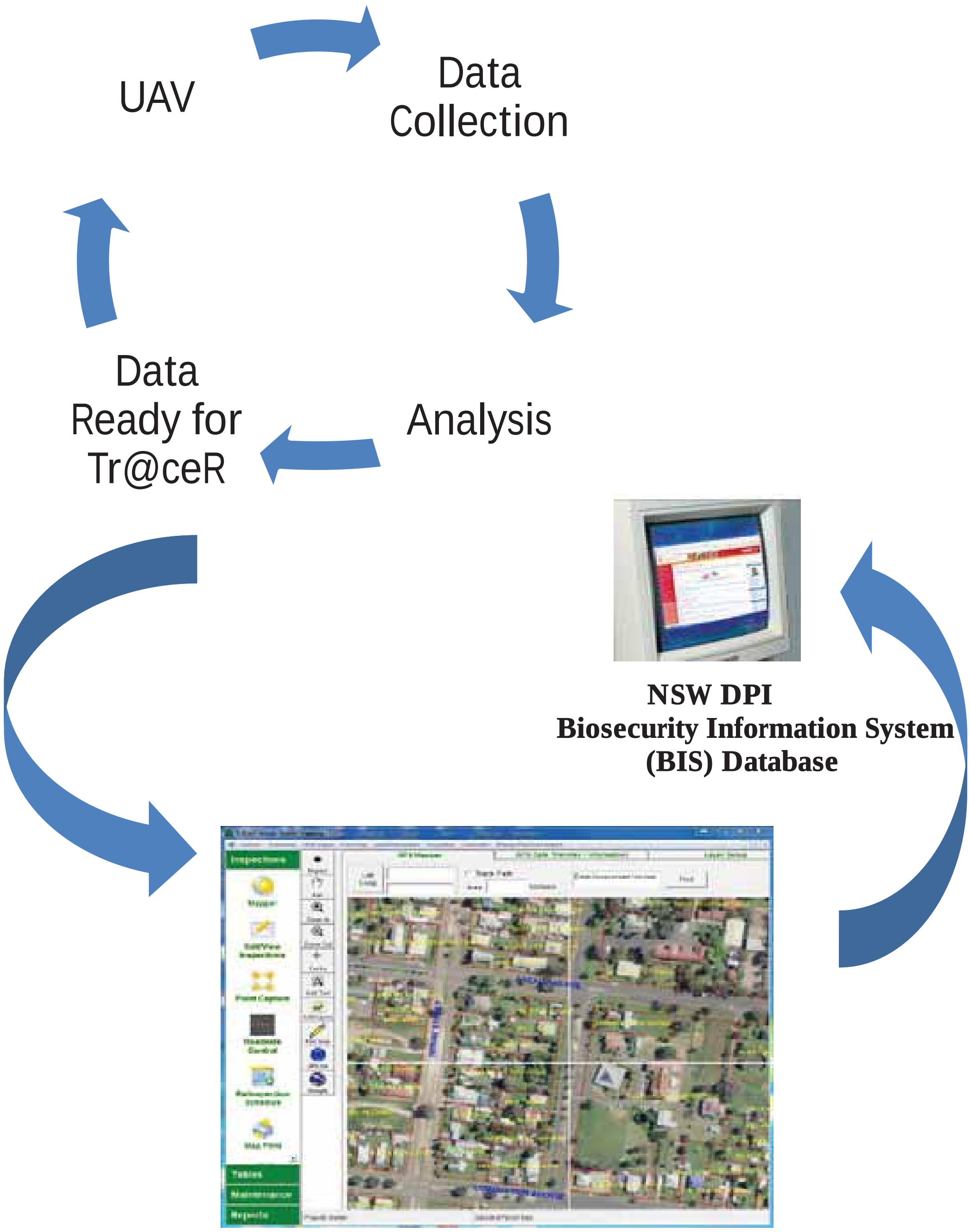


Figure 3: Integration of UAV data into Weedtr@ceR mapping system and NSW DPI'

4.3 Stage Three: Cost Benefit Analysis:

RM Consulting Group was commissioned by NIWAC to undertake an economic assessment of the use of UAVs and weed classification analysis as part of their trial of the technology.

This analysis suggests that UAVs and weed identification analysis are likely to be cost-effective tools for some components of NIWAC weed inspection activities, particularly riparian waterway inspection and to a lesser extent small block inspection. Large block inspection and high risk pathway inspection appear less cost-effective than current methods.

This analysis explores the cost-effectiveness of incorporating the technology into NIWAC's management activities in a number of ways. It is important to recognise that the technology continues to be trialled and developed, and as such a concrete understanding of its technical effectiveness and expected method of incorporation into weed management activities is not yet known.

Of value to NIWAC and the project funders at DPI is exploration of the cost-effectiveness of UAV use for various inspection functions undertaken by NIWAC, compared to the cost of the current approach to inspections. This current approach is focussed on manual inspection by NIWAC staff, who inspect properties from their vehicles and on foot.

Incorporating UAVs and weed identification analysis into NIWAC activities has the potential to reduce the cost of some of these activities, in some cases by a significant proportion.

4.3.1 Approach

RM Consulting Group first developed costing scenarios for four weed inspection activities undertaken by NIWAC, with their assistance. It was then explored how these costs would change with the incorporation of UAVs and weed identification analysis, with the assistance of NIWAC and Professor Salah Sukkarieh of the University of Sydney. The four scenarios explored were:

1. 20 hectare block inspections, which are visually inspected whilst driving around the property.
2. 250 hectare block inspections, which are also visually inspected by driving around the property.
3. Riparian waterway inspections, which are currently undertaken by vehicle and on foot and are labour intensive activities.
4. High risk pathway inspections, which are undertaken by two officers in a vehicle, where one drives and the other inspects either side of the pathway.

Two alternative scenarios were developed for UAV use:

1. Hand-held UAV use by NIWAC staff, which involves the ownership and operation of a fleet of UAVs by NIWAC, and bringing them on-site to assist with inspection activities. Data was then sent to the University of Sydney for analysis and returned to NIWAC. Where weeds are identified, staff returned to the site for confirmation.
2. A fly-over approach to UAV data collection, in which a service provider is commissioned to fly the region in advance of inspections, the data sent to the University of Sydney for analysis and returned for use in the inspection. Sites with identified weeds are inspected manually for confirmation.

4.3.2 Results

Results from the analysis are summarised in the charts below which compare the cost-effectiveness of UAVs for each scenario.

Figure 4 shows the current costs of a 20 hectare site inspection (in green) compared with the estimated costs of the inspection using hand held (blue) and fly-over (purple) UAVs. As can be seen, hand held costs are slightly more expensive and fly-over costs slightly lower.

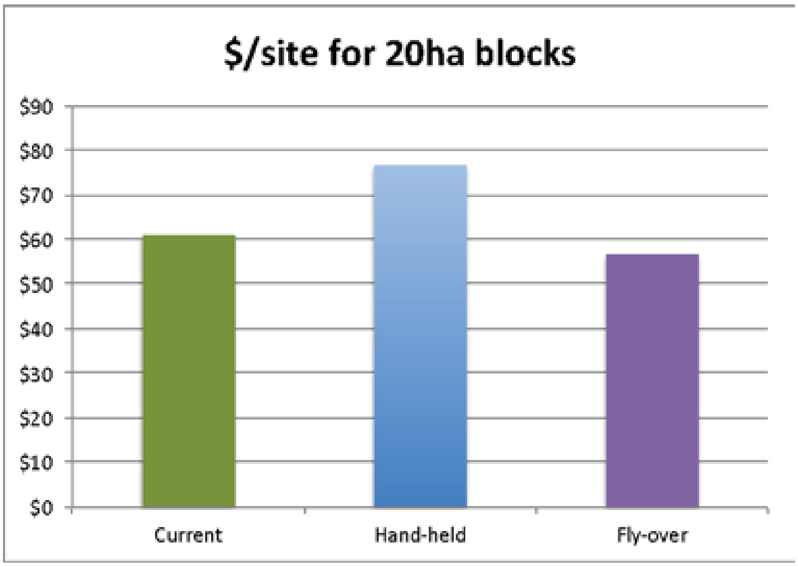


Figure 4: Cost-effectiveness assessment for 20 hectare sites

Figure 5 provides the same comparison for 250 hectare blocks. In contrast to 20 hectare blocks, the labour and vehicle cost savings for larger blocks are more than offset by the additional cost in data collection and weed identification analysis.

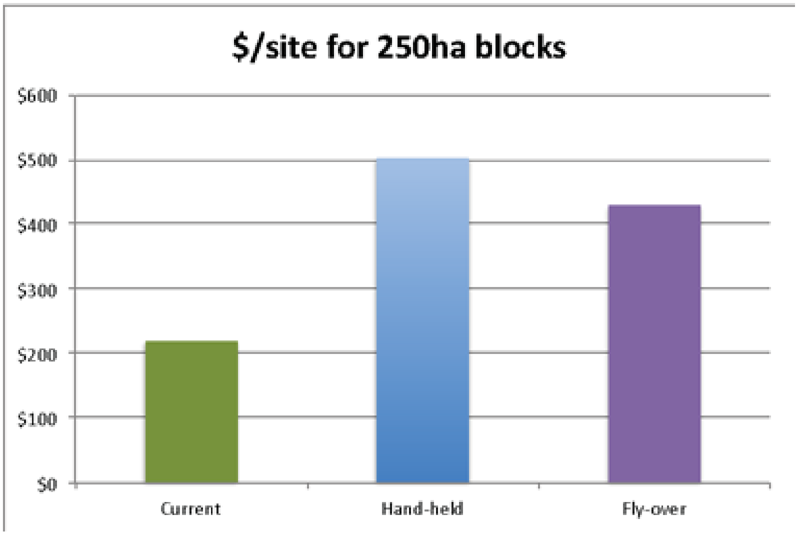


Figure 5: Cost-effectiveness assessment for 250 hectare sites

Figure 6 summarises the results of riparian waterway inspections, which suggest that the incorporation of UAV technology would be highly cost-effective. This is especially so for a fly-over approach, which in addition to significant labour cost savings from reduced manual inspection, has the added benefit of delimiting the inspection area by identifying which tributaries are affected and where the source of the infestation begins. This approach is estimated at less than 50 per cent of current inspection costs.

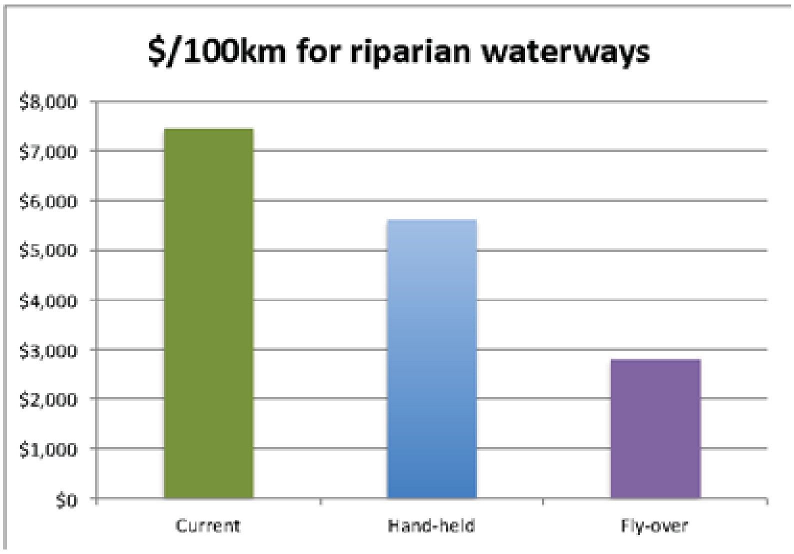


Figure 6: Cost-effectiveness assessment for riparian waterways

Figure 7 summarises the cost-effectiveness of different methods of high risk pathway assessment, using the example of a fire trail.[2] This scenario may not lend itself as well to hand held UAV use, as it does not reduce labour costs and has added data collection and weed identification costs. A fly-over approach is cost-comparable with current inspection methods.

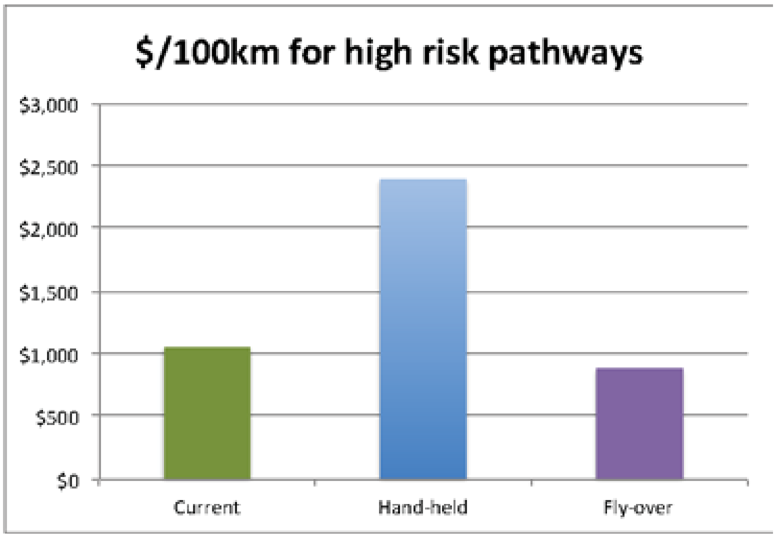


Figure 7: Cost-effectiveness assessment for high risk pathways

[2] Some high risk pathways may not be accessible to UAVs, such as highways that have a no-fly zone around them.

4.3.3 Discussion and Summary

This analysis shows that UAVs have the potential to be cost-effectively employed by weed management agencies for a variety of inspection activities. Some uses appear more favourable than others. Riparian waterway inspections appear particularly cost-effective compared to current methods.

The analysis also suggests that a fly-over approach may be more cost-effective than a hand-held approach to incorporating UAVs, in that they reduce labour and vehicle costs more significantly than the hand-held approach.

Importantly, the analysis rests on a number of assumptions relating to data collection costs and weed identification analysis that cannot be known with greater certainty at this stage, as commercial arrangements are in their infancy or not yet in existence. The feasibility of UAVs depends significantly on these future costs.

The detailed report on the cost-effectiveness and findings of the use of UAVs in weed management are detailed in Appendix 6.

5. OPERATIONAL REQUIREMENTS, TECHNICAL AND LEGAL IMPLICATIONS OF USING UAVS[3]

5.1 Operational Requirements – Deployment Methods

There are two principle mechanisms for deploying the technology demonstrated in this project:

- In-house operations – where the remote sensing data capture and reporting is undertaken within the organisation.
- Outsourcing – where the whole operation, or parts of the operation, are outsourced.

In either case there is also the option of conducting manned flights for the remote sensing capture. In many cases UAVs cannot be deployed due to regulation issues and operational constraints. In these situations manned remote sensing flights can be conducted and the data fed to the software system. There are a number of aerial remote sensing companies with high-resolution image capture that could be deployed for the purposes of a regional weed inspection program.

Refer to Appendix 7 for further information on UAV Platforms.

i) In-house Operations

In-house operations involve the registration for UAV operations and the process by which the data captured is then used for weed detection. This detection can happen manually or through the algorithms developed at the USYD.

[3] Final Report – Milestone 4 Low Altitude Aerial Images – Weed Classification
Zhe Xu, Calvin Hung and Salah Sukkarieh

ii) UAV Operations

The skill-sets required for such an operation can be divided into those required for UAV operations and those required for the subsequent data analysis.

UAV operations can be structured to utilise two or more team members with complementary skill-sets:

- A pilot, responsible for safe operation of the vehicle. The pilot is likely to have airmanship skills developed through training and/or previous experience flying UAVs professionally or flying radio-control aircraft. The pilot will need to be aware of and comply with relevant regulations of the Civil Aviation Safety Authority (CASA) and procedures set out in the organisation's Operator's Certificate.

- The pilot will also have an appropriate level of knowledge of UAV sub-systems specific to the vehicle(s) being operated, which can be acquired through training by the UAV manufacturer or a UAV training organisation.

- An operator, responsible for directing the UAV and its payload to achieve mission objectives. While the operator does not fly the UAV directly, the operator will also need to be aware of and comply with relevant regulations and procedures set out in the organisation's Operator's Certificate. The operator will need to understand and be able to operate UAV sub- systems and the sensor payload, which can be acquired through training by the UAV manufacturer or a UAV training organisation. In addition, the operator should understand the theory and practice of remote sensing – how to collect data so as to support subsequent analysis – and domain expertise in weed species.

Finally, UAV operations need to be supported by maintenance carried out by appropriately trained staff. It should be noted that one individual may fill more than one of these roles.

If the type of UAV being operated requires regulatory oversight, staff shall hold appropriate certification. The organisation will additionally need to nominate a Chief Remote Pilot and a Maintenance Controller.

In many cases UAVs may not be an option, due to regulation issues and operational constraints. In these situations manned remote sensing flights could be conducted and the data fed to the software system developed by ACFR.. There are a number of aerial remote sensing companies with high-resolution image capture that could be deployed for the purposes of aerial surveillance.

The key advantage of the Small class of UAV (100g to 2kg weight range) is that regulatory oversight is more relaxed than other classes, subject to certain conditions. These conditions include:

- Visual line of sight operations, in accordance to the definition outlined in the Notice of Proposed Rule Making (NPRM).
- At or below an altitude of 400' above the ground or water
- Over non-populous areas
- More than 30m away from any person not directly involved in the operations
- Day visual meteorological conditions
- Outside controlled airspace
- Outside prohibited, restricted and danger areas
- Greater than 3NM from an aerodrome boundary.

Further information regarding CASA regulations can be found in Appendix 8.

6. CONCLUSION

This innovative study, an Australian first, has found that the use of UAVs and image classification algorithms to accurately detect weeds in a rural landscape could be employed cost effectively as part of regional inspection programs.

With further development to operationalise the technology, the study suggests that UAVs could play an important role in early detection of outbreaks of high-risk new and emerging weeds, to complement existing field inspection methods.

Where a rapid response is required for a new incursion, the small hand held UAV has potential to reduce the time required to locate the spread of the incursion and subsequent treatment of the area.

In looking to the future, there may be opportunity to build on these findings to explore the merits of applying the technology at multiple scales:

a) A Local Land Services (LLS) regional fly over capturing data for multiple uses by a number of organisations – eg farm management, feral animals and weed management.

b) A fly over on a sub-regional scale, similar to (a) but on a smaller scale.

c) A fly over of riparian areas in an LLS region.

Photo 4: The Macleay Valley, site used for the Tropical Soda Apple aerial imagery collection.

APPENDIX 1: PROJECT TASKS & BUDGET ESTIMATES

NIWAC Integrated Aerial Surveillance, Thermal Imaging and Mapping Pilot Project

	Project Budget Schedule : Measurable Outcomes and Yearly Targets								
						Totals			
ISP Objectives mandatory	Measurable Outcomes	yrs	Year 1 Agency	Year 1 Project	Year 2 Agency	Year 2 Project	Agency funds	Project funds	Overall Program TOTAL
1.2 develop and implement early detection capabilities	Feasibility Study outlining recommendations on the integration of unmanned aerial vehicels, thermal imaging and mapping in the NIWAC region	1	$20,000	$95,000			$20,000	$95,000	$115,000
	Cost Benefit analysis of the implementation of the recommendations of the feasibility study (above) within the NIWAC region	2				$55,000		$55,000	$55,000
	Report to NSW DPI on results of Pilot Project	2					$10,000	$0	$10,000
4.7 Improve Konwledge base for invasive species management	More inspection/surveillance methods available.	2			$8,000	$8,000	$8,000	$8,000	$16,000
	strengthen research by encouraging co-operative partnerships	1	$3,000	$10,000			$3,000	$10,000	$13,000
	Better understanding of new technologies for weed inspection and mapping	1	$3,000	$8,000			$3,000	$8,000	$11,000
			Year 1 Agency	Year 1 Project	Year 2 Agency	Year 2 Project	Agency funds	Project funds	Overall Program TOTAL
TOTALS			$26,000	$113,000	$8,000	$63,000	$44,000	$176,000	$220,000

APPENDIX 2: WORKSHOP IN ARMIDALE

A workshop was held on Tuesday 10th June 2014 to update participants on the unmanned aerial vehicle technology and weed detection.

Over 40 delegates attended the workshop, including members of the Noxious Weeds Advisory Committee (NWAC), NSW Department of Primary Industries, Northern Inland Weeds Advisory Committee, University of Sydney, and RM Consulting Group.

Guest Speakers included Wayne Deer and Josh Biddle from the New England Weeds Authority, and Professor Salah Sukkarieh from the University of Sydney.

Dr Calvin Hung and Dr Zhe Zu demonstrated the UAV technology on a local serrated tussock field site.

Northern Inland Weeds Advisory Committee
Integrated Aerial Surveillance Innovative Project
Workshop

The Northern Inland Weeds Advisory Committee (NIWAC)
in association with the
NSW Department of Primary Industries

Invites you to a field day and information session on our project -

Unmanned Aerial Vehicle Technology & Weed Detection

Moore Park Inn
63 Moore Park Lane, Uralla Road, Armidale

Tuesday 10th June 2014 – 9.00 am to 2 pm
Lunch provided.

Please RSVP for catering purposes to Heather – happs@newa.nsw.gov.au
by Wednesday 4th June 2014.

Program of activities:

9.00 am	Morning tea on arrival
9:30 am	Welcome to delegates by Chair of NIWAC – Clr Maria Woods
	Introduction to the NIWAC Innovative Project Wayne Deer and Josh Biddle
10:00 am	Travel to field site – UAV field demonstration – Serrated Tussock

Participants in the June 2014 Workshop

Below are the television interviews that featured the workshop:
http://au.prime7.yahoo.com/n2/news/a/-/local/24206554/fighting-weeds-from-above-video/

and
http://www.nbnnews.com.au/index.php/2014/06/10/new-technology-to-be-used-in-pilot-weed-detection-program/

APPENDIX 3: PROJECT WORKPLAN SUMMARY

ISP Objectives	Measurable Outcomes	Activities	Overall target # 2yrs	Yr 1 target	Budget Agency	Budget Project	Project Team	Est # work days	Stakeholders/Partners	Est # work days	Timeline	Status
												Completed
1.2 Develop and implement early detection capabilities	**Feasibility study outlining recommendations on the integration of unmanned aerial vehicles, thermal imaging and mapping in NIWAC region**	Form a Project Management Team from all key participating stakeholders with regular meetings	1	1	**$20,000**	**$95,000**	Establish Project Management Team. Meetings to discuss requirements of feasibility study.		Input to and participate in working groups	6	1 July 2013	Completed
		Prepare Project Management Plan and specification	1	1			Project Management Plan circulated for addition/comment. Draft Workplan and timeline circulated	5	Add technical advise to Project Management Plan	6	Aug – Nov 2013	Completed
		Engage partners with expertise in UAVs, thermal imaging and mapping systems	1	1			Meeting preparation with key stakeholders	10	Technical input	3	1 July 2013	Completed
		Prepare Feasibility Study with recommendations	1	1			Feasibility Study trial sites, Landowner Agreements, logistics set up	10	Technical input	5	Nov-13	Completed
							Trials commence on 4 trial sites	10	Completing trials	5	Feb-14	Completed
							Weed Officer inspections completed for feasibility study		Weed Officer inspections	7	Mar-14	Completed
							Information collated for feasibility study	20	Technical input to feasibility study	5	April - May 2014	Completed
		Press releases and articles developed to promote the pilot program and outline key highlights	1	5			Press releases circulated	3			June 2014	Completed
YEAR 2	**Cost benefit analysis in the implementation of the recommendations of the Feasibility Staudy within the NIWAC region**	Form Project Team to prepare terms of reference for Cost Benefit Analysis	1	**YEAR 2**		**$55,000**	Establish Project Management Team. Meetings to discuss requirements of Cost Benefit Analysis and Terms of reference	5	Input to and participate in working groups.	2	Year 2	Completed
		Terms of Reference for Cost Benefit Analysis prepared	1	**YEAR 2**			Terms of Reference developed	2	input to Terms of Reference	1	Year 2	Completed
		Engage professional organisation to carry out a Cost Benefit Analysis	1	**YEAR 2**			Professional group engaged	2			Year 2	Completed
		Cost Benefit Analysis with recommendations prepared.	1	**YEAR 2**			Assistance given to professional organisation	10	Technical assistance to professional organisation	3	Year 2	Completed
YEAR 2	**Report to NSW DPI on results of Pilot Project**	Consult with NSW DPI on outcomes of the Feasibility Syudy and Cost Benefit Analysis	1	**YEAR 2**			Meetings with DPI	3	Input to and participate in working groups.	2	Year 2	Completed
		Final report on Feasibility Study and Cost Benefit Analysis referred to NSW DPI.	1	**YEAR 2**			Information collated for NSW DPI	8	Technical input	3	Year 2	Completed
4.7 Improve knowledge base for invasive species management	**More inspection/surveillance methods available**	Workshop presentation to Weed Officers at various stages of the project	8	**8**		**$8,000**	Information presented at Weed Officer meetings and NIWAC meetings				Year 1	Completed

APPENDIX 3: PROJECT WORKPLAN CONT'D

ISP Objectives	Measurable Outcomes	Activities	Overall target # 2yrs	Yr 1 target	Budget Agency	Budget Project	Project Team	Est # work days	Stakeholders /Partners	Est # work days	Timeline	Status
		Workshops on outcomes of the feasibility Study and Cost Benefit Analysis	4	YEAR 2			Organise and participate in workshops	6			Year 2	Completed
												Completed
	Strengthen research by encouraging co-operative	Project Management Team to include representatives of partnering Universities and other stakeholder organisations.	4	4	**$3,000**	**$10,000**	Liaise with Stakeholders	10			Ongoing	Completed
		Liaise with adjoining Regional Weeds Advisory Committee for input to the Pilot Project	3				Contact RWAC for input into project	4			Ongoing	Completed
	Better understanding of new technolgies for weed inspection and mapping	Presentations in relation to the outcomes of the Pilot projects to all relevant stakeholders	10	**YEAR 2**	**$3,000**	**$8,000**	Organise presentations on outcomes of the project	5	participate in presentations	10	Year 2	Completed

APPENDIX 4: - STAGE ONE - LOW ALTITUDE AERIAL IMAGE COLLECTION

Study Report - March 2014

Project Title:
Low Altitude Aerial Images – Data Collection

University of Sydney Reference:
12942

Item:
Study Report

Prepared for:
Northern Inlands Weeds Advisory Committee

Authors:
Calvin Hung and Salah Sukkarieh

Date:
22 March 2014

1 Document Purpose

This document outlines the preliminary study on weed detection using low altitude aerial images. This report focuses on the data collection stage.

2 Overview

Field trials were performed at four different sites in New South Wales to collected aerial images of different weed species using a hexacopter. The weed species surveyed were:

1. Water hyacinth at Moree (Section 4.1)
2. Serrated tussock at Armidale (Section 4.2)
3. Tropical soda apple near Armidale (Section 4.3)
4. Alligator weed at Girvan (Section 4.4)

The overall objective of this study is to investigate the accuracy of the classification algorithm on different weed species at different altitude settings (5, 10, 20 and 30+ metres) to determine the optimal settings for future data collection operations.

The methodology is presented in Section 3, followed by results and discussions in Section 0, and the conclusion is presented in Section 5.

3 Methodology

The methodology can be divided into two stages, data collection and data pre-processing. In the data collection, we used a hexacopter with a camera to take images. In the image pre-processing stage, the images are divided into different groups according to their altitude settings.

3.1 Data Collection

The hexacopter used for data collection is shown in Figure 1. The vehicle was equipped with a downward pointing camera for data collection. The technical specification of the vehicle and camera are summarised in Table 1 and Table 2.

Figure 1: The hexacopter used in data collection. The camera is mounted under the vehicle.

Make, Model	Mikrokopter Hexacopter
Gross weight	1.5 kg
Dimensions	80cm x 80cm
Endurance	6 minutes
Typical speed	1.0 m/s
Typical operating altitude	20 m
Typical Range	< 100m

Table 1: UAV technical characteristics

Make, model	Sony NEX 7
Resolution	6000 x 4000 pixels
Lens	16 mm f2.8
Angular field of view	76 x 55 deg.
Typical foot-print size	30 x 20 m
Typical spatial resolution	5 mm/pixel

Table 2: Camera specifications

3.2 Data Pre-processing

The aim of this stage is to group images by their altitudes. The GPS altitude estimate is known to have low accuracy (±23 metres) due to the geometry of the satellite configuration. Instead of using the inaccurate GPS estimates, in this study we laid down checker boards of know dimension (1×1 metres) and used them in combination with the known camera parameters to estimate the altitude. For example, a checker board with 750 pixels indicated the image was taken at 5.1 metres altitude (shown in Figure 2).

Figure 2: Estimating the flight altitude using a checker board

Some of the images did not have any checker boards in view. We made an assumption that the altitude of the hexacopter did not change dramatically between each observation and then used first order interpolation to fill the missing altitudes. An example is shown in Table 3.

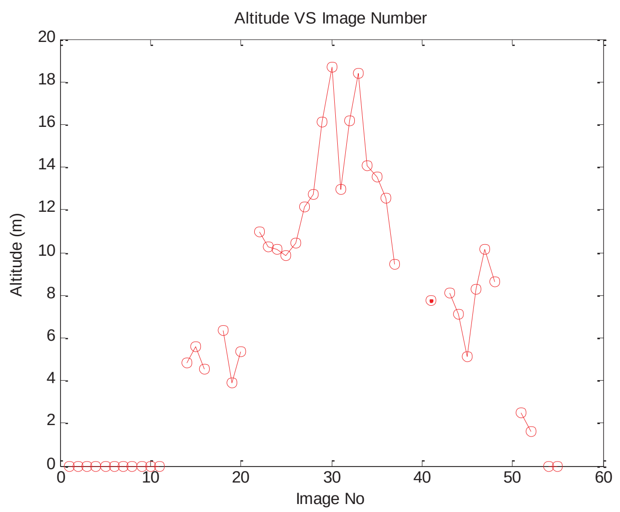
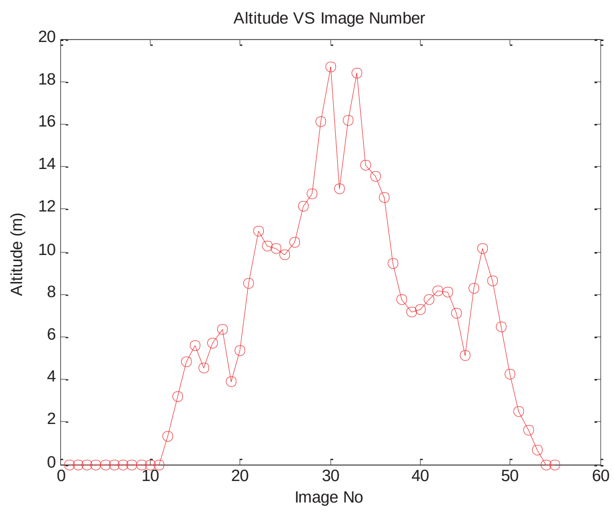
Altitude estimation based on checker board dimension	Altitude estimation after smoothing
	

Table 3 Filling the missing altitude using interpolation

4

With an altitude estimate per image, the images were then grouped into different altitude brackets for further analysis and are shown in Table 4. We have also hand selected image patches containing weed and others at different altitude for classification analysis. Different patch sizes were used for different altitude settings (Table 4) to make sure each patch contains enough detail of the weed and at the same time is not dominated by the background. An example of weed and non-weed patches is shown in Table 5.

Altitude Range (m)	Patch Dimension (pixels)
0-5	256
5-10	128
10-20	128
20-30	64
30+	64

Table 4: Altitude brackets and the corresponding patch dimension used for classification.

Table 5: Example patches of weeds (water hyacinth shown here) and non-weeds.

4 Results and Discussions

4.1 Water Hyacinth

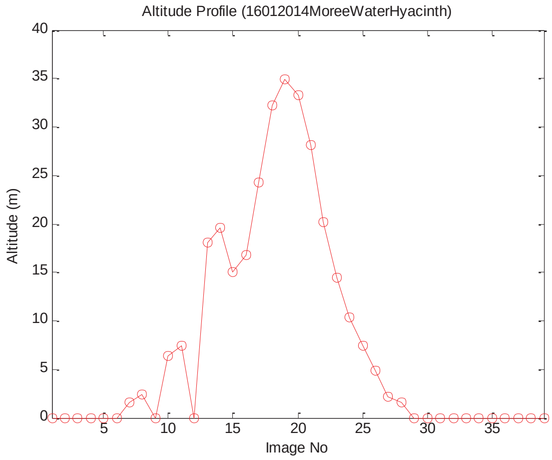
The overview of the water hyacinth site at Moree (29º 14’ 33.647”S 149º 17’ 51.552”E) is shown in **Figure 3**. An example frame and the close-up view are shown in Figure 4. The altitude profile of the flights is shown in Table 6. The examples of positive and negative training patches at different altitude settings are shown in Table 7.

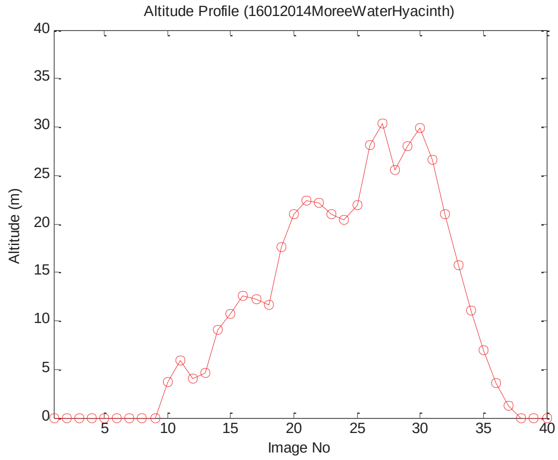
Figure 3: Mosaic picture of the images collected at Moree water hyacinth site.

Original Image

Close-up View

Figure 4: An example aerial image of water hyacinth collected at Moree.





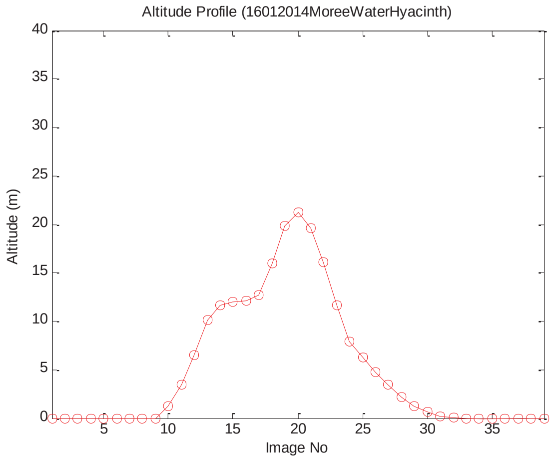
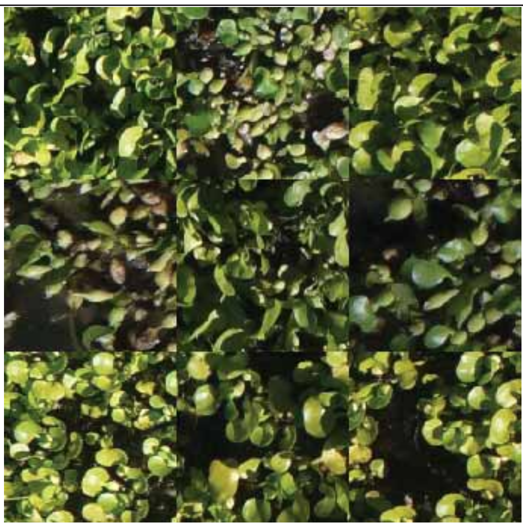
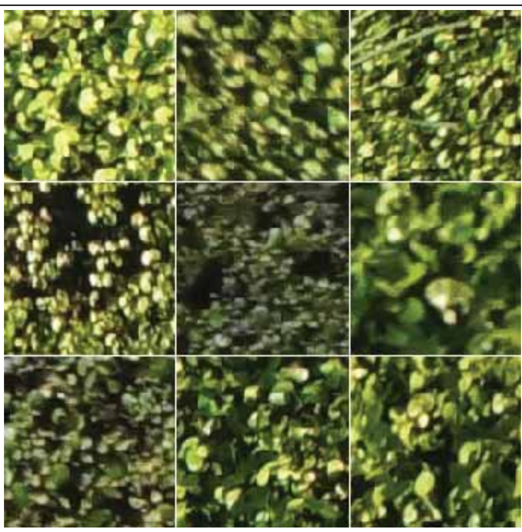
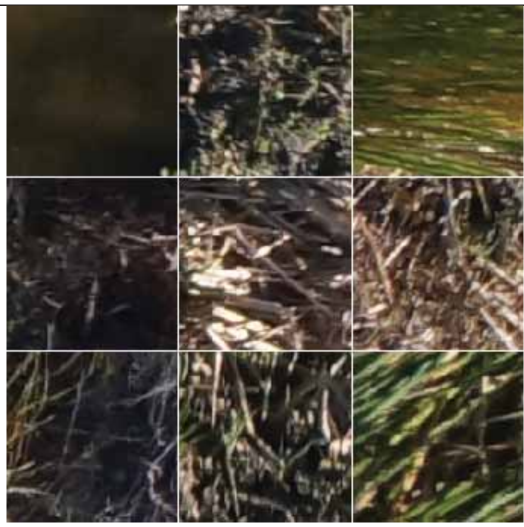


Table 6: Altitude profile of the water hyacinth surveys

Altitude Range	Weed Examples	Non-Weed Examples
0-5		
5-10		
10-20		

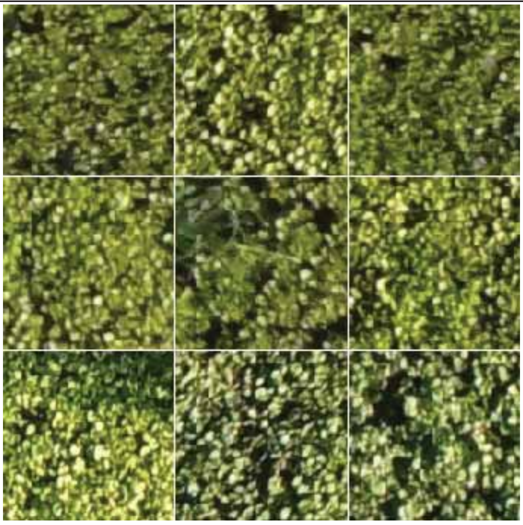
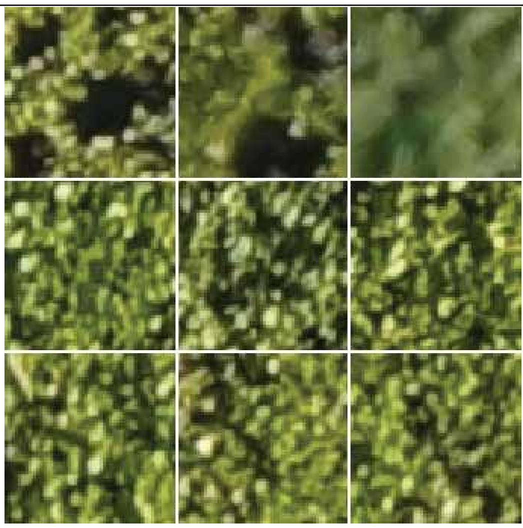
20-30		
30+		

Table 7 Example of water hyacinth at different altitude settings

4.2 Serrated Tussock

The overview of the serrated tussock site at Armidale (30º 36' 44.881"S 151º 42' 2.845"E) is shown in Figure 5. An example frame and the close-up view are shown in Figure 6. The altitude profile of the flights is shown in Table 8. The examples of positive and negative training patches at different altitude settings are shown in Table 9.

Figure 5: Mosaic picture of the images collected at Armidale serrated tussock site.

Original Image

Close-up View

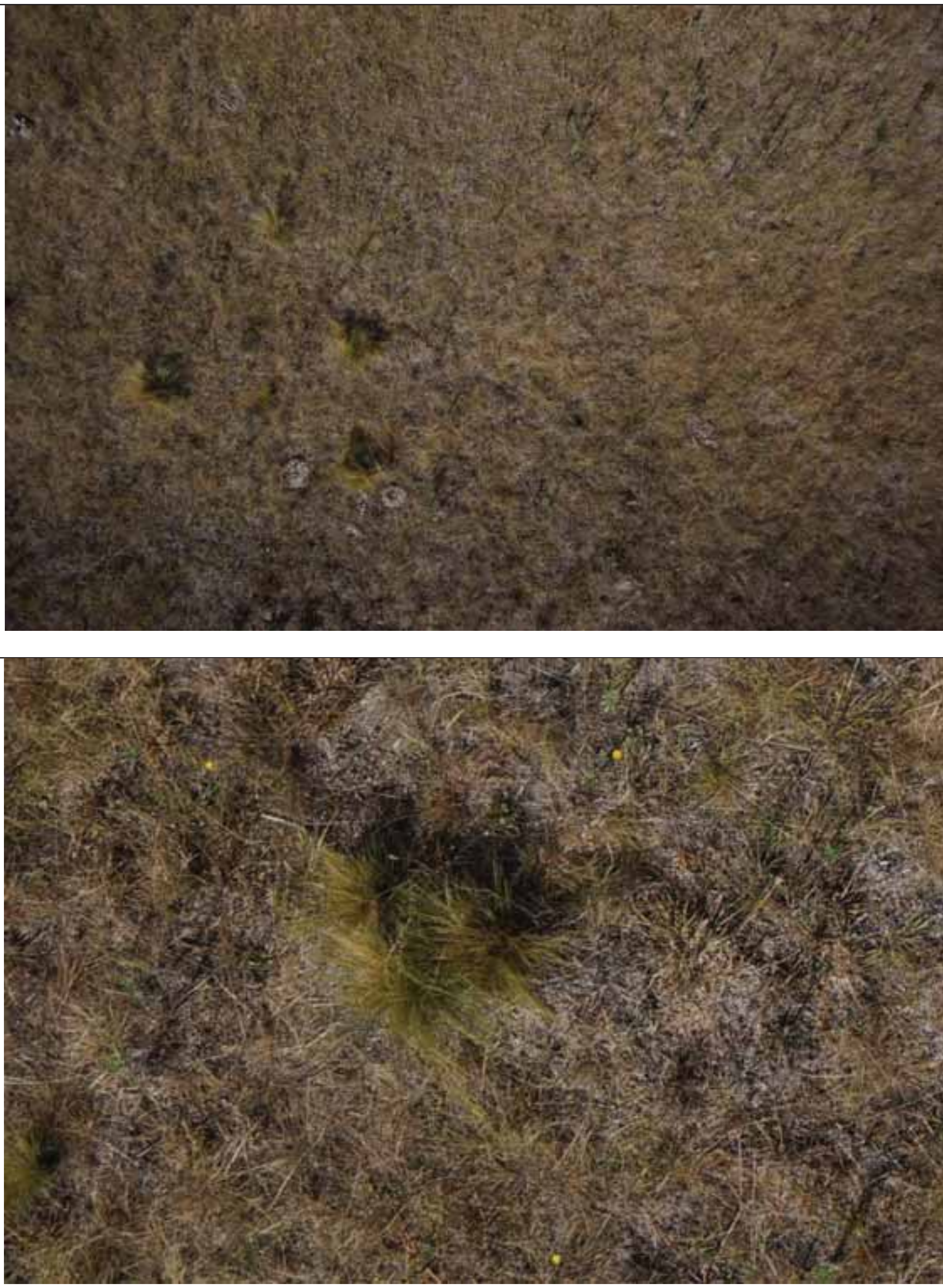


Figure 6: An example aerial image of serrated tussock collected at Armidale.

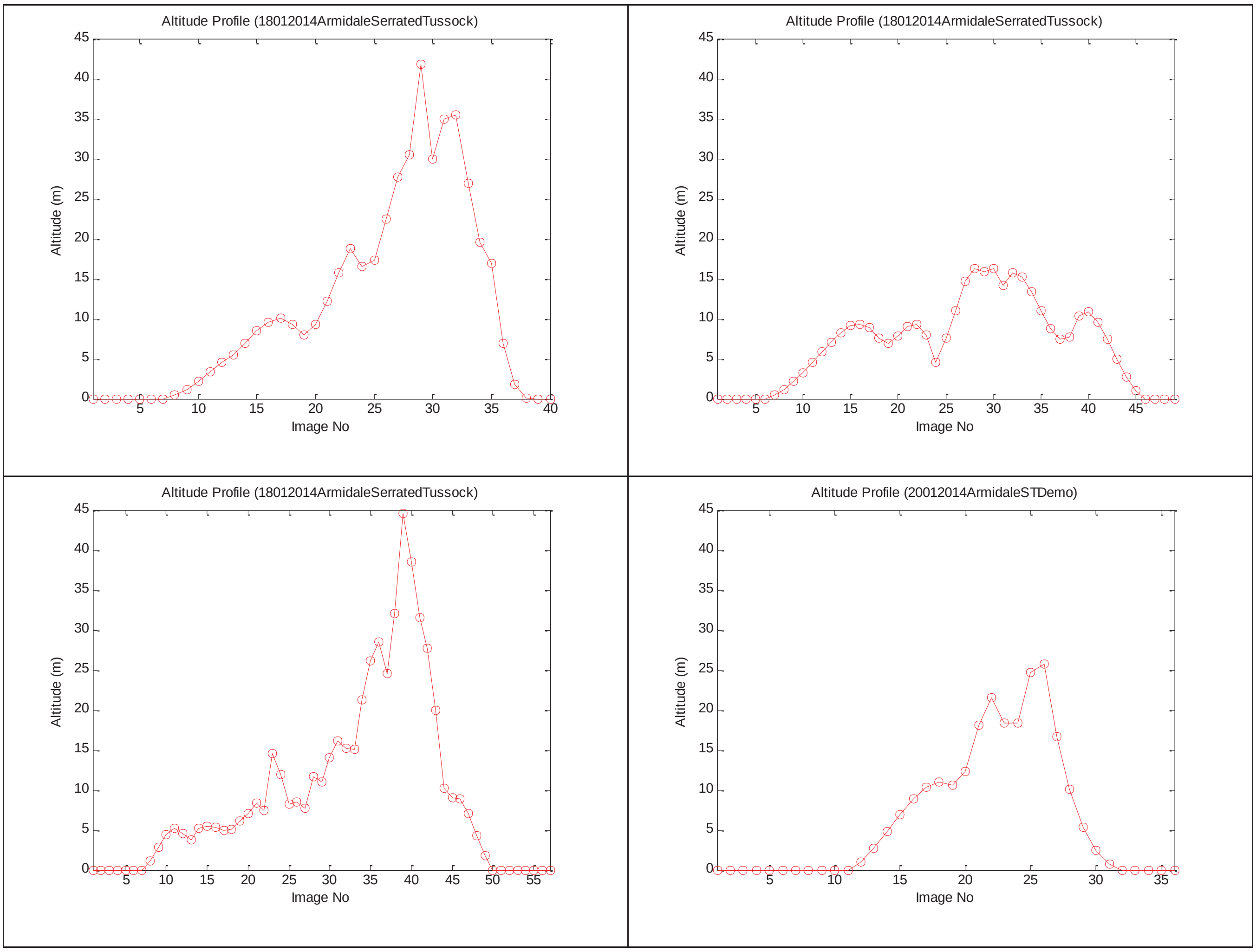
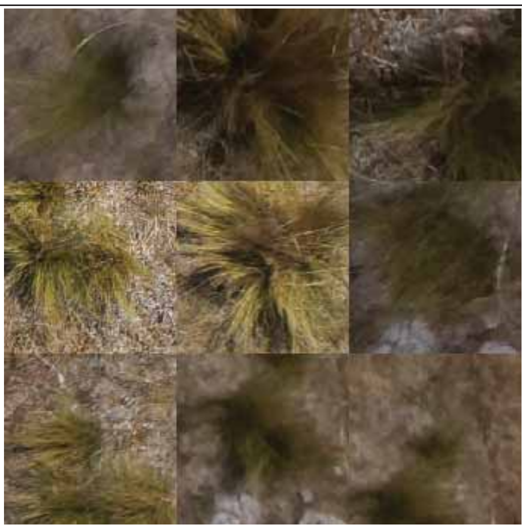
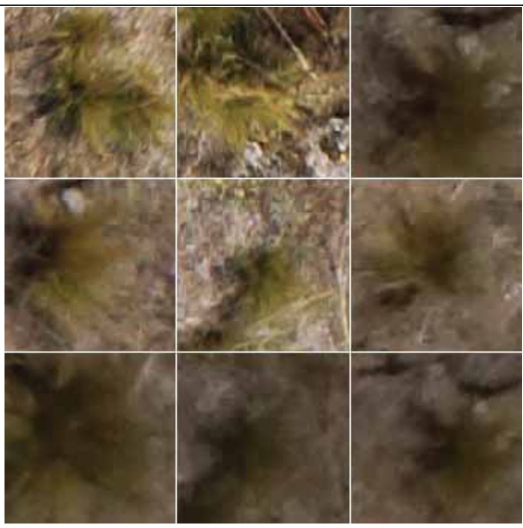


Table 8: Altitude profile of the serrated tussock surveys

Altitude Range	Weed Examples	Non-Weed Examples
0-5		
5-10		
10-20		

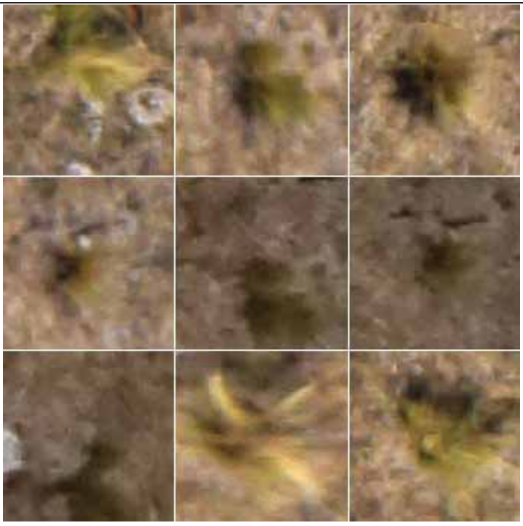
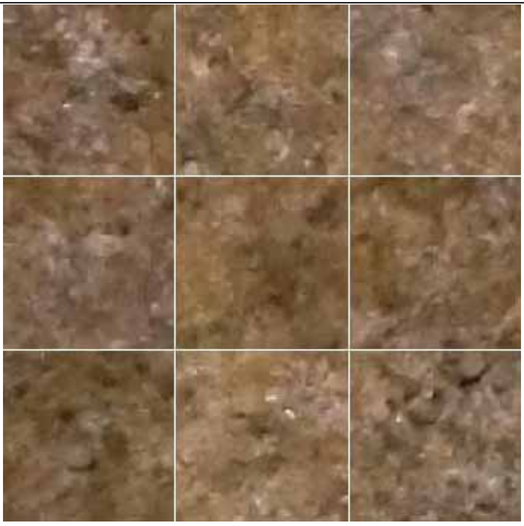
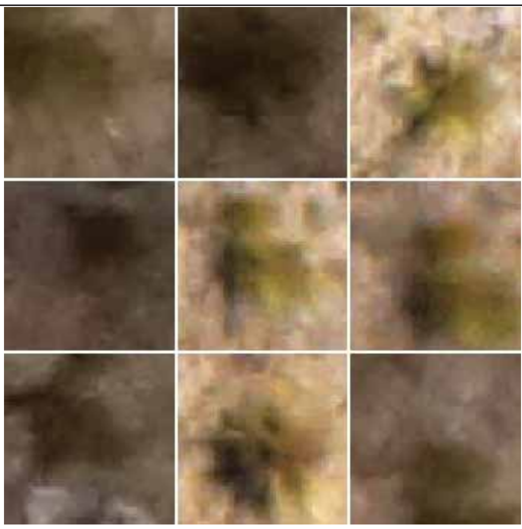
20-30		
30+		

Table 9 Example of serrated tussock at different altitude settings

4.3 Tropical Soda Apple

The overview of one of the tropical soda apple sites near Armidale (30º 45’ 50.434”S 152º 20’ 25.250”E) is shown in Figure 7. An example frame and the close-up view are shown in Figure 8. The altitude profile of the flights is shown in Table 10. The examples of positive and negative training patches at different altitude settings are shown in Table 11.

Figure 7: Mosaic picture of the images collected near Armidale at the tropical soda apple site.

Original Image

Close-up View

Figure 8: An example aerial image of tropical soda apple collected near Armidale. Two flights were performed at this site. In the second flight the tropical soda apple plants were labelled with orange markers by the weed officers for ground truthing.

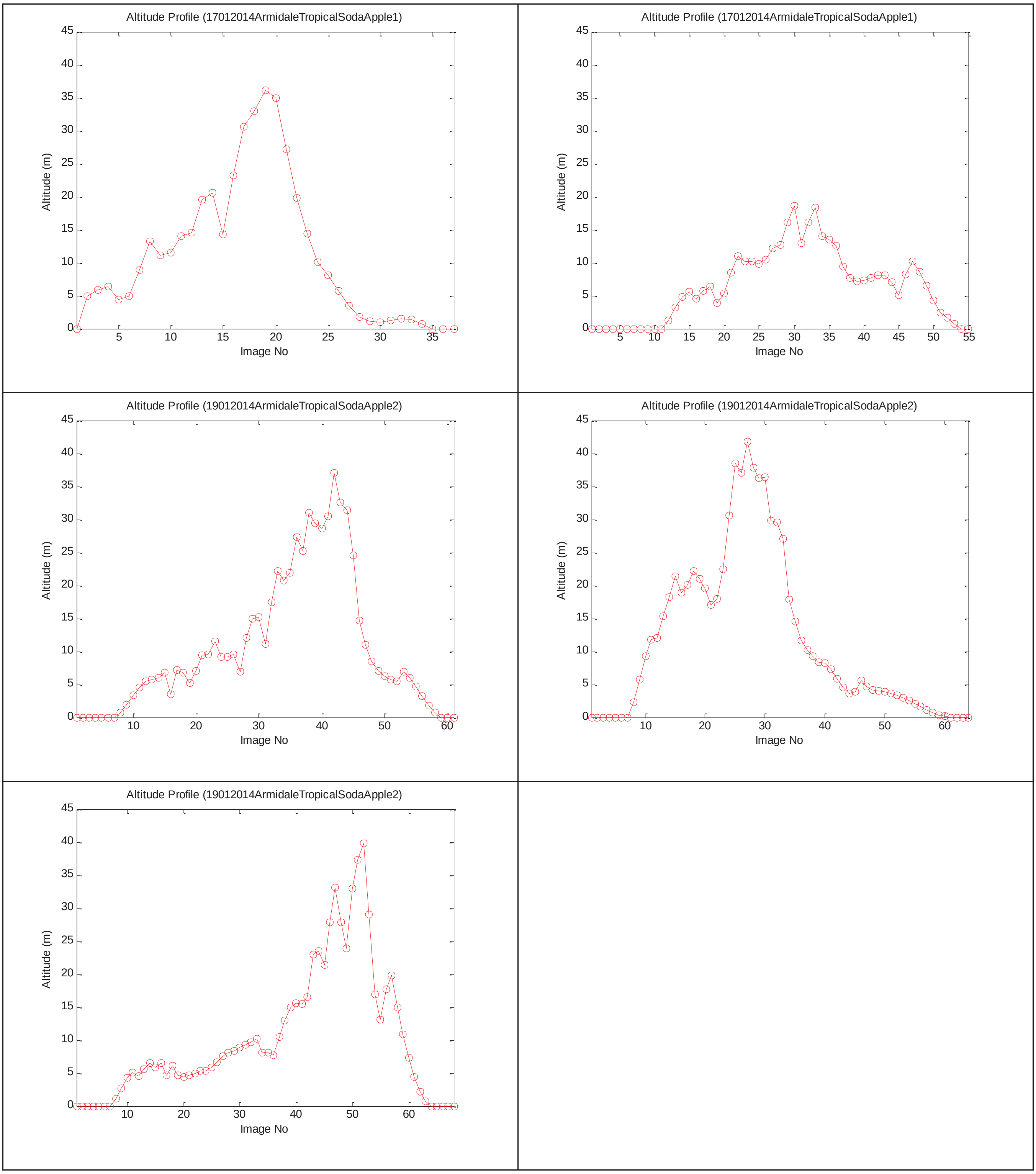
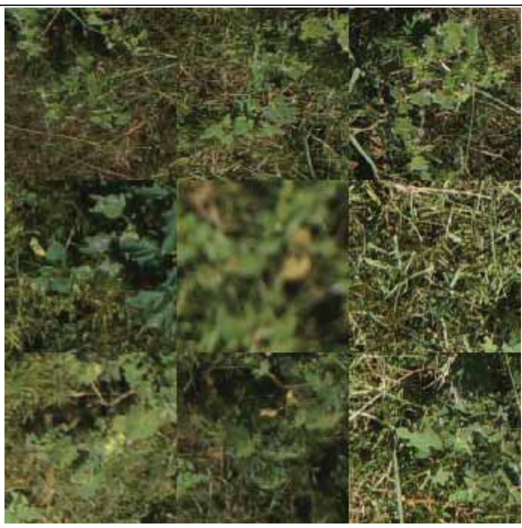
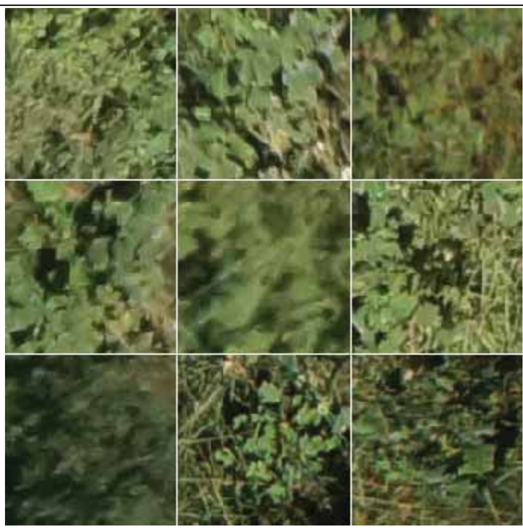
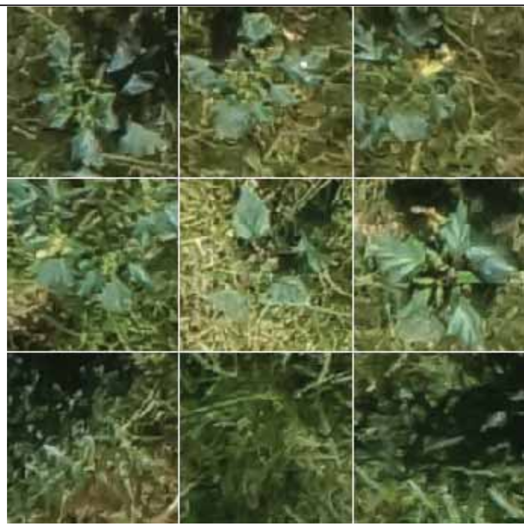


Table 10: Altitude profile of the tropical soda apple surveys

Altitude Range	Weed Examples	Non-Weed Examples
0-5		
5-10		
10-20		

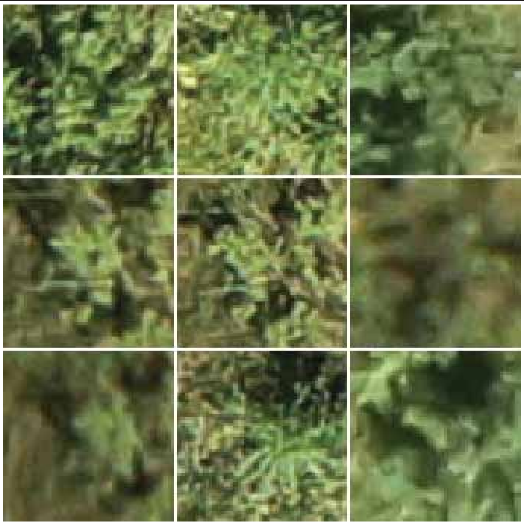
20-30		
30+		

Table 11 Example of tropical soda apple at different altitude settings

4.4 Alligator Weed

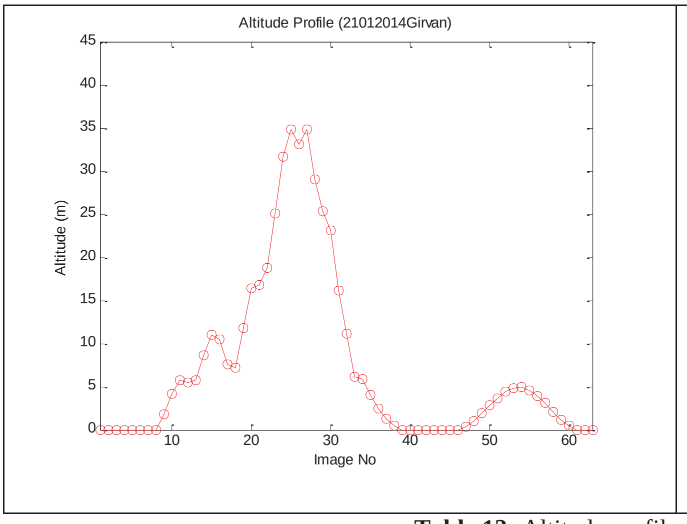
The overview of one of the alligator weed site at Girvan (32º 28' 14.106"S 152º 03' 30.608"E) is shown in Figure 9. An example frame and the close-up view are shown in Figure 10. The altitude profile of the flights is shown in Table 12. The examples of positive and negative training patches at different altitude settings are shown in Table 13.

Figure 9: Mosaic picture of the images collected at Girvan alligator weed site.

Original Image

Close-up View

Figure 10: An example aerial image of the alligator weed collected at Girvan.



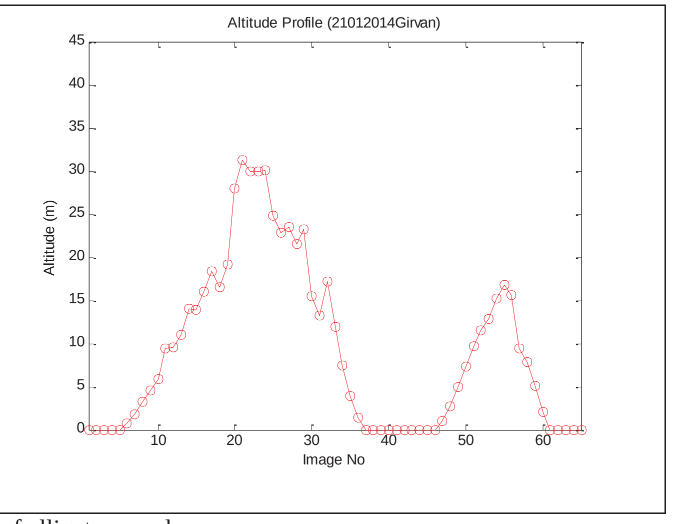
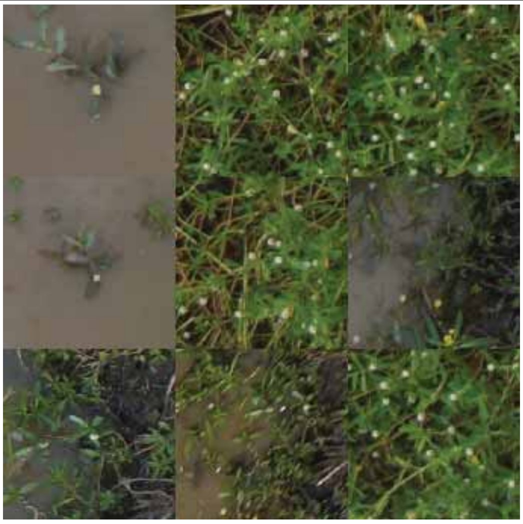
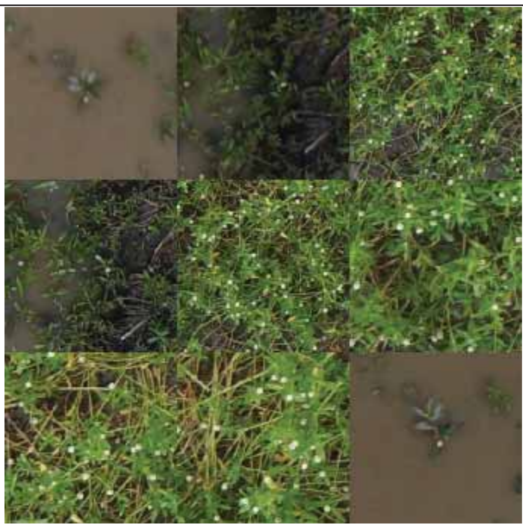
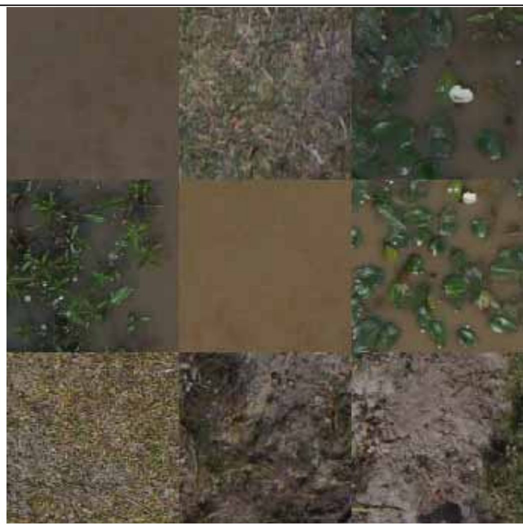
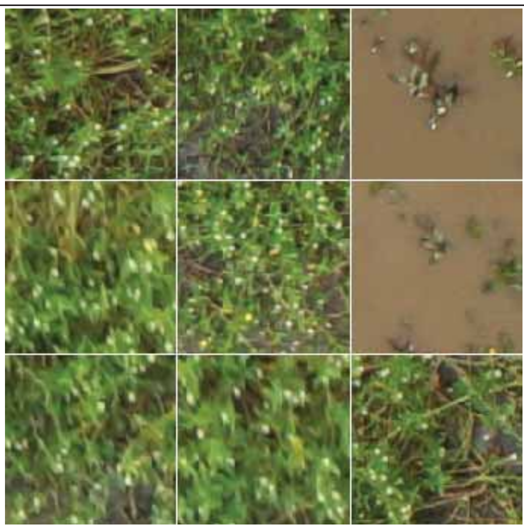
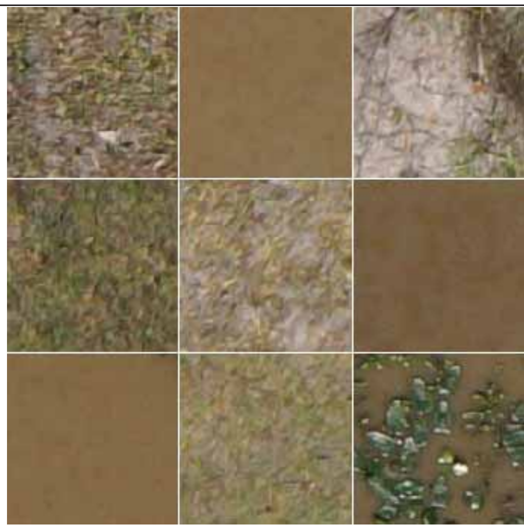


Table 12: Altitude profile of alligator weed surveys

Altitude Range	Weed Examples	Non-Weed Examples
0-5		
5-10		
10-20		

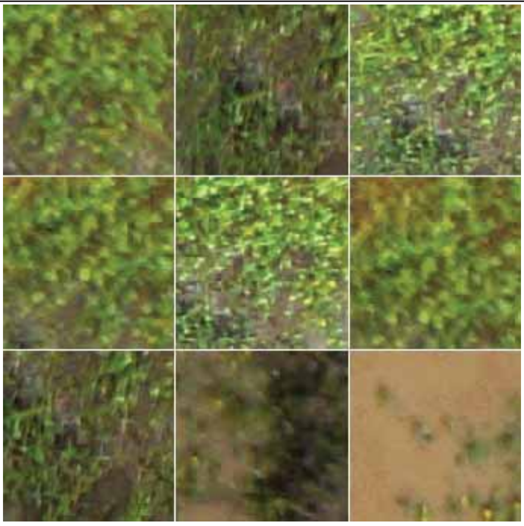
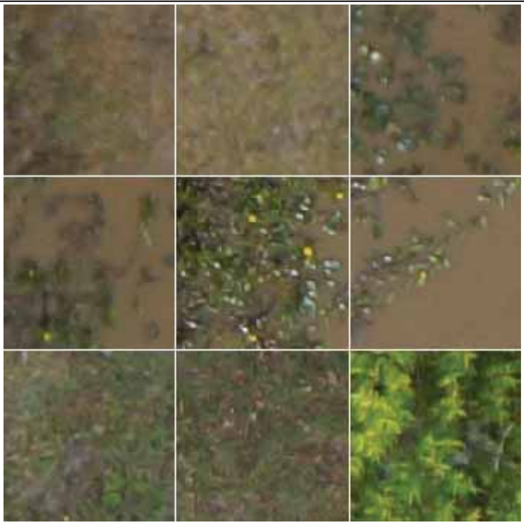
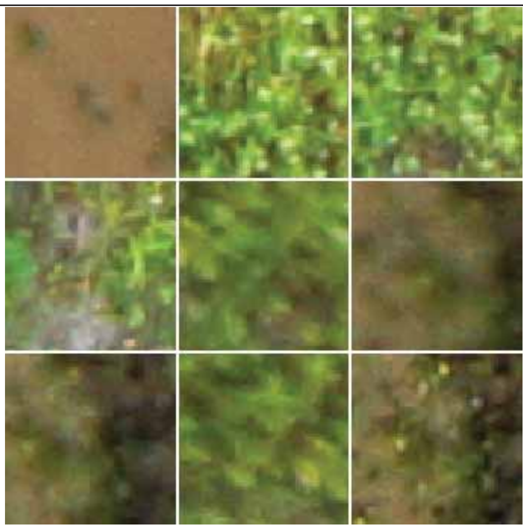
20-30		
30+		

Table 13 Example of alligator weed at different altitude settings

5 Conclusion

This report outlined the aerial image collection process of 4 different weed species (water hyacinth, serrated tussock, tropical soda apple and alligator weed) at different altitudes. The field trial went well and aerial image data of different weeds at different altitudes were successfully collected.

This report also presented the data pre-processing stage by grouping images of different altitudes, followed by weed/non-weed patch extraction for further classification analysis.

Our next step is to conduct the classification analysis with report due on 30/05/14.

APPENDIX·5:·STAGE·TWO·-·WEED·CLASSIFICATION¶

Milestone 2 Report - May 2014

Project Title:
Low Altitude Aerial Images – Weed Classification

University of Sydney Reference:
12942

Item:
Milestone 2 Report

Prepared for:
Northern Inlands Weeds Advisory Committee

Authors:
Calvin Hung and Salah Sukkarieh

Date:
15 June 2014

1 Document Purpose

This document outlines the preliminary study on weed detection using low altitude aerial images. This report focuses on weed classification.

2 Overview

The purpose of this study is to investigate the accuracy of the classification algorithm on different weed species at different altitude settings (5, 10, 20 a nd 30 metres) to determine the optimal settings for future data collection operations.

The data collection and pre-processing were discussed in the first milestone report. This report uses the extracted patches to train and evaluate the weed classification algorithm.

The classification methodology is presented in Section 3, followed by results in section 4, discussion in section 5, and the conclusion is presented in Section 6. The weed species studied were:

1. Water hyacinth at Moree (Section 4.2)
2. Serrated tussock at Armidale (Section 4.3)
3. Tropical soda apple near Armidale (Section 4.4)
4. Alligator weed at Girvan (Section 4.5)

3 Classification Methodology

In this study we extracted patches containing either weeds or non-weed (shown in Table 1) from the collected images to evaluate the weed classifier. Feature learning was applied to generate the filter bank, followed by pooling to summarise the image statistics before passing to texton based linear classifier.

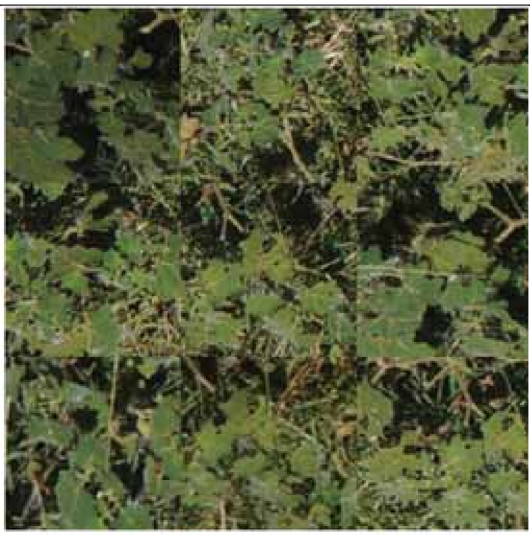
Weeds (water hyacinth)	Non-weeds
	

Table 1: Example patches of weeds (tropical soda apple shown here) and non-weeds.

3.1 Feature Learning and Pooling

It has been shown that in classification problems, the algorithms perform better on meaningful features instead of classifying the raw (noisy) data. For example, in RGB image segmentation problems it is standard to perform classification using colour, texture and shape features.

The state-of-the-art approach to generating representative features for image classification is via feature learning. Feature learning is a type of deep learning in which a set of trainable modules implementing complex non-linear functions are stacked together to capture the underlying patterns in unlabelled data. These patterns are represented as filter banks which are convolved with the image to extract feature responses.

In this study we use a standard approach for learning the filter banks. In this approach, a sparse autoencoder learns the filter bank from an established training dataset, CIFAR 10. The sparse autoencoder is an algorithm based on neural networks that minimises the squared reconstruction error with an extra sparsity constraint. Examples of the learnt features used in this study is shown in Figure 1.

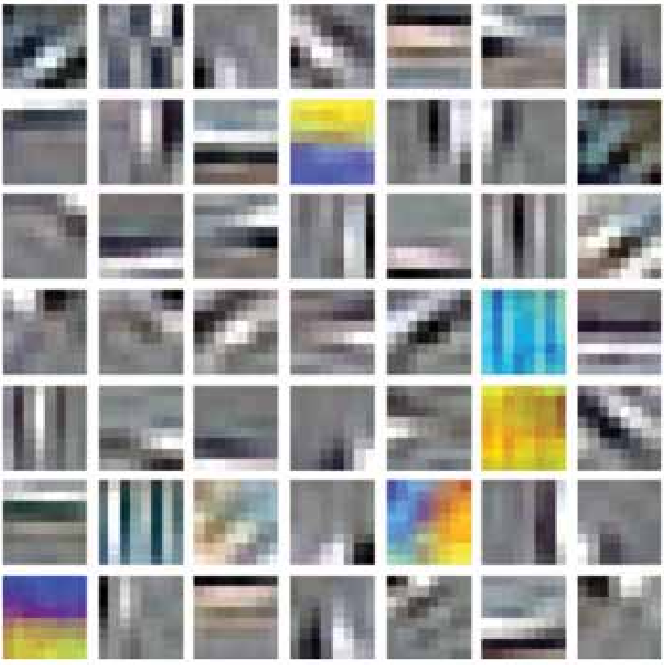


Figure 1 Filter bank obtained using feature learning. The learning algorithm has automatically generated filters that extract edge information (the grey-scale filters), colour information (the coloured filters) and texture information.

While feature responses can be used with the classifier directly, this approach can be computationally expensive. In the study we use the standard practice of pooling to summarise the feature responses before applying the classifier. Pooling is an operation that divides an image into regions and collects statistics for each region. In this study we use *max-pooling*, which summarises each region by the maximum feature response. The feature learning, feature extraction and pooling pipeline are shown in Figure 2.

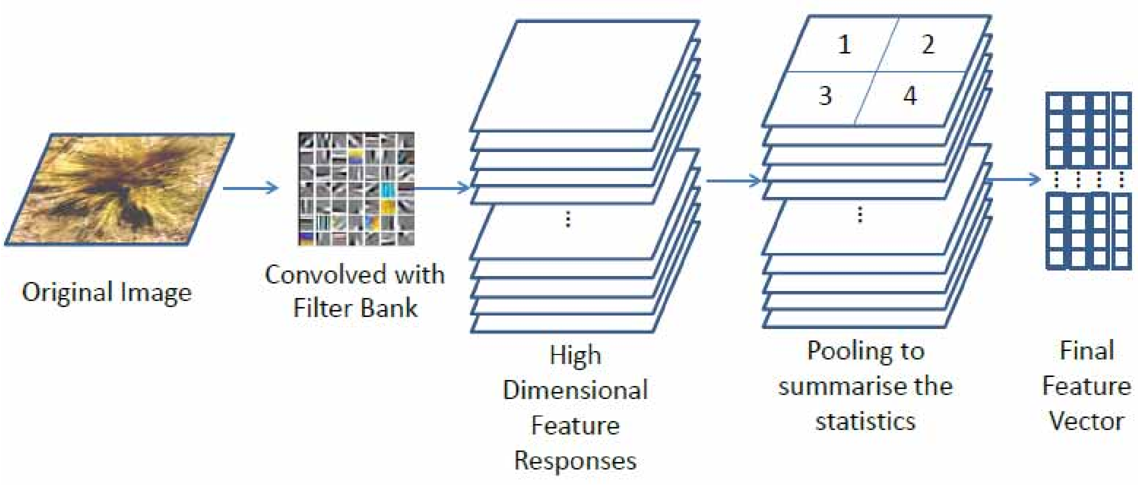


Figure 2 Feature extraction is performed by convolving the learnt feature bank over the image. The high dimensional feature responses are then summarised using pooling before classification.

3.2 Classification

We applied the texton approach to classifying feature responses as it has been shown to result in a high accuracy for image classification tasks. During the training phase K-means clustering is performed over the pooled feature responses from both the weed and non-weed class. The centroids of each cluster are called *textons*. A class is modelled by one or more textons. Examples of textons that model the water hyacinth class and non-weed class are shown in Figure 3. The histograms are visually distinct, demonstrating that the classes are easily separable. During the prediction stage, the input feature responses are compared against the texton(s) modelling each class. The most similar model becomes the predicted class.

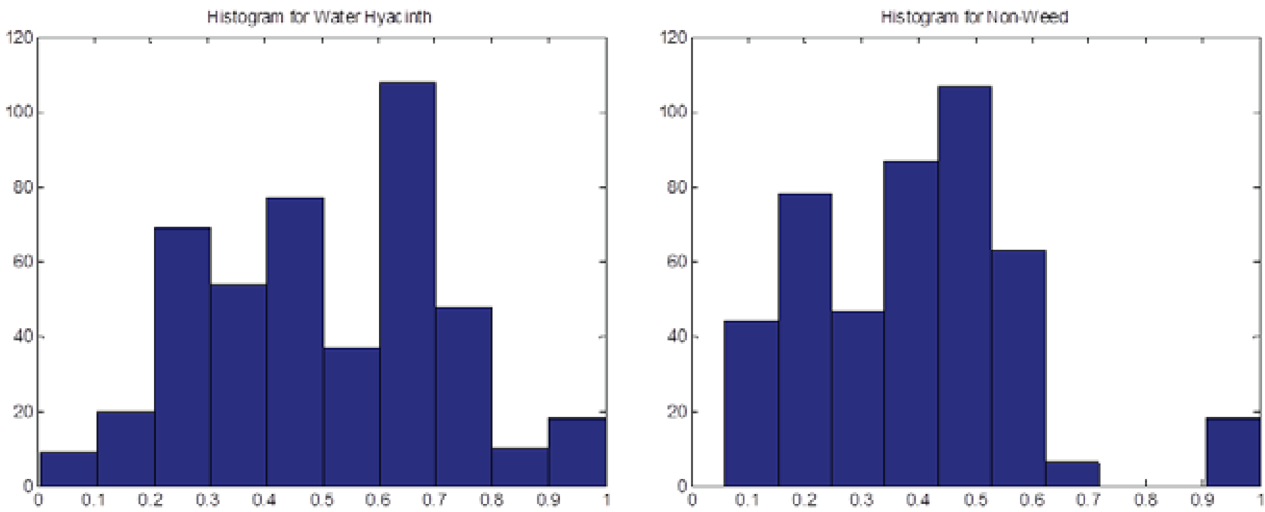


Figure 3 The histogram of the texton representing the water hyacinth and non-weed class. The histograms are visually distinct, indicating that the classes are easily separable.

4 Results

4.1 Evaluation

The experimental setup is defined by three components: (1) the approach used to extract training and evaluation data, (2) classification algorithm parameter selection and (3) definition of the accuracy metric.

4.1.1 Training and Evaluation Data

The image collection was divided into patches and each patch was labelled as either weed or non-weed. The labelling process was done visually for weed species that were easily distinguishable from the background, for example water hyacinth and serrated tussock.

Tropical soda apple plants were more difficult to distinguish visually. To provide reliable ground truth data, we performed two flights for each site. The first flight was used to collect the raw image data used for evaluating the classification algorithm. Weed experts then marked tropical soda apple plants with red tape. A second flight was performed to collect aerial images with these markings. An example of the raw and marked images are shown in Figure 4. The class labelling was guided by these markings. The images from the second flight were not used as part of the evaluation as we did not want to bias the classifier by associating the unnatural red tape markings with tropical soda apple plants.

Figure 4 Two flights were performed at the tropical soda apple sites. The first flight was used to collect the raw image data for algorithm evaluation (left) and the second flight to identify the tropical soda apple plants, which had been marked by weed experts (right).

4.1.2 Algorithm Parameters

For feature learning the size of the filter bank was 50. For pooling, each image was divided into 9 regions (3 x 3). Thus, the final feature vector has 450 dimensions. For classification, 5 textons were used to model each class (weed and non-weed).

4.1.3 Accuracy Metric

Two-fold cross validation was used to evaluate the classification algorithm. In two-fold cross validation, half of the patches were randomly selected as the training set and the remainder as the test set. The classification accuracy was measured with precision, recall and F1 score. Precision is the ratio between the number of accurately classified weeds and the total number of image patches (including false positives). Recall is ratio between the number of accurately classified weeds and the total number of weeds that should have been correctly classified. The F1 score is the harmonic mean of precision and recall. These measures are summarised in Table 2 and Equation 1-3.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Weeds</td></tr>
<tr><td>Positive</td><td>Negative</td></tr>
<tr><td rowspan="2">Algorithm Prediction</td><td>Positive</td><td>True positive (TP)</td><td>False positive (FP)</td></tr>
<tr><td>Negative</td><td>False negative (FN)</td><td>True negative (TN)</td></tr>
</table>

Table 2: Confusion matrix

$$\boldsymbol{Precision} = \frac{TP}{TP+FP}$$ **Equation 1**

$$\boldsymbol{Recall} = \frac{TN}{TN+FP}$$ **Equation 2**

$$\boldsymbol{F1} = \frac{Precision \times Recall}{Precision + Recall}$$ **Equation 3**

Experiments were performed for 4 different altitudes and 4 different window size settings. For each setting, 20 runs were performed and the accuracy metric was averaged. The F1 scores are shown for each setting, and the detailed precision and recall breakdowns are shown for the best window size setting.

4.2 Water Hyacinth

Examples of correctly classified weed, non-weed and the mis-classified patches are shown in Figure 5. The classifier performance with different altitudes and window sizes is summarised in Table 3. The performance scores for the best window size is shown in Table 4.

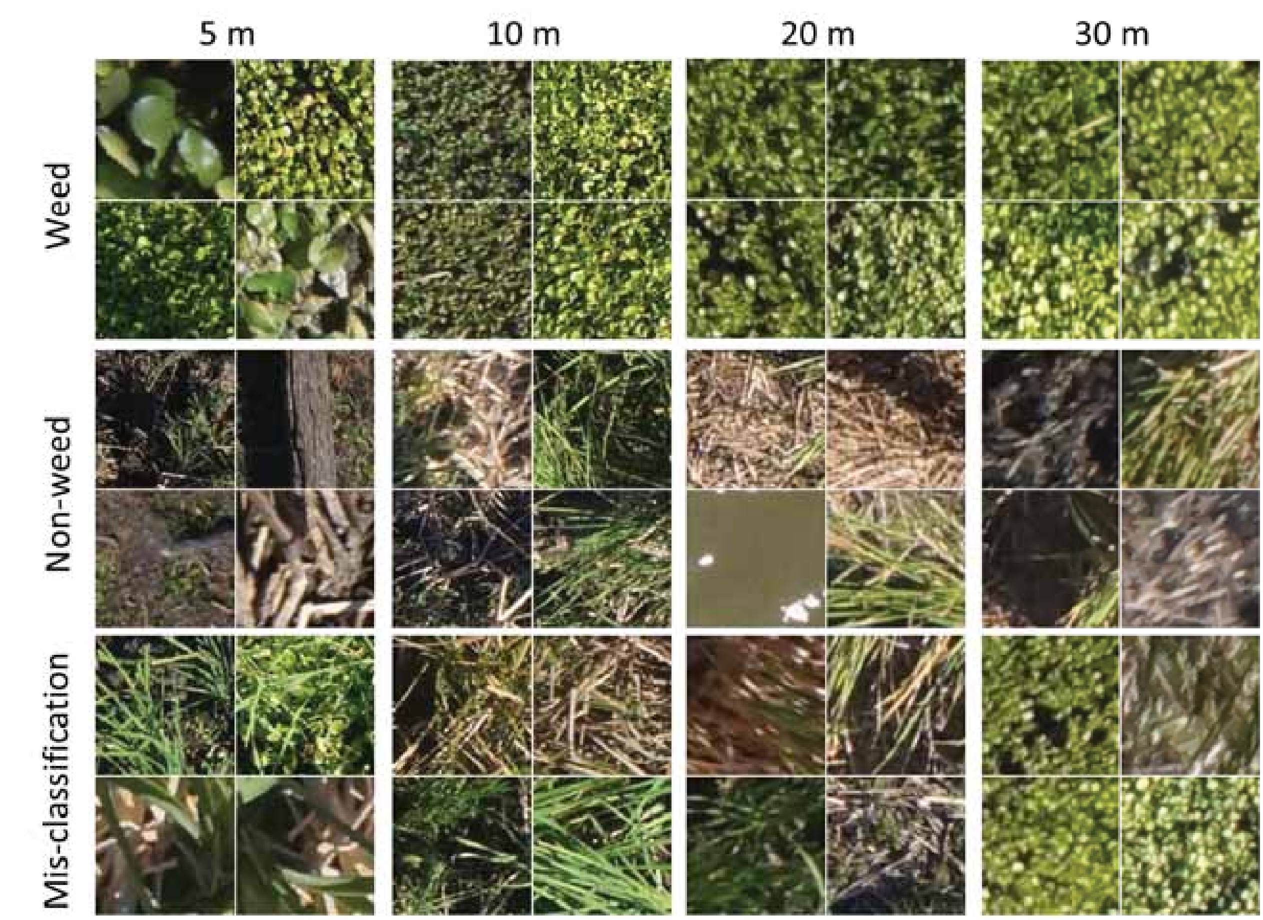


Figure 5: Water hyacinth patch classification results.

Our results showed that the classification accuracy improved with larger window sizes. We hypothesise that this is because water hyacinth grows in large patches at this site. Thus, the larger the patch window the better the classifier is at distinguishing water hyacinth from the background. Further, we found that the accuracy did not change significantly with increasing altitude. The algorithm was able to distinguish water hyacinth from other classes at different altitudes with F1 scores of greater than 90%. The main reason is that this data is amenable to classification; most of the green area was infested by water hyacinth.

Altitude Range\Window Size	128	256	384	512
5 m	80.28	82.39	92.17	91.77
10 m	81.33	81.24	90.90	94.31
20 m	80.00	81.63	89.90	91.45
30 m	79.98	80.59	87.99	90.00

Table 3: Water hyacinth classification performance at different window size and altitude settings

Altitude Range	Precision	Recall	F1
5 m	88.59	95.19	91.77
10 m	91.79	96.98	94.31
20 m	86.59	96.89	91.45
30 m	84.39	96.42	90.00

Table 4: Water hyacinth classification performance: precision, recal and F1 scores at the best window size

4.3 Serrated Tussock

Examples of correctly classified weed, non-weed and the mis-classified patches are shown in Figure 6. The classifier performance with different altitudes and window sizes is summarised in Table 5. The performance scores for the best window size is shown in Table 6.

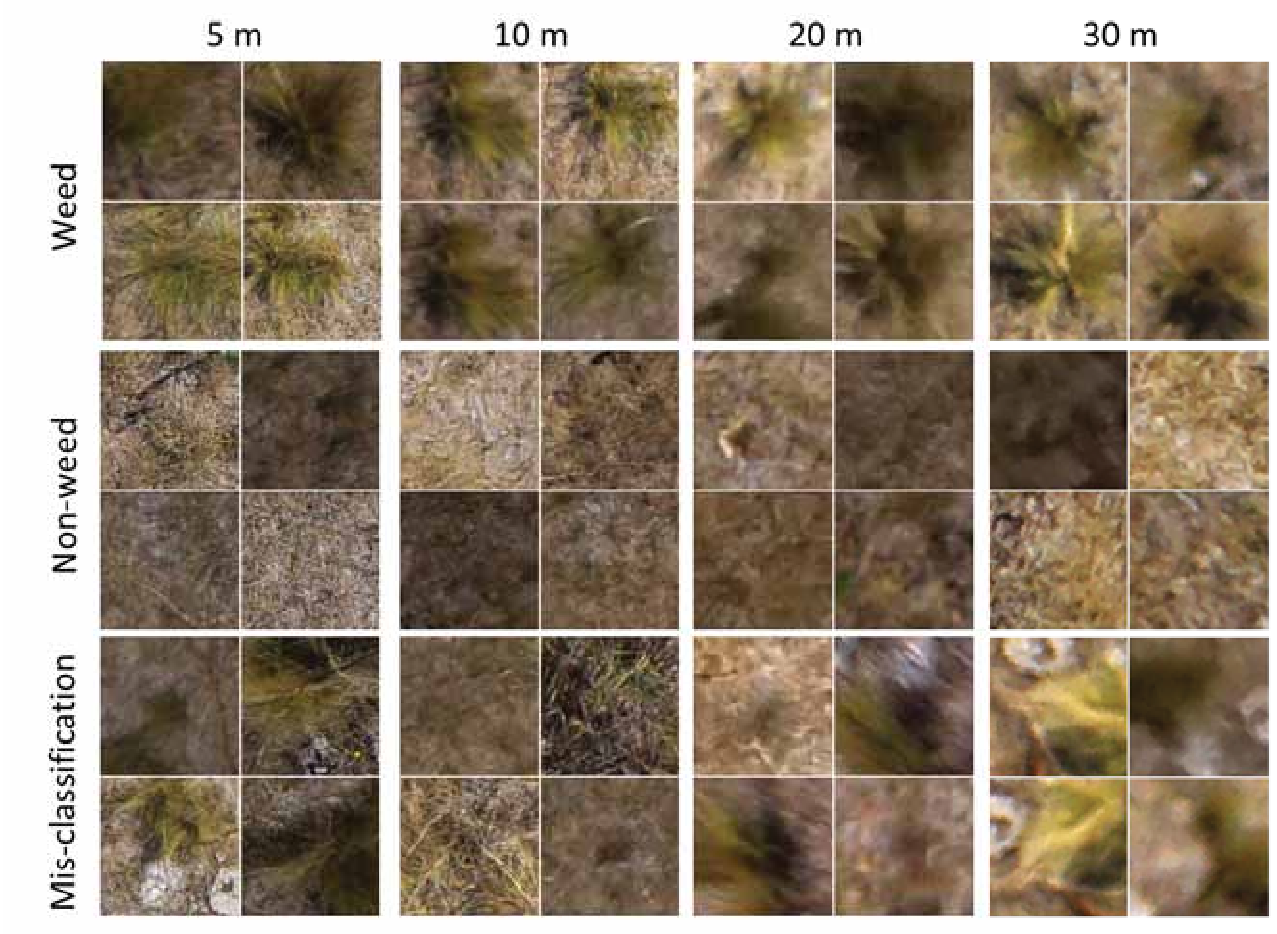


Figure 6: Serrated tussock patch classification results.

The classification accuracy improved with increasing window size up to 384 x 384 pixels. Interestingly, this is the dimension at which most of the serrated tussock plants can be fully observed (shown in Figure 7). The classification accuracy reduced slightly with increasing altitude as fewer details of the serrated tussock plant could be resolved.

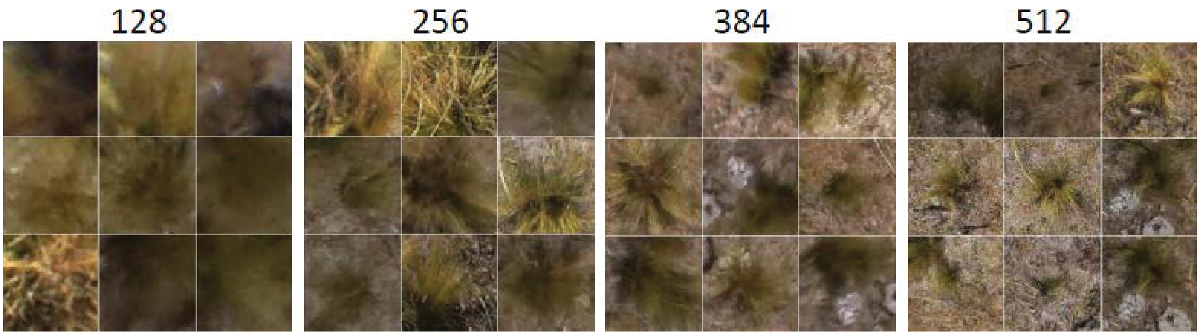


Figure 7: Serrated tussock patches sampled with different window size.

Altitude Range\Window Size	128	256	384	512
5 m	91.73	91.86	92.90	87.60
10 m	87.46	89.21	92.08	92.98
20 m	84.36	87.49	90.70	90.01
30 m	83.95	82.54	87.23	88.54

Table 5: Serrated tussock classification performance at different window size and altitude settings

Altitude Range	Precision	Recall	F1
5 m	93.02	92.79	92.90
10 m	93.13	91.07	92.08
20 m	92.02	89.42	90.70
30 m	88.24	86.25	87.23

Table 6: Serrated tussock classification performance: precision, recal and F1 scores at the best window size

4.4 Tropical Soda Apple

Examples of correctly classified weed, non-weed and the mis-classified patches are shown in Figure 8. The classifier performance with different altitudes and window sizes is summarised in Table 7. The performance scores for the best window size is shown in Table 8.

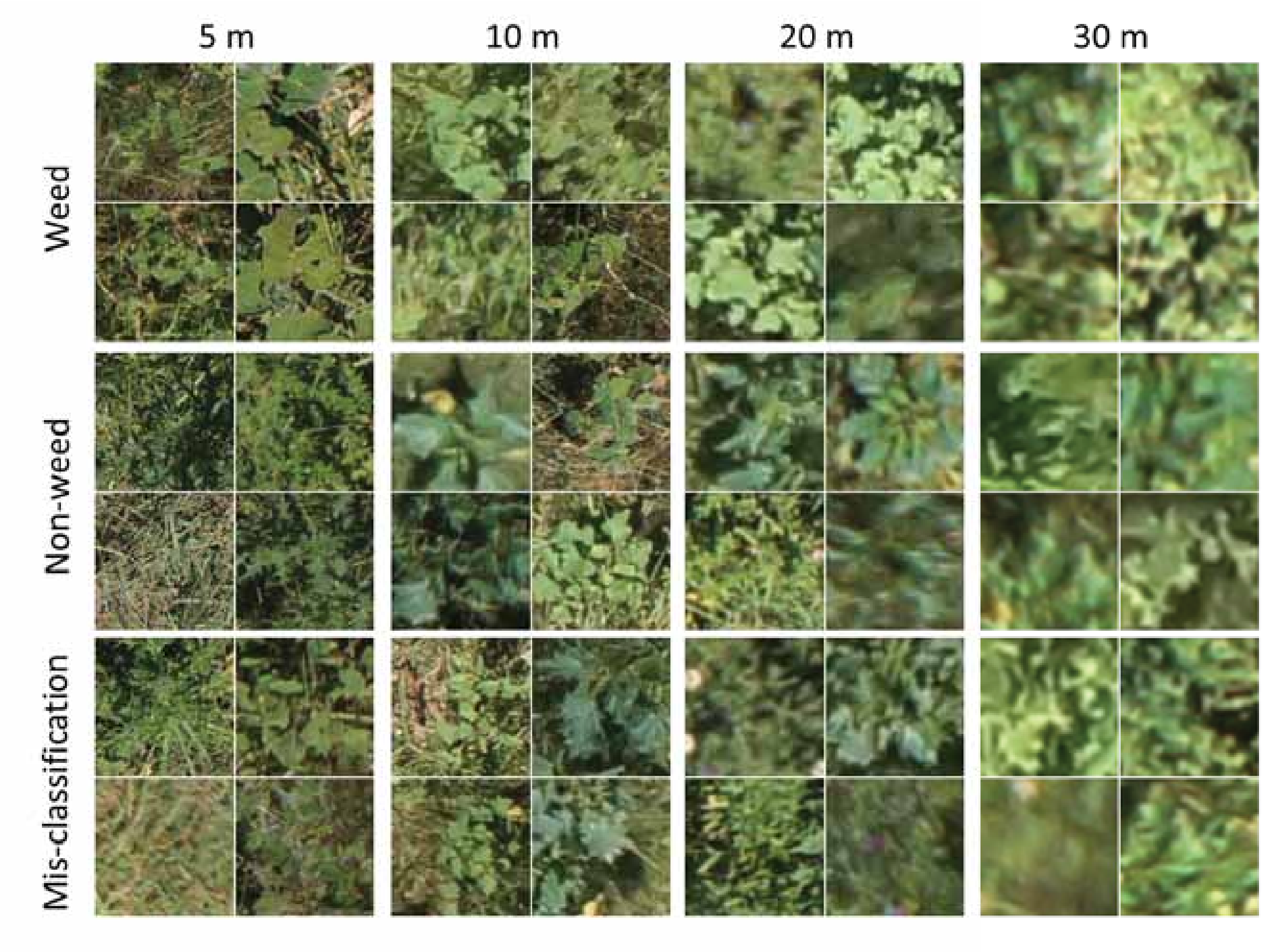


Figure 8: Tropical soda apple patch classification results.

The results showed that the window size did not affect the classification performance significantly. Further, our results showed that the altitude had a significant impact on the classification accuracy; the best results were obtained at 10 metres. Figure 8 shows that only images collected below 10 metres had enough resolution to see the prickly leaves. It becomes increasingly difficult to resolve the distinctive leaves of the tropical soda apple from above 10 metres.

The classification results in Table 1 showed that the classifier did not perform as well as for the other weed species. The reason was that the current feature bank is populated with mostly colour and texture filters. While these cues were useful for water hyacinth and serrated tussock, they were not enough to describe the subtle differences between tropical soda apple and other plants of similar appearance. Further developments of a sp ecialist classifier to incorporate the extra shape information of the leaves similar to the work on flower classification [1] can potentially improve the classifier performance.

Altitude Range\Window Size	128	256	384	512
5 m	65.95	62.74	62.91	60.85
10 m	71.33	72.19	71.54	72.05
20 m	69.29	69.82	69.54	68.20
30 m	68.17	69.29	68.86	69.10

Table 7: Tropical soda apple classification performance at different window size and altitude settings

Altitude Range	Precision	Recall	F1
5 m	63.09	62.39	62.74
10 m	70.18	74.31	72.19
20 m	67.26	72.59	69.82
30 m	68.42	70.17	69.29

Table 8: Tropical soda apple classification performance: precision, recal and F1 scores at the best window size

4.5 Alligator Weed

The area of alligator weed infestation is shown in Figure 9. Unfortunately this sample size was too small for meaningful algorithm evaluation. It was too difficult to sample training and evaluation data without any overlaps. Additional data is required in future trials for meaningful performance assessment.

Figure 9: The small patch of alligator weed infestation at Girvan.

However we have conducted alligator weed trials previously with Victorian DPI using the same platform at Dandenong, Victoria. The previous results showed that the algorithm was able to classify alligator weed from the aerial images with 80% accucracy.

5 Discussion

For area infestations such as water hyacinth, the classification algorithm is less sensitive to the altitude setting and more sensitive to the window size setting. The large window size allows a large area of observation, and the more consistent colour and texture features leads to higher classification accuracies.

For the classification of individual plants, such as serrated tussock and tropical soda apple, both the window size and altitude settings are important. The altitude dictates the amount of detail that can be resolved in the images, which is important because certain species can appear similar without those details. It can also be important if additional features which describe the specified properties of the plants (such as leaf shape and spikes of tropical soda apple) is incorporated. The windows size should be selected according to the physical size of the target plants; it should be large enough to include the entire plant but not too large to introduce noise from the neighbouring plants.

Our results showed that classification accuracy depended highly on how distinguishable the weed was from its surroundings. Thus, the survey strategy is as important as the classification algorithm. There are three strategies that can be applied to maximise the distinction between the weeds and its surroundings. The first (and potentially best) approach is to time the survey to coincide with seasonal changes that maximise the difference in appearance, for example during flowering season. Secondly we can perform the survey at lower altitudes to obtain more detail at the cost of lower coverage. The third approach is to use sensors with higher resolution to obtain the same amount of detail at higher altitudes. One disadvantage of flying at higher altitudes is that the observations become more sensitive to the vehicle's motion. Any perturbations in the platform pose at higher altitudes will cause large displacements in the sensor's orientation and may cause motion blur. Therefore to obtain the same amount of detail at higher altitudes will require a higher resolution sensor and a more stable vehicle.

6 Conclusion

In this study, we described an automated system for weed classification. We demonstrated that image classification algorithms are able to correctly classify weeds of interest from remote sensing data collected from a small UAV. This system was evaluated on three different weed species: water hyacinth, serrated tussock and tropical soda apple. As part of this evaluation, we collected data from 5-30m and experimented with classifier parameters to determine the best altitude and classifier tuning.

Our results showed that for area infestations such as water hyacinth, the classifier worked well at all altitudes, and that larger classifier window sizes resulted in more accurate results. With the best window size, F1 scores of in excess of 90% were achieved. For individual plants such as serrated tussock and tropical soda apple, both altitude and window size settings were important. With the best window size, a F1 score of more than 90% can be achieved for serrated tussock. A lower F1 score of 70% was achieved for the tropical soda apple data set because of the similarity between the weed and other surround plants.

Reference:

[1] M.E. Nilsback and A. Zisserman. A visual vocabulary for flower classification. In IEEE Computer Vision and Pattern Recognition (CVPR2006), pages 1447-1454, 2006.

APPENDIX 6: THE COST EFFECTIVENESS OF UAVS IN WEED MANAGEMENT

RMCG
Environment | Water | Agriculture
Policy | Economics | Communities

8 May 2015

Cost-Benefit Assessment of UAVs in weed management
Final Report

Northern Inland Weeds Advisory Committee (NIWAC)

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Contents

Executive summary

This analysis suggests that UAVs and weed identification analysis are likely to be cost-effective tools for some components of NIWAC weed inspection activities, particularly riparian waterway inspection and to a lesser extent small block inspection. Large block inspection and high risk pathway inspection appear less cost-effective than current methods.

RM Consulting Group was commissioned by NIWAC to undertake an economic assessment of the use of UAVs and weed classification analysis as part of their trial of the technology.

This analysis explores the costs and benefits of incorporating the technology into NIWAC's management activities in a number of ways. It is important to recognise that the technology continues to be trialled and developed, and as such a concrete understanding of its technical effectiveness and expected method of incorporation into weed management activities is not yet known.

Of value to NIWAC and the project funders at DPI is exploration of the cost-effectiveness of UAV use for various inspection functions undertaken by NIWAC, compared to the cost of the current approach to inspections. This current approach to weed inspections is focussed on manual inspection by NIWAC staff, who inspect properties from their vehicles and on foot.

Incorporating UAVs and weed identification analysis into NIWAC activities has the potential to reduce the cost of some of these activities, in some cases by a significant proportion.

Approach

RM Consulting Group first developed costing scenarios for four weed inspection activities undertaken by NIWAC, with their assistance. We then explored how these costs would change with the incorporation of UAVs and weed identification analysis, with the assistance of NIWAC and Professor Salah Sukkarieh of the University of Sydney. The four scenarios explored are:

1. 20 hectare block inspections, which are visually inspected whilst driving around the property
2. 250 hectare block inspections, which are also visually inspected by driving around the property
3. Riparian waterway inspections, which are currently undertaken by vehicle and on foot and are labour intensive activities
4. High risk pathway inspections, which are undertaken by two officers in a vehicle, where one drives and the other inspects either side of the pathway

Two alternative scenarios were developed for UAV use:

1. Hand-held UAV use by NIWAC staff, which involves the ownership and operation of a fleet of UAVs by NIWAC, and bringing them on-site to assist with inspection activities. Data is then sent to the University of Sydney for analysis and returned to NIWAC. Where weeds are identified, staff return to site for confirmation.

2. A fly-over approach to UAV data collection, in which a service provider[1] is commissioned to fly the region in advance of inspections, the data sent to the University of Sydney for analysis and returned for use in the inspection. Sites with identified weeds are inspected manually for confirmation.

Results

Results from the analysis are summarised in the below charts which compare the cost-effectiveness of UAVs for each scenario.

Figure 1 shows the current costs of a 20 hectare site inspection (in green) compared with the estimated costs of the inspection using hand held (blue) and fly-over UAVs (in purple). As can be seen, hand held costs are slightly more expensive and fly-over costs slightly lower.

Figure 1: Cost-effectiveness assessment for 20 hectare sites

Figure 2 provides the same comparison for 250 hectare blocks. In contrast to 20 hectare blocks, the labour and vehicle cost savings for larger blocks are more than offset by the additional cost in data collection and weed identification analysis.

[1] The Civil Aviation Safety Authority (CASA) currently restricts the use of UAVs to within line of site of the UAV operator. It is expected that this restriction will be reduced over time, and regional UAV fly-overs will become possible options. In the absence of the existence of commercial prices, UAV costs used for this scenario were drawn from the costs of manned fixed-wing aircraft flights. It is likely that the use of UAVs would be less expensive, and the use of this cost is therefore a conservative assumption in the context of the analysis.

Figure 2: Cost-effectiveness assessment for 250 hectare sites

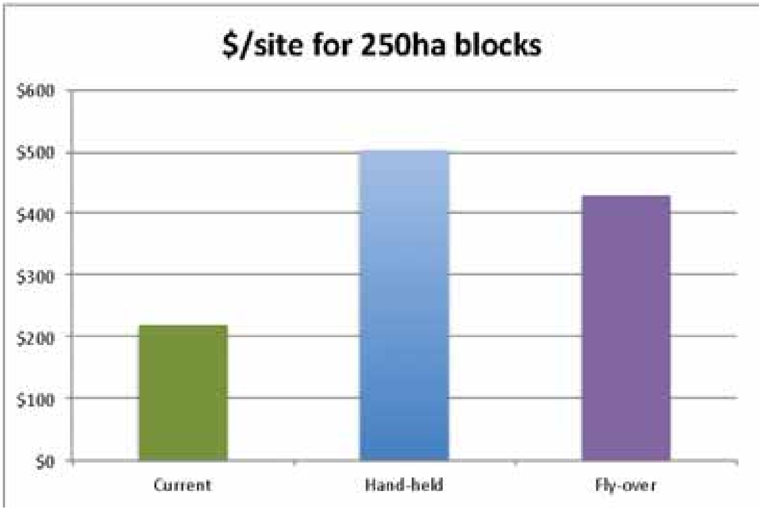


Figure 3 summarises the results of riparian waterway inspections, which suggest that the incorporation of UAV technology would be highly cost-effective. This is especially so for a fly-over approach, which in addition to significant labour cost savings from reduced manual inspection, has the added benefit of delimiting the inspection area by identifying which tributaries are affected and where the source of the infestation begins. This approach is estimated at less than 50 per cent of current inspection costs.

Figure 3: Cost-effectiveness assessment for riparian waterways

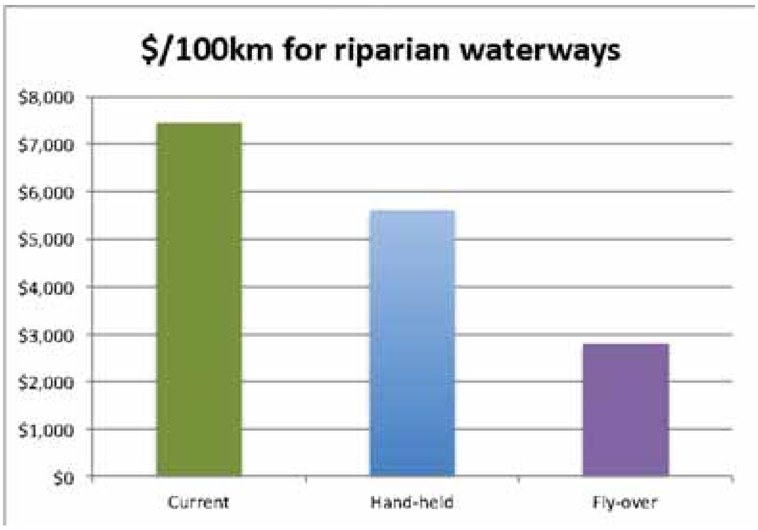
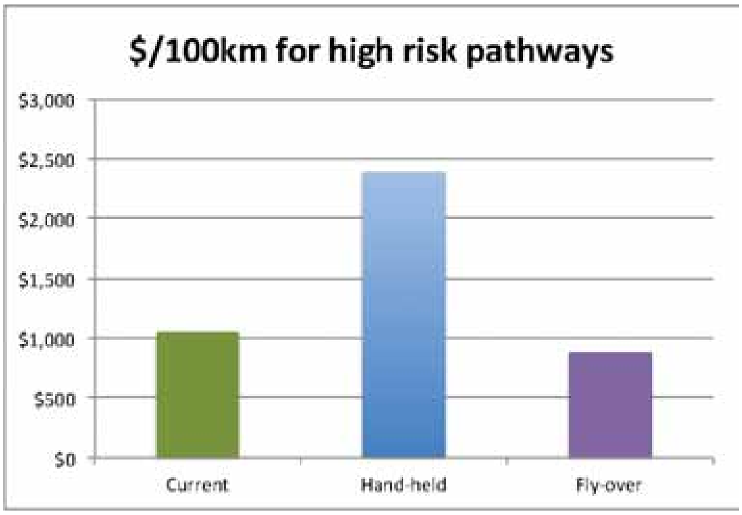


Figure 4 summarises the cost-effectiveness of different methods of high risk pathway assessment, using the example of a fire trail.[2] This scenario may not lend itself as well to hand held UAV use, as it does not reduce labour costs and has added data collection and weed identification costs. A fly-over approach is cost-comparable with current inspection methods.

[2] Some high risk pathways may not be accessible to UAVs, such as highways that have a no-fly zone around them.

Figure 4: Cost-effectiveness assessment for high risk pathways



Discussion and Summary

This analysis shows that UAVs have the potential to be cost-effectively employed by weed management agencies for a variety of inspection activities. Some uses appear more favourable than others. Riparian waterway inspections appear particularly cost-effective compared to current methods.

The analysis also suggests that a fly-over approach may be more cost-effective than a hand-held approach to incorporating UAVs, in that they reduce labour and vehicle costs more significantly than the hand-held approach.

Importantly, the analysis rests on a number of assumptions relating to data collection costs and weed identification analysis that cannot be known with greater certainty at this stage, as commercial arrangements are in their infancy or not yet in existence. The feasibility of UAVs depends significantly on these future costs.

1 Introduction

In 2014, NIWAC undertook a technological trial involving unmanned aerial vehicles (UAVs), thermal imaging and a proven existing mapping system for the detection and surveillance of high risk invasive weed species.

As part of this trial, the project funder NSW DPI requires a cost-benefit analysis to explore the feasibility of using the technology as part of on-going weed management activities. This document presents the results of this economic analysis.

The structure of this report is as follows:

- Section 2 provides analysis context and outlines the methodological approach to the study.
- Section 3 presents the analysis scenarios and reports project results
- Section 4 provides an analysis summary and a discussion of key results

2 Analysis context and framework

The trial by NIWAC of UAVs, imaging technology and mapping sits at the frontier of weed management in Australia and internationally.

As summarised in our literature review (attached to this document), there are a number of trials of the technology that have been undertaken or are being undertaken in Australia in the context of weed management, and several studies in the international literature that report on the use of UAVs in both weed management and agricultural production.

All studies identified and reviewed by RMCG appropriately focus their attention to the technological capacity to accurately identify weeds in the field. While some studies suggest potential cost-effectiveness of the technology in replacing expensive manual inspection, RMCG has seen no detailed analysis of the cost-effectiveness of UAVs and imaging technology as a consistent part of weed management by a responsible agency. This is understandable for the following reasons:

- sitting as it does on the frontier of technological advancement, attention is appropriately focussed on its technological effectiveness, rather than its economic feasibility;
- implementation of the technology is being trialled, and its ultimate configuration for weed management and other uses is not yet known (e.g. how many algorithms would be needed for practical implementation? Which UAVs are most appropriate to weed management? What service arrangements would be used and what would they cost? How would imaging costs be shared between a variety of government agencies or non-government entities?);
- as a result of the above points, how the technology would be used by weed management agencies in practice is largely unknown at this stage. For example, would it be used to completely replace the need for site visits, or perhaps to better inform site visits? Or, would it instead be used in specific contexts, such as replacing difficult or dangerous inspections of inaccessible areas? And lastly,
- a precise understanding of the technology's impact on weed management effectiveness is not yet estimable. That is, by how much will weed management effectiveness be improved as a result of the technology? How many weed incursions will be prevented, or more rapidly identified and removed? How many hectares of productive land will be spared from weed management expenses and lost productivity? How many hectares of national park or state forest? What is the dollar value of this avoided cost?

Answers to these questions would be necessary in order to frame a full assessment of costs and benefits of the technology being trialled by NIWAC for DPI. Clearly, detailed information on these aspects does not yet exist, and data on the changed areas affected by weeds in the NIWAC region going forward cannot be reliably estimated at this stage.

However, useful scenarios can be developed around the cost-effectiveness of applying the technology to different weed management uses by NIWAC, based on:

- the NIWAC team's estimates of the costs of various current weed management activities;
- expected impacts on these activities of incorporating the technology (for example, time savings for site visits); and
- estimated costs of UAV technology and service provision, provided by Professor Sukkeriah of the University of Sydney.

By exploring these scenarios and testing key assumptions, DPI can be provided with a useful understanding of how the technology might be used over time, and where that use might be cost-effective and practical. This assumes that the technology proves to be suitably effective in identifying invasive weed species, which is the subject of other parts of this project.

2.1 Methodological framework used

For the reasons described above, while this analysis adopts a cost-benefit framework, we are not at this early stage of technological development able to model the influence of the technology on weed extent over time. As such, while we use the term 'cost-benefit analysis' (CBA) to describe this analysis, the technical methodology may be better described as cost-effectiveness assessment (CEA)

In the context of this analysis, we have taken the costs of a number of scenarios relating to weed management, and compared them to scenarios in which the UAV/algorithm technology has been incorporated into current practice. The costs of these two scenarios are then compared to inform us of whether the technology is cost-effective compared to current practice.

A number of qualitative points are also discussed.

2.2 Scenarios

Four key scenarios are explored in this analysis:

3. A standard site inspection of a small block of 20 hectares
4. A standard site inspection of a large block of 250 hectares
5. Inspection of a riparian waterway in response to a new incursion
6. Inspection of a high risk pathway (a fire track)

We now outline the inspection costs associated with these scenarios, with and without UAVs. Two possible approaches to using UAVs are explored:

- hand-held UAVs, manually operated by the site inspector. For NIWAC, this involves owning and operating a fleet of UAVs, undertaking training for UAV operation replacing them at end of life; and
- regional fly-overs of NIWAC regions, with the photographic data sent to the University of Sydney for analysis and return to NIWAC for use. Instead of owning and operating UAVs, NIWAC would commission service providers to fly the region prior to manual inspections.

2.2.1 Consistent inputs to all scenarios

Some inputs are consistent to all scenarios:

- Travel time to sites are assumed to be ten minutes
- Every property receives a report, taking ten minutes to prepare
- Staff costs are $45 per hour[3]

[3] Source: NIWAC

- Vehicle costs are assumed at $40 per hour of active use, covering share of capital and maintenance costs as well as petrol[4]
- For all scenarios in which interpretation is required of weed classification mapping information by NIWAC officers, this is assumed at ten minutes of staff time.

2.2.2 Small block inspection – 20 hectares

Current inspection method

Small, 20 hectare blocks are the standard small block across the region, that NIWAC plans to visit every 4-5 years. NIWAC estimates that inspection of a small block currently involves:

- Total assessment time of 40 minutes (10 minutes engagement, 25 minutes inspection, 5 minutes reporting)
- Car use time is estimated at 25 minutes as the inspection is undertaken by driving around the site

Using this method, the entire 20 hectares can be inspected during the visit

Incorporation of UAVs – hand held

Hand held UAVs could be incorporated into small block inspection by flying UAVs across multiple blocks from a central location, as opposed to flying a single block for each flight. This could allow 8 blocks to be covered in one 40 minute flight, plus five minutes for flight set-up and another five minutes for pack-up. Site visits are therefore limited to 10 minutes discussion with the landholder.

The data would be sent by email or post to the University of Sydney[5] for analysis under a 'subscription' service, and returned to NIWAC upon completion. The data would then be interrogated by the NIWAC staff for the presence of key invasive weed species (we assume 10 minutes), and those properties with identified weeds or inconclusive results would be revisited for confirmation. We assume 10% of sites are revisited, incurring the standard cost of current inspection.

Incorporation of UAVs – fly-over

Alternatively to a hand-held approach, a regional fly-over of areas subject to inspection could be undertaken by a service provider, and the mass data sent to the University of Sydney for processing and return to NIWAC. This would allow NIWAC to avoid the cost of owning and operating their own fleet of UAVs, but would incur the service charge of the regional fly-over.[6]

Data is interpreted by NIWAC staff, and as per the hand-held approach, only those properties with identified weeds or inconclusive data require a site visit.

The key difference between the regional fly-over and the hand held approach is that site visits are only required for those with identified weeds or inconclusive results. The first round site visit is not required at

[4] Source: NIWAC
[5] Over time, a number of service providers may be established. However, the University of Sydney has provided estimates of service-provision costs to be used in the analysis. This monthly cost would include algorithm development and tweaking as required, and practically unlimited area of analysis (scale is not a key factor in their analysis).
[6] As we discuss in Section 4.2, the regional fly-over data may have multiple uses and a cost-share approach may develop over time between agencies and / or with private sector users (including the property owners themselves.

all, saving staff time and vehicle use. For properties not requiring site visits, reports are emailed to landholders.

It is worth noting that The Civil Aviation Safety Authority (CASA) currently restricts the use of UAVs to within line of site of the UAV operator (although exceptions can be made in particular circumstances). It is expected that this restriction will be reduced over time, and regional UAV fly-overs beyond line of sight will become possible options. In the absence of the existence of commercial prices, UAV costs used for this scenario were drawn from the costs of manned fixed-wing aircraft flights. It is likely that the use of UAVs would be less expensive, and the use of this cost is therefore a conservative assumption in the context of the analysis.

2.2.3 Large block inspection – 250 hectares

Current inspection method

Large, 250 hectare blocks are currently inspected manually by NIWAC staff. This involves 10 minutes engagement with the landholder, 1 hour and 45 minutes driving around the property, and 10 minutes report writing.

Incorporation of UAVs – hand held

Hand-held UAVs could be incorporated into large block inspections by driving to a central location on site and flying the UAV around the entire block. This involves ten minutes landholder engagement, ten minutes of driving on-site (return), five minutes to set up, 40 minutes flight time and five minutes pack-up.

Collected photography data is then sent to the University of Sydney for analysis and returned to NIWAC for analysis (assumed at ten minutes of NIWAC time). Those properties with identified weeds or inconclusive data are revisited for manual inspection, estimated at the cost of a 20 hectare block inspection (inspectors need only go to specific areas of weed infestation). We estimate 10 per cent of sites require a return manual inspection.

This scenario produces time savings from site inspections, but has added costs of UAV ownership and University of Sydney analysis costs.

Incorporation of UAVs – fly-over

Under this scenario, NIWAC commissions a fly-over from a UAV service provider,[7] and the data is sent to the University of Sydney for analysis. The returned data is inspected for evidence of weeds, and those sites that show evidence or are inconclusive receive a site visit. This site visit takes the time of a small block inspection, as only specific areas of weed infestation are visited. We estimate 10 per cent of sites require a manual inspection.

This scenario produces time savings from site inspections, but has added costs of the fly-over and University of Sydney analysis costs. Fly-over costs used in the analysis are drawn from fixed wing aircraft costs, and are thus considered a conservative cost assumption.

[7] Again, we note that this service is not currently able to be provided due to CASA regulations, but we anticipate that these restrictions will be removed over time.

2.2.4 Riparian waterway

One potentially effective use of UAVs could be in the identification of aquatic weeds once an incursion has been recorded. Significant time and effort is spent identifying every weed along a waterway once an incursion has occurred, in tracking the incursion upstream to its source. UAVs could be particularly useful in both identifying weeds along the waterway, and (if using a fly-over approach) in delimiting a search by remotely monitoring large areas of waterway and locating the source of the incursion.

Current inspection method

Once an invasive species is identified in a waterway, the riparian strip on both sides of the waterway is manually inspected both upstream and downstream by NIWAC staff. This is estimated at 45 minutes per kilometre for one side of the waterway. Waterway area is searched until the furthest downstream and upstream weed is identified.

Incorporation of UAVs – hand held

Hand held UAVs could be incorporated into this activity by replacing the manual search with a hand-held UAV flight. The UAV could be flown an average 500m downstream and 500m upstream, covering both sides of the waterway. Following this, the inspector would drive a further 1km along the waterway and repeat the activity.

The data would be sent to the University of Sydney as per previous scenarios, and returned for interrogation by the NIWAC staff. Identified or inconclusive sites would require a return visit for confirmation and control. We assume at least one site per kilometre requires a return inspection.

This approach saves time involved in the manual inspection, but does require the physical presence of site inspectors every kilometre along the waterway to fly the UAV, plus a return visit every kilometre. Additional costs of UAV ownership and University of Sydney analysis costs are also required. Importantly, this approach does not delimit the search compared to the manual inspection – many tributaries may be searched that prove to have no weeds, until the source is found.

Incorporation of UAVs – fly-over

As an alternative to hand-held UAV use, NIWAC might commission a regional fly-over of the affected area, or a specific UAV flight up identified waterways, with the bulk data sent to the University of Sydney for analysis and return to NIWAC. After interrogation of the data by NIWAC, the specific sites with identified weeds could be visited for confirmation and removal.

One key advantage of this approach is that the fly-over can be used to delimit the search. With regional data, it should be clear which tributaries are affected by the weeds, and the upstream source should be readily identifiable. It is likely that the pathway for downstream weed transportation would be easily identified, and significant savings from the search area manually inspected could be produced.

NIWAC staff suggest that a 25 per cent reduction in search area is plausible, based on the experiences of responding to recent incursions.

2.2.5 High risk pathways

High risk pathways are currently inspected manually by NIWAC staff, and are another area of operations that might involve the use of UAVs. High risk pathways include highways, fire trails and train tracks. Importantly, not all of these could employ UAVs – for example, highways are no-fly zones.

We explore the scenario of a fire trail, which would not be subject to restricted flying.

Current inspection method

Fire trails are currently inspected by NIWAC staff by driving the length of the trail and inspecting by site. Two staff are required – one to drive and the other to spot. Using this method, 100km can be covered in an eight hour day.

Incorporation of UAVs – hand held

Incorporation of hand-held UAVs into this activity may be challenging, as line-of-sight requirements mean that the assessor will fly the UAV over a limited length of the trail before having to pack up and drive further down the road. We assume that each flight covers five kilometres (trails are typically straighter than waterways).

As per previous scenarios, the data is sent to the University of Sydney for analysis, returned to NIWAC for interrogation, and sites with identified weeds require return visits.

Under this scenario, only one staff member will be required per fire trail, but a shorter distance is covered per day due to UAV set up, flight and pack up time. The full length of the fire trail must be driven as well, and return visits also require staff time.

Incorporation of UAVs – fly-over

NIWAC could commission a UAV fly-over covering the fire trail, with the data sent to the University of Sydney for analysis and return to NIWAC for interrogation. Only the specific sites of identified weeds or inconclusive data would be revisited for inspection – we assume one site for every 100km, taking 30 minutes for one inspector.

Unlike the hand-held approach, there are significant labour savings produced in this scenario.

3 Cost-benefit assessment

In this section, the inspection costs of the four scenarios described in Section 2.2 are presented, with the costs of the current approach compared with hand-held UAVs owned and operated by NIWAC, and with a regional fly-over cost undertaken by a contractor.

It is important to acknowledge that much of this economic analysis rests on assumptions made by the project team, with the assistance of NIWAC for their time and costs, and Professor Salah Sukkarieh for UAV-related costs. These assumptions and inputs are detailed for each scenario.

The purpose of this analysis is to compare the costs of the current assessment method with approaches that incorporate UAV technology. As previously discussed, this analysis assumes that use of the UAV technology is equally effective compared with current methods – this assumption is subject to the current trial, and will presumably require a future work plan to determine over time.

In this context, this analysis seeks to answer the following question: if the technology is functionally effective in weed detection, will its use be cost-effective compared to the current approach to weed detection in the NIWAC region?

3.1 Costs and assumptions used

Some data inputs and assumptions are constant across scenarios, specifically:

- the cost of NIWAC labour is estimated at $45 per hour;
- the cost of vehicle use is estimated at $40 per hour;
- time spent by NIWAC in analysing weed classification data returned by the University of Sydney is estimated at 10 minutes per unit;[8]; and
- average travel time to site is estimated at ten minutes

3.1.1 UAV and weed classification analysis costs

In addition to NIWAC staff costs associated with using and analysing the UAVs and weed classification data, there are two main additional costs involved in the alternative arrangements:

1. Data collection costs, which involve the costs to NIWAC of owning and operating UAVs, or paying contractors to undertake regional fly-overs of areas subject to analysis; and
2. The cost of data analysis undertaken by the University of Sydney under a monthly contract or similar arrangement.

These costs are highly uncertain at this stage, as commercial arrangements for both are in their infancy and can be expected to change significantly over time. However, data has been provided on both by

[8] It is anticipated that data will be analysed by NIWAC in map form, and identified weeds or inconclusive data are able to be quickly identified. As such, the time spent analysing weed classification data is not so much a function of scale of the area analysed (size of property, length of waterway, length of high risk pathway) as it is time spent navigating the I.T. environment to produce the relevant maps.

Professor Sukkarieh, based on his knowledge of UAVs and their costs. The project team has used a single cost per hectare of data collection based on these inputs

Details on costing for these inputs and their calculations can be found in Appendix 1. A summary of these costs is provided in Table 1.

Table 1: Unit costs associated with UAV use and analysis[9]

Cost item	Cost	Note
Data collection costs	$1.00/ha	Please see Appendix 1 for estimation method
Data analysis University of Sydney	$0.65/ha	Based on current subscription costs provided by the University of Sydney for similar services

Using this data as inputs, we can calculate the data collection and analysis costs for each scenario, which is summarised in Table 2. These costs are used in calculating the relative costs of applying the UAV technology to each of the four scenarios.

Table 2: Total cost of UAV data collection and weed analysis costs by scenario[10]

Scenario	Cost item	Cost used
20 hectare property	Data collection	$20.00
	Weed analysis	$12.94
	Total cost	$32.94
250 ha property	Data collection	$250.00
	Weed analysis	$161.73
	Total cost	$411.73
Riparian (per km)	Data collection	$5.00
	Weed analysis	$3.23
	Total cost	$8.23
High risk pathway (per 100km)	Data collection	$500.00
	Weed analysis	$323.46
	Total cost	$823.46

Remaining data inputs and assumptions for each scenario are provided below.

3.2 Analysis and results

This section details the analysis undertaken for each of the four scenarios, building on the analysis provided above. For each scenario, the costs of the 'base case' or the current approach to weed management is estimated, and the costs of the alternative approaches using hand held UAVs or a regional fly-over are estimated for comparison.

[9] Please see Appendix 1 for data underpinning these outputs
[10] Source: RMCG analysis

Results are provided in a figure which presents the total costs of each approach to the scenario. By comparing the alternatives with the current approach provides insight into the relative cost-effectiveness of using the technology as part of weed management.

3.2.1 Scenario 1: 20 hectare block inspection

Scenario 1 compares the current cost of a 20 hectare block inspection with the two modes of incorporating UAV technology that are explored in this analysis.

The results of Scenario 1 analysis are provided in Figure 5, which summarises the data inputs and assumptions used in each approach, the calculations for each, and a chart summarising the total cost of each approach per block. The following observations can be made:

- Based on the inputs and assumptions used, the costs of all three approaches are very similar per block
- Reductions in staff and vehicle time were generally offset by the weed classification cost (data collection, and analysis by the University of Sydney)
- Lower vehicle and labour costs associated with the fly-over approach make it more cost-effective than the hand-held approach.

This analysis suggests that there are potentially significant savings to staff time of using the new technology, and that the cost of data collection and analysis are critical to the cost-effective use of the technology in this context.

3.2.2 Scenario 2: 250 hectare block inspection

Scenario 2 compares the current cost of a 250 hectare block inspection with the two modes of incorporating UAV technology that are explored in this analysis.

The results of this comparison are provided in Figure 6, and differ significantly from Scenario 1. The scale of a 250 hectare block inspection significantly affects the cost-effectiveness of the approaches to inspection using UAV technology, regardless of whether the hand-held approach or the fly-over is used.

The following observations can be made:

- The staff and vehicle cost reductions achievable are significant, but are offset by larger additional costs for UAV data collection and analysis
- The analysis suggests that the current method of inspection is the least cost approach for a 250 hectare block

As with the 20 hectare block, the cost of data collection and analysis are critical. We test the sensitivity of these assumptions in Section 3.2.5.

Figure 5: 20 hectare block cost-effectiveness assessment

Scenario 1 - Small Block (20 hectares)

Conventional visit - Inputs and assumptions:
- Assessment time 40 minutes
- 10 min engagement, 25 inspection, 5 reporting
- 40 minutes assessor time
- 25 minutes car time

UAV for every site, hand held - Inputs and assumptions:
- Drive to central location on block, fly UAV around entire site
- Assessment time 21.25 minutes
- 10 engagement, 6.25 proportion of drone time (8 sites in 50 minutes inc. set up and pack up), 5 report
- NIWAC staff spend 10 minutes analysing data from Uni Sydney
- Return to 10% of sites where weeds identified for confirmation
- Cost of conventional visit applied to return visit (40 min site assessment)

UAV for every site, fly-over - Inputs and assumptions:
- UAV regional fly-over occurs prior to visit
- Data analysed by Uni Syd and returned to NIWAC
- NIWAC staff spend 10 minutes per property analysing data from Uni Sydney, and 5 minutes reporting per property
- 90% of sites do not require a site visit
- 10% have standard site assessment (weeds identified or inconclusive)

Calculation

Conventional visit

	Unit	Cost
Area (Ha)	20	
Labour (hours)	0.67	$30.00
Vehicle (hours)	0.4	$16.67
Travel time to site (hours)	0.17	$14.17
Total cost per site		$60.83
Cost per hectare		$3.04
Cost per 100 sites		$6,083.33

UAV for every site, hand held

	Unit	Cost
Area (Ha)	20	
Labour (hours)	0.35	$15.94
Vehicle (hours)	0.00	$0.00
Travel time to site (hours)	0.17	$14.17
Return visit (% sites)	10%	$6.08
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$32.94
Total cost per site		$76.63
Cost per hectare		$3.83
Cost per 100 sites		$7,662.61

UAV for every site, fly-over

	Unit	Cost
Area (Ha)	20	
% conventional visit	10%	$4.67
Labour (hours)	0.25	$10.13
Vehicle (hours)	0.00	$0.00
Travel time to site (hours)	0.17	$1.42
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$32.94
Total cost per site		$56.65
Cost per hectare		$2.83
Cost per 100 sites		$5,664.69

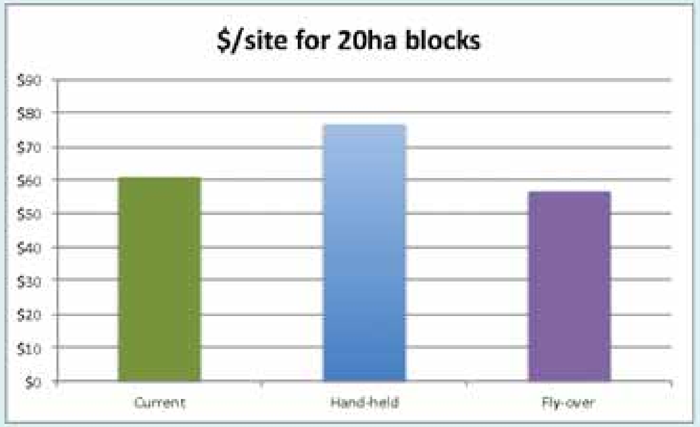


Figure 6: 250 hectare block cost-effectiveness assessment

Scenario 2 - Big Block (250 hectares)

Conventional visit - Inputs and assumptions:
- Assessment time 2.5 hours
- 10 mins engagement, 2.25 hrs inspection, 5 mins report
- Assumes average travel time to sites of 10 minutes
- 2 hours and 20 minutes car time on site

UAV for every site, hand held - Inputs and assumptions:
- Assessment time 1 hour and 15 minutes
- 10 min engagement, 40 min flight, set up time 5 mins, pack up 5 mins, 10 driving and 5 report
- 10 minutes of driving total
- Return to 10% of sites for manual inspection of identified weeds
- NIWAC staff spend 10 minutes analysing data from Uni Sydney

UAV for every site, fly-over - Inputs and assumptions:
- Regional fly-over in advance
- 90% of properties do not require a site visit (10 minutes for data analysis, 5 for report)
- 10% require conventional site assessment (weeds identified or inconclusive)
- This site assessment is as per 20 ha block - only go to the weeds

Calculation

Conventional visit:

	Unit	Cost
Area (Ha)	250	
Labour (hours)	2.5	$112.50
Vehicle (hours)	2.33	$93.33
Travel time to site (hours)	0.17	$14.17
Total cost		*$220.00*
Cost per hectare		*$0.88*
Cost per 100 sites		*$22,000.00*

UAV for every site, hand held:

	Unit	Cost
Area (Ha)	250	
Labour (hours)	1.25	$56.25
Vehicle (hours)	0.17	$6.67
Travel time to site (hours)	0.17	$14.17
Return visit (% sites)	0.10	$6.08
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$411.73
Total cost		*$502.40*
Cost per hectare		*$2.01*
Cost per 100 sites		$50,239.91

UAV for every site, fly-over:

	Unit	Cost
Area (Ha)	250	
% conventional visit	0.1	
Labour (hours)	0.08	$3.38
Vehicle (hours)	0	$0.00
Conventional visit cost		$6.08
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$411.73
Total cost		**$428.69**
Cost per hectare		$1.71
Cost per 100 sites		$42,869.08

3.2.3 Scenario 3: Riparian waterway assessment

Scenario 3 compares the cost-effectiveness of the current approach to riparian waterway site assessment with the two alternative approaches involving UAV technology. Figure 7 summarises the inputs and assumptions, the calculations, and presents the analysis results.

The following observations can be made:

- The staff and vehicle cost reductions achievable by using UAV technology are significant, and more than offset the additional cost of UAV data collection and analysis. Both the hand-held and fly-over approaches to UAV incorporation can be undertaken at lower cost than the current approach.
- The analysis suggests that the use of 'fly-over' UAV technology as part of riparian weed management could reduce costs by more than 50 per cent compared to current manual inspection. This is in part due to the significant staff time spent in manual inspections of waterways, and also the ability of the fly-over approach to delimit the area searched by identifying the scope of the infestation prior to manual inspections.

Riparian waterway assessment is a clear example of where the incorporation of UAV technology could significantly reduce the cost of inspection in the NIWAC region.

3.2.4 Scenario 4: High risk pathways

Scenario 4 compares the cost-effectiveness of the current approach to specific high risk pathways with the two alternative approaches involving UAV technology. Figure 8 summarises the inputs and assumptions used in the analysis, the calculations, and presents the analysis results. The analysis compares the cost of inspecting 100km of high risk pathway.

The following observations can be made:

- The use of hand held UAVs is a more expensive method of inspecting a high risk pathway such as a fire trail. This is because the same length of pathway must be travelled by an inspector, but stopping every five kilometres to set up, fly, and pack up the UAV. Following analysis by the University of Sydney, if weeds are identified an inspector must then return to site and confirm or remove the weed. This is essentially an inefficient process and the analysis demonstrates this point.
- The use of a UAV fly-over can be undertaken for around the same cost as the current method. Significant time savings can be produced if two staff are not required to drive the length of the pathway, and these savings are similar to the estimated cost of the UAV data collection and weed classification analysis required.

This analysis underscores that there are some aspects of NIWAC weed inspection that do not lend themselves easily to hand-held UAV use. It also underscores that the cost of data collection and weed classification analysis are critical to cost-effectiveness.

Figure 7: Riparian waterway cost-effectiveness assessment

Scenario 3 - Riparian waterway

Conventional visit - Inputs and assumptions:
- Assessment time 3/4 hour per km on foot, one side

UAV for every site, hand held - Inputs and assumptions:
- Fly UAV 500m each way along river
- Flight time 20 minutes (inc set up and pack up)
- Following flight, drive 1km along waterway (5 mins)
- Covers both sides of waterway
- Identification of weeds 1 every km
- Requires return visit for manual inspection (15 minute inspection)

UAV for every site, fly-over - Inputs and assumptions:
- Regional fly-over in advance
- 100% of km stretches require reinspection (weeds identified or inconclusive)
- Manual inspection 15 minutes
- Saving due to scoping the extent of infestation of 25% of conventional search

Calculation

Conventional visit	Unit	Cost
Length (km - both sides)	1.00	
Length covered per day (km)	4.00	
Labour (hours)	1.50	$67.50
Vehicle (hours)	0.08	$3.33
Travel time to site (hours)	0.17	$3.54
Total cost ($/km)		$74.38
Cost per 100 km		$7,437.50

UAV, hand held	Unit	Cost
Length (km)	1.00	
Labour (hours)	0.42	$18.75
Vehicle (hours)	0.08	$3.33
Travel time to site (hours)	0.17	$1.77
Time spent at return visit	0.25	
Return visit (% sites)	100%	$16.35
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$8.23
Total cost		$55.94
Cost per 100 km		$5,594.30

UAV, fly-over	Unit	Cost
Length (km)	1.00	
Proportion sites requiring re-inspection	100%	
Labour (hours)	0.25	$11.25
Vehicle (hours)	0.08	$3.33
Travel time to site (hours)	0.17	$1.77
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$8.23
% of area manually inspected	75%	
Total cost		$32.09
Cost per 100 km		$2,800.03

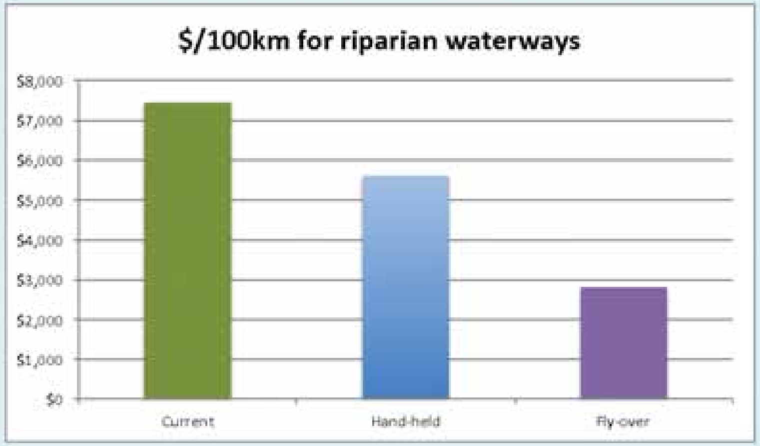


Figure 8: High risk pathways cost-effectiveness assessment

Scenario 4 - High Risk Pathways

Conventional visit - Inputs and assumptions:
- 2 assessors per vehicle
- 100km covered per day - 8 hours

UAV for every site, hand held - Inputs and assumptions:
- 1 assessor per pathway
- Flight distance on average 5km (line of site only)
- Flight time 20 minutes (inc set up and pack up)
- Following flight, drive 2km up road (2 mins)
- NIWAC staff spend 10 minutes analysing data from Uni Sydney
- Return visit required once per 100km
- Return visit takes 20 minutes of driving (labour and car)

UAV for every site, fly-over - Inputs and assumptions:
- Regional fly-over in advance
- Data sent to Uni Sydney for analysis
- NIWAC staff spend 10 minutes analysing data from Uni Sydney
- Site visit required once per 100km
- Return visit takes 30 minutes of driving (labour and car)

Calculation

Conventional visit:

	Unit	Cost
Length covered per day (km)	100	
Labour (hours)	16.00	$720.00
Vehicle (hours)	8.00	$320.00
Travel time to site (hours)	0.17	$14.17
Total cost ($/km)		$10.54
Cost per 100 km		**$1,054.17**

UAV for every site, hand held:

	Unit	Cost
Length (km)	100	
Labour (hours)	26.67	$1,200.00
Vehicle (hours)	8.00	$320.00
Travel time to site (hours)	0.17	$14.17
Return visit cost		$28.33
Weed classification data analysis NIWAC (hours	0.17	$7.50
Data collection and weed classification cost		$823.46
Total cost ($/km)		$23.93
Cost per 100 km		**$2,393.46**

UAV for every site, fly-over:

	Unit	Cost
Length (km)	100	
Labour (hours)	0.50	$22.50
Vehicle (hours)	0.50	$20.00
Travel time to site (hours)	0.17	$14.17
Weed classification data analysis NIWAC (hours)	0.17	$7.50
Data collection and weed classification cost		$823.46
Total cost ($/km)		$8.88
Cost per 100 km		**$887.63**

3.2.5 Sensitivity assessment

As noted throughout this document, the results presented here depend critically on the data collection and analysis costs used in the analysis. While the estimates used in the central case are logical, their actual costs in practice are unable to be determined at this early stage of technology adoption.

As such, it is important to test the sensitivity of these data inputs. Table 3 provides the central estimates used in the analysis, as well as low and high estimates tested for sensitivity.

Table 3: Data collection and weed classification assumptions[1]

Cost item	Assumption type	Data point
Data collection costs	Low	$0.40
	Central	$1.00
	High	$2.63
Weed classification analysis	Low	$0.15
	Central	$0.65
	High	$1.48

We then explore the sensitivity of these data inputs in Table 4, which applies them to our four scenarios. The central cost assumptions are the assumptions used in the analysis as reported, for the conventional approach to weed management, and the hand held and fly-over alternative approaches. We then produce the cost outputs using the low and high assumptions summarised above.

Table 4: Sensitivity test of data collection and weed classification services costs

Scenario	Cost assumption	Weed management approach		
		Conventional	Hand held	Fly-over
20 hectare property	Low		$54.71	$34.73
	Central	**$60.83**	$76.63	$56.65
	High		$99.50	$79.52
250 ha property	Low		$228.48	$154.77
	Central	**$220.00**	$502.40	$428.69
	High		$788.36	$714.66
Riparian (per km)	Low		$5,046.46	$2,252.19
	Central	**$7,437.50**	$5,594.30	$2,800.03
	High		$6,166.23	$3,371.96
High risk pathway (per 100km)	Low		$1,845.63	$339.79
	Central	**$1,054.17**	$2,393.46	$887.63
	High		$2,965.39	$1,459.56

[1] Source: RMCG analysis

As can be seen in the results, they are unsurprisingly sensitive to cost assumption applied. For example, if low costs are applied to the 20 hectare property inspection, both the hand held and fly-over approaches are less expensive than the current approach. However, when the high cost assumption is used, both of these alternative approaches are more expensive than the current approach.

Results for the 250 hectare property are less sensitive, as the alternative approaches remain more expensive than the current approach, with the exception of the fly-over approach under low cost assumptions.

For riparian waterway inspection, the reverse is true – both the hand held and fly-over approaches remain less expensive than the current approach regardless of the cost assumption used. This suggests that UAVs may be particularly well suited to riparian waterway inspection.

For high risk pathways, hand held UAVs remain more expensive than the current approach regardless of cost assumptions used. Under a low cost scenario, however, a fly-over approach is around one third of the cost of current manual inspection. This suggests it may be a feasible option for high risk pathway inspection.

Interpretation

This sensitivity assessment confirms the central argument of this analysis – that the use of UAVs in weed management shows significant promise in terms of cost effectiveness, subject to its technical feasibility and the cost of data collection and weed classification.

4 Summary and discussion

This analysis shows that there are several circumstances in which the incorporation of UAV technology could be cost-effective for NIWAC, and by extension, weed managers across New South Wales.

Undertaking this quantitative assessment has been challenging for a number of reasons that largely stem from the fact that this is a new application of a rapidly changing technology on the frontier of its potential uses:

- The subtleties of the technology's effectiveness in weed management are not yet well understood. Is it more or less effective for water-borne weeds than terrestrial ones? To achieve sufficient weed identification effectiveness, are photographs required at different heights for different weeds, and does this require different types of UAVs?
- As the commercial application of the technology is not yet widespread, the costs of data collection and weed classification analysis are likely to change over time. What are the likely costs going forward for UAVs and associated technology, or for contracting specific flights as required? Will commercial providers of weed classification analysis exist in future?
- Consequently, how the technology will be embedded as part of weed management practice by groups such as NIWAC is not yet known, for the reasons stated above.

4.1 Summary of results

What this analysis shows is that under plausible scenarios and given the available data, UAV technology and weed classification analysis can be used by weed managers in a cost-effective way. This cost-effectiveness varies by activity:

- Small block assessments can be undertaken using UAV technology at a similar order of magnitude cost to current practice.
- Large block assessments (250 hectares) using UAVs appear to be more expensive than current practice, regardless of whether hand held or fly-over approaches are used, largely due to the larger scale of the area producing higher data collection and weed classification analysis costs.
- Riparian water assessments using UAVs appear to be significantly more cost effective than current practice, due to the labour-intensity of current manual inspection and the ability to use a fly-over approach to help delimit the area requiring manual visits.
- High risk pathways have somewhat limited use for UAVs, as highways are no-fly zones and the use of hand held UAVs for other pathways do not appear to produce significant time savings. However, the use of fly-overs appears to be similarly cost effective compared to current practice.

These results suggest that further work on the technical effectiveness of the technology is warranted due to the potential cost-effectiveness of its application should it be proven to be an effective method of weed identification over time.

It also suggests that its cost-effectiveness differs by weed management activity, and that it may be more cost-effectively used in some circumstances than others. Riparian waterways appear particularly well suited to UAV use.

4.2 Discussion

The cost-effectiveness of UAVs in weed management is, unsurprisingly, affected by the cost of using the technology, which will more accurately be determined over time, as these services are more broadly provided over time for a variety of uses.

This is a very important point, not only because technological advancement may reduce the cost of data collection and analysis over time, but also because there may prove to be a number of different uses for the data by both Government and private business.

For example, if landholders could use the data for crop management or business planning, they may be willing to co-fund data collection with weed management agencies. Similarly, there may be many uses of aerial photography data across agencies and tiers of Government, leading to opportunities for cost-sharing among Government departments and other entities over time.

Furthermore, technological advancement in camera resolution may result in cost-effective state-wide data collection for multiple purposes.

If so, it is conceivable that annual data collection and weed identification analysis across a region or even the state could become standard practice over time. In such a scenario, the identification and control of weeds could become far more coordinated and effective than is currently possible. The benefits to Government, landholders and the community of such an outcome are likely to be significant.

However, a number of barriers need addressing over time, including acceptance by the community of UAV use and clarification on CASA rules and regulations for UAV use.

Appendix 1: UAV data collection costs and weed classification costs

There is considerable uncertainty about the cost of photographic data collection using UAVs, and analysis of that data for weed classification purposes over time.

Professor Sukkarieh of The University of Sydney has provided assistance in sketching out scenarios for these costs, but it must be acknowledged that information on the costs of data collection is quite limited.

Two distinct scenarios for data collection appear likely for weed management agencies such as NIWAC:

1. owning and operating a suite of UAVs for use by NIWAC staff; and
2. commissioning external providers to undertake fly-overs of regions or specific areas such as waterways on a fee-for-service basis.

We consider the costs of these two options in more detail below.

Owning and operating UAVs

Should NIWAC implement a significant program involving UAVs, it would incur a number of costs associated with such ownership and operation. Some of these costs would be fixed, such as the capital cost of purchasing UAVs themselves.

Other costs would depend upon the scale of the program – if used infrequently, a UAV may require quite minimal maintenance costs and have a lifetime of 5-10 years. If however it is used daily, maintenance costs would be high and its lifetime could be very short. Engineering staff may be required full time to keep the UAV fleet in operation.

The scenario described in Table 5 identifies a range of costs that would be required for UAV ownership and operation by NIWAC. Costs are shared between a lifetime area of use to produce a cost per hectare of $0.40.

Table 5: Cost break-down of UAV ownership and operation

Cost item	Estimated cost	Note
UAV training cost	$1,500	Fixed wing or rotary, hand held
Capital cost of UAV (hand held)	$100,000	
UAV Operating and maintenance costs	$20,000	20% of capital cost/year
Operating certificate cost (annual)	$10,000	
UAV lifetime (years)	2	Intensive use would limit their lifetime significantly
Hand held coverage per day (hectares)	1000	Equivalent to 4 x 250 hectare blocks
Number of active days per year	200	
Total hectares covered in lifetime	400,000	
Total lifetime cost	$161,500	
Hand held UAV cost per hectare	$0.40	

Fly-over costs

An alternative to owning and operating UAVs is one in which NIWAC commissions a service provider specialising in this space to undertake the data collection for them using UAVs. This could involve a regional fly-over, or a flight up a specific waterway after identification of an incursion.

As noted, the Civil Aviation Safety Authority (CASA) currently restricts the use of UAVs to within line of site of the UAV operator. It is expected that this restriction will be reduced over time, and regional UAV fly-overs will become possible options. In the absence of the existence of commercial prices, UAV costs used for this scenario were drawn from the costs of manned fixed-wing aircraft flights. It is likely that the use of UAVs would be less expensive, and the use of this cost is therefore a conservative assumption in the context of the analysis.

Professor Sukkarieh provided the project team with cost data from a recent quote for similar photographic data as is used in weed classification analysis, from a fixed wing aircraft. Given that equivalent costs from a UAV would be expected to be less expensive than this cost, use of this cost information is considered to be a conservative assumption. This data covered an area of 22,800 hectares and cost $30,000. This produces a cost per hectare of $1.32.

Choice of data collection cost data for analysis

The cost of data collection by the two methods outlined above are summarised in Table 6. As can be seen, the estimated fly-over costs are almost four times the estimated cost of owning and operating UAVs. This divergence in data reflects the uncertainty around this data.

Table 6: Data collection costs

Data collection method	Cost ($/ha)	Calculation method
Own and operate UAVs	$0.40	"Top-down" – price divided by area
Fly-over by contractor	$1.32	"Bottom-up" – estimate of contributing costs
Estimate adopted	**$1.00**	Within upper and lower estimate, closer to real cost provided by contractor

In practice, it might be expected that the actual cost of data collection may fall between these two costs, as fly-over costs can be expected to fall over time (as demand for these services increases), and the practical reality of owning and operating UAVs reveals costs not anticipated in this analysis.

Actual costs of both should be quite similar in practice, as the contractor price should be set slightly below the cost of owning and operating to encourage take-up.

Given that the fly-over cost is an actual quote, and as such is an actual price used in the market, we have chosen a cost closer to this price as a 'central estimate' used in the analysis - $1/ha. Sensitivities are provided on $0.40 and $1.32, as well as one at double the upper bound ($2.64/ha) to test the sensitivity of the upper bound.

Weed classification analysis costs

No commercial weed classification analysis providers currently operate in Australia. Professor Sukkarieh's team at the Australian Centre for Field Robotics a the University of Sydney provide an analysis service to clients as part of their ongoing operations, and the project team understands that the ACFR intends to develop a commercial service over time.

Based on their current activities and costs, we asked Professor Sukkarieh to estimate a cost per hectare of weed classification services for this analysis. A monthly subscription cost of $14,750 was provided, with an estimate of 22,800 hectares per month of analysis. This equates to a cost per hectare of $0.65.

APPENDIX 7: UAV PLATFORMS

This section written by Dr Zhe Xu, Dr Calvin Hung and Professor Salah Sukkarieh focuses on the vehicles that are used to fly the sensing payloads.

First, the various classes of UAV platforms will be identified and evaluated on the application domains to which these classes are suited.

Following this, the power-plants will be described and levels of autonomy available to UAV platforms.

7 .1 Platform Classes

Six classes of UAV that have been used in remote sensing applications are identified in the table below. These classes are: (1) fixed wing vehicles, (2) rotary wing vehicles, (3) multirotors, (4) kites, (5) blimps and (6) paragliders. The distinction between classes is made according to the platform's main lift generating mechanism; that is, the manner in which the platform remains airborne in an aerodynamic sense.

Class	Use (cases)
Fixed Wing 	**Fixed wing vehicles** have one or more fixed lift generating surfaces (wings) and rely on the vehicle's forward motion to remain airborne. Fixed wing vehicles are often used in applications requiring long endurance or heavy payloads. However, operational constraints are often imposed by the launch and recovery of all but the smallest fixed wing platforms due to their reliance on forward motion to remain airborne. For example, a large, flat site may be required for take-off and landing, limiting the areas from which the UAV can be operated. Alternatively, the vehicle could require specialised infrastructure, such as a catapult for launch and a net or hook for recovery. Another limitation inherent to fixed wing vehicles is a minimum operating speed, below which the vehicle is no longer able to remain airborne. In remote sensing applications, this limitation imposes constraints on the rate at which the payload sensor must collect data. For example, to achieve a desired along-track overlap with an imaging sensor, the sensor must achieve a minimum shutter rate. In summary, key application areas are: • Long endurance missions • Large payloads (>50kg) • Environments with adequate operating sites or if specialised launch and recovery infrastructure is available

Rotary wing 	**Rotary wing vehicles** rely on the rotating motion of its primary lift generating surface (rotors) to remain airborne. Unlike fixed wing vehicles, rotary wing vehicles have the ability to hover. This capability relaxes the constraints imposed by launch and recovery operations, and makes operations in more confined areas possible. Further, the vehicle is able to freely modify itsspeed to suit the payload sensor(s). However, rotary wing vehicles are less aerodynamically efficient than fixed wing vehicles. A typical rotary wing vehicle has a lift-to-drag ratio that is approximately half of its fixed wing counterpart. The lift-to-drag ratio is an aerodynamic parameter that influences the endurance of anaircraft; a key limitation of rotary wing vehicles is their limited endurance. Key application areas are: • Medium sized payloads (3-50kg) • Operations from confined areas
Multi-rotor 	**Multirotors** are a sub-class of rotary wing vehicles. Unlike conventional rotary wing platforms that rely on a single set of rotors (or occasionally, two sets), multirotors use configurations of four, six, or eight rotors. These configurations are known as “quadcopters”, “hexacopters” and “octocopters” respectively. The key advantage of multirotors over conventional rotary wing vehicles is their mechanical simplicity. The only moving components in a conventional multirotor are its motors. Control of the vehicle is exercised by differentially changing the rotational speeds of rotor pairs. Like other rotary wing vehicles, multirotors typically have short endurances. This drawback is exacerbated by the limited choice of power-plants available to multirotors. Further, multirotors are dynamically unstable and require active electronic stabilisation; thus, a multirotor’s handling characteristics and response to winds is dependent on the stabilisation control laws. However, this electronic stabilisation often means the stability and handling characteristics can be tuned for the application. Key application areas for multirotors are: • Small payloads (<3kg) • Operations from confined areas

Paragliders 	**Paragliders** are a sub-class of fixed wing vehicles. Unlike other fixed wing vehicles, the main lift generating surface of a paraglider is non-rigid, and often resembles a parachute. The non-rigid wing makes the system more portable than a conventional fixed wing vehicle. Like fixed-wing vehicles, paragliders have a relatively high aerodynamic efficiency. Application areas are: • Similar to those for fixed wing platforms and • When a compact/portable vehicle is required
Kites 	**Kites** have also been used as a mechanism to fly remote sensing payloads. While kites are a low cost and easy-to-operate platform, they are restricted to operations under favourable weather conditions.
Blimps 	**Blimps** are lighter than air vehicles that may be tethered or able to move under their own power. While blimps can offer longer endurance than their heavier than air vehicle counterparts, their maneuverability can be limited, especially in windy conditions.

7.2 Application Domains

A wide range of performance metrics can be used to compare the suitability of aerial vehicles for a given application. These metrics include endurance, payload capability, operational ceiling, cruise speed and range. This section will focus on the first two metrics, endurance and payload capability. In remote sensing applications, the remaining metrics are often constrained by operational, practical or mission considerations rather than the vehicle itself. For example, the cruising altitude in a remote sensing mission is typically defined by the desired spatial resolution and the capabilities of the payload sensor(s), or by legal constraints aimed at segregating UAV operations from manned aircraft. Further, the operating speed may be constrained by the shutter rate of the payload sensor(s) and the desired along-track overlap. Finally, the range of a vehicle is often constrained by the need to keep the vehicle within line-of-sight (due to legal requirements or the need to manually fly the UAV) or by limitations of the telemetry, command and control datalink.

In order to define the domains to which each class of vehicle is suited, we plot the endurance and payload capabilities of UAVs used in remote sensing applications as a function their gross weight. Here, the gross weight is used as the independent variable since it is one measure of the size of a platform, and since the acquisition and operating costs of UAVs are known to be well correlated with their weight.

Figure 1 illustrates the relationship between vehicle gross weight and endurance. It can be seen that there is a trend for larger vehicles to have longer endurance. It can also be seen that for a given size, fixed wing vehicles often have a longer endurance than rotary wing vehicles or multirotors. This has clear implications for remote sensing missions, and the spatial extent of image acquisition. Clearly multirotor platforms with their low flight duration must be launched and recovered very close to the area of interest. Larger fixed wing platforms are better suited to broad scale coverage applications.

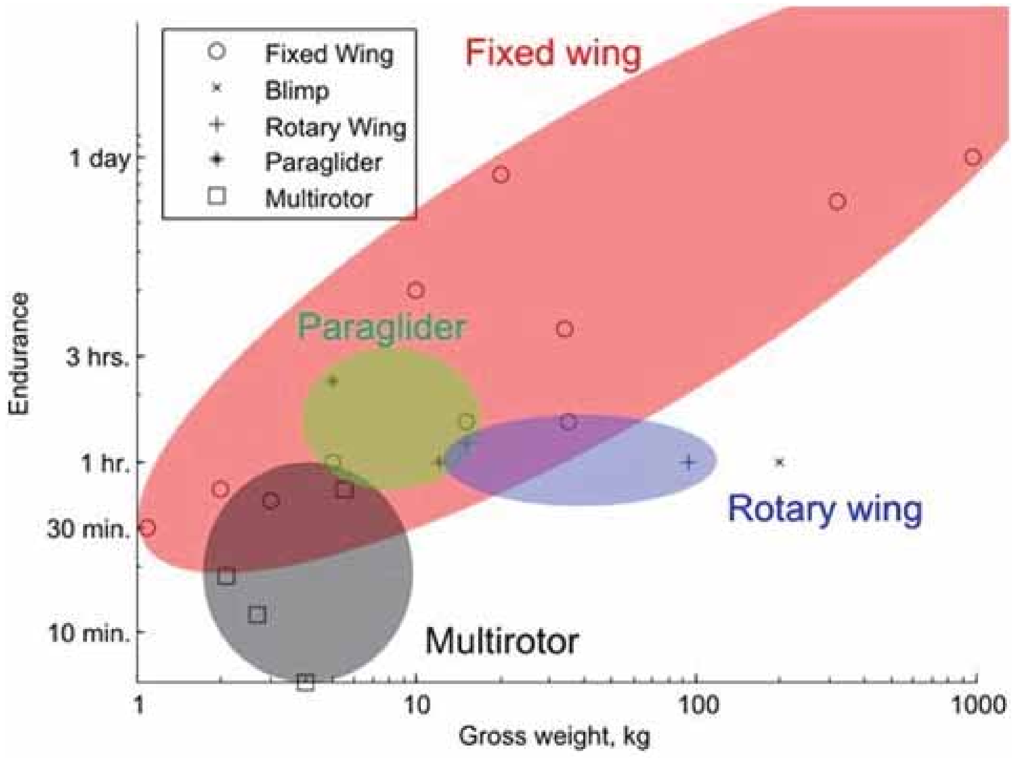


Figure 1: Relationship between UAV platform size (gross weight) and endurance

Figure 2 illustrates the relationship between UAV size and payload capability. Again, there is a trend for larger vehicles to have higher payload capabilities. Both figures also illustrate the weight ranges that each class spans. Fixed wing UAVs are the most diverse class, spanning gross weights of 1kg to 1000kg. Further, it can be seen that multirotors and rotary wing UAVs each spans their own niche: multirotors span the range from 1-10kg, while rotary wing UAVs span the >10kg range.

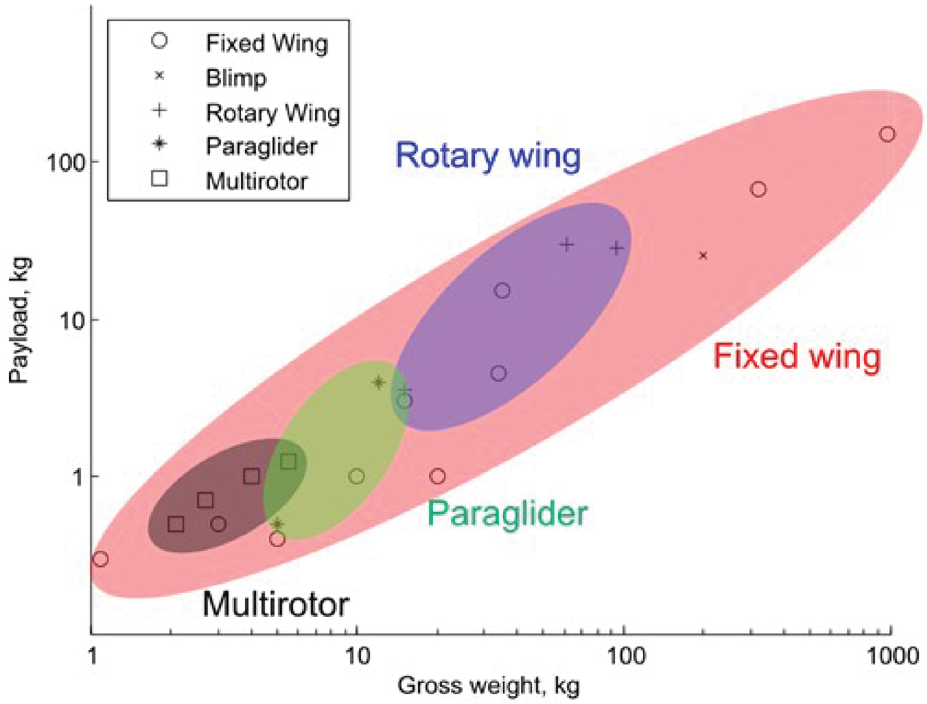


Figure 2 Relationship between UAV platform size (gross weight) and payload capability

Platform	Type	Weight (kg)	Endurance (hrs)	Payload (kg)
General Atomics ATLUS II	Fixed wing	975	24	150
Carolo P330	Fixed Wing	5	1	0.4
Smartone	Fixed Wing	1.1	0.5	0.3
AeroVironment Pathfinder	Fixed Wing	318	15	67.5
Boeing Insitu Scan Eagle	Fixed Wing	20	20	1
MLB Bat 3	Fixed Wing	10	6	1
Trimble Gatewing	Fixed Wing	2	0.75	-
Elimco E300 Viewer	Fixed Wing	15	1.5	3
Vector P	Fixed Wing	34	4	4.5
Sirius 1	Fixed Wing	3	0.66	0.5
Yamaha RMAX	Rotary Wing	94	1	28
UAV Vision G18	Rotary Wing	61.5	-	30
SUSI	Paraglider	5	2.3	0.5
Pixy	Paraglider	12	1	4
Microdrones MD4-1000	Multirotor	5.6	0.75	1.25
Ascending Technologies	Multirotor	2.1	0.3	0.5
Mikrokopter Octocopter	Multirotor	4	0.1	1

7.3 Power-Plants

With the exception of unpowered kites and tethered balloons, all classes of platforms require one or more power-plant(s). Power- plants can be divided into two groups: internal combustion and electric. The key advantage of internal combustion power-plants is their high energy density, which translates to a larger payload capability, or longer endurance. However, internal combustion engines are also more complex and thus requires more operator training. The availability of power-plant options is summarised in the table below.

Class	Power-plants
Fixed wing	Both
Paragliders	Both
Rotary Wing	Both
Multi-rotors	Electric

7.4 Autonomy

The level autonomy of UAV used in remote sensing applications range from manually controlled platforms to UAV equipped with flight management systems capable of flying a pre-programmed route and landing autonomously.

While not inherently a part of the platform, the integration of a flight management system to allow a UAV to follow a pre-programmed path has a number of advantages. Firstly, this capability makes beyond line of sight operations possible.

Secondly, it makes repeatable and precisely defined surveys possible. Lastly, many flight management systems can provide navigation solutions, which can be used for geo- registration of sensor data and stabilisation of payload sensors.

APPENDIX 8: CASA REGULATIONS[4]

The operation of UAVs in Australia is regulated by the Civil Aviation Safety Authority (CASA).

CASA offers advice on how operators can comply with legislation through Advisory Circular 101-1 (AC101-1). At the time of writing, CASA was reviewing AC101-1 to align the regulation of UAV with international guidelines. This section is based on the contents of a Notice of Proposed Rule- Making (NPRM) document issued by CASA, and may or may not be reflective of the final form of AC101-1.

While focused on *remote-piloted* aircraft, this NPRM leaves open the possibility for automation to be considered on a case-by-case basis subject to a safety case presented to CASA..

The CASA Notice of Proposed Rule Making (NPRM) classifies UAV into four categories based on their gross weight. These categories are outlined in the table below.

Category	**Weight Range**
Micro	<100g
Small	100g - 2kg
Medium	2kg - 150kg
Large	>150kg

The categories of most interest are the small and medium classes.

The key advantage of the Small class is that regulatory oversight is more relaxed than other classes, subject to certain conditions. These conditions include:

- Visual line of sight operations, in accordance to the definition outlined in the NPRM
- At or below an altitude of 400' above the ground or water
- Over non-populous areas
- More than 30m away from any person not directly involved in the operations
- Day visual meteorological conditions
- Outside controlled airspace
- Outside prohibited, restricted and danger areas
- Greater than 3NM from an aerodrome boundary.

[4] **Dr Zhe Xu, Dr Calvin Hung and Professor Salah Sukkarieh, USYD ACFR**

Examples of UAV applications that *may* be operated under the Small vehicle classification include:

- A multi-rotor used to survey small, inaccessible regions.
- A small fixed wing UAV used to survey hobby farms or smaller properties.
- If public access to high-risk pathways can be controlled – and the abovementioned conditions met – short segments (several kilometers) of high risk pathways may also be surveyed.

The higher weight range available to the Medium class UAV leads to longer platform endurance (several hours) and opens opportunities to survey larger areas. However, these advantages come at the expense of additional regulatory oversight – the operation of Medium class UAV requires certification by CASA.

The key certifications required are:

- A Remote Pilot (RP) Certificate for individual pilots and
- An Unmanned Aircraft System Operator's Certificate for the organisation

The requirements for obtaining these certifications are outlined in the NPRM. In summary, an RP certificate can be obtained through self-study or via a CASA-approved training organisation and includes a requirement to be licensed to use an aeronautical radio. This certificate is associated with a rating for a specific UAV platform. To obtain an operator's certificate, an organisation must demonstrate its processes by providing documentation (operations manual, flight manual, maintenance manual) and through a series of assessments comprising interviews, demonstration of the UAV, and inspection of documentation, facilities and maintenance activities. Additionally, the constraints outlined for the Small UAV category still apply, unless the operator and pilot are specially certified.

UAV operators also need to consider regulations around the use of radio-frequency spectrum. Amongst other things, these regulations define the frequencies and radiated power from radio-frequency transmitters, including those used for radio control of UAV or the uplink and downlink of command, control or mission data. Examples include the operator's telemetry link to the airborne vehicle or the downlink of a video feed to sensor operators. The Australian Communications and Media Authority is the government point of contact for radio-frequency spectrum issues.

APPENDIX 9: LITERATURE REVIEW

RMCG

Environment | Water | Agriculture
Policy | Economics | Communities

Cost-benefit analysis of incorporating UAV technology into NIWAC activities

Literature review

NIWAC

28th August 2014

Introduction

This document forms the first deliverable of a cost-benefit analysis (CBA) in the incorporation of unmanned aerial vehicles and thermal imaging (henceforth 'UAV technology' for short) into NIWAC weed management activities.

The purpose of this document is to inform the development of the CBA framework for the study.

Recommendations on potential options for the use of UAV technology are forthcoming from Professor Salah Sukkarieh, as is a response to these recommendations by NIWAC in their Feasibility Study document. The details of the economic framework that we will adopt for this CBA will be finalised after reviewing these documents.

The structure of this document is as follows:

- We first explore the literature on UAV technology in weed management and agriculture, in the Australian and international context. This literature is complemented by some initial consultation with experts in UAVs and weed management
- We then review on the economic literature relating to the costs and benefits of weeds in the Australian and NSW context, and frameworks for assessing their costs and benefits.
- We then propose a preliminary economic framework for the analysis, drawing on the first two steps.

Use of UAV technology for weed management and other uses

A review of the literature and preliminary consultation reveals several studies that have used UAV technology, sometimes with associated algorithms for weed management. Many of these involve Professor Sukkarieh. Studies include:

- Land and Water Australia funded Professor Sukkarieh to explore the feasibility of UAVs in detecting and spraying aquatic weeds (LWA 2008)

- UAV Surveillance Systems for the Management of Woody Weeds – a project involving Professor Sukkarieh for Meat and Livestock Australia exploring use of the technology for woody weeds (Bryson and Sukkarieh 2011)
- Demonstration of an unmanned aerial vehicle to detect alligator weed, for the Victorian Department of Environment and Primary Industries (Clements et al 2014)
- The Queensland Government announced in 2013 that it would use UAVs to identify and spray weeds on 250,000 hectares per year, using contracting services.[1]
- Melbourne Water is trialling the use of UAVs for asset monitoring for large water supply assets and constructed wetlands.[2]
- CSIRO and Biosecurity Queensland are trialling the use of UAVs for weed management in rainforests.[3]

RMCG is aware of no Australian analysis that has considered the cost-effectiveness of using UAV technology for weed management.

Similarly, the international literature focuses on the UAV's technological capacity to identify weeds or other agricultural uses. Among many studies:

- NASA's Pathfinder-Plus UAV was used in 2002 to monitor a coffee plantation in Hawaii, exploring potential for mapping weeds, revealing irrigation and fertiliser anomalies and observing fruit harvest maturity (Herwitz *et al* 2003)
- A 2007 PhD thesis trialled the use of UAVs and manned helicopters in vegetation mapping as part of rangeland monitoring. The study focussed on the technological feasibility, predicting that UAV technology may soon revolutionise rangeland monitoring as has GPS technology affected navigation
- A 2010 review of the potential of UAVs in site-specific weed management at the farm scale concluded that the technology was not cost-effective due to prohibitive operating costs. The study identified two main limitations; firstly, the time and education required for applying new technological advances; and secondly the high cost of the technology and the lack of compatibility of the machinery (Granados 2010)
- A study in Idaho explored the potential for use of UAVs to complement or replace existing monitoring methods for sagebrush steppe ecosystems, finding that if a high degree of detail and data accuracy is desired then a helicopter UAV may be preferred. If data collection is to assess broad-scale landscape level changes, then a fixed-wing system is more appropriate
- A study in Germany explored the potential to use UAV technology to monitor vegetation communities as part of ecological monitoring, concluding potential exists to significantly reduce labourious field surveys (Knoth *et al* 2013)
- Another German study considered the effectiveness of UAVs in site-specific weed management on cropping land, concluding that the technology was relatively easy to integrate as a tool in weed research, and offers great potential for site-specific weed management (Rasmussen *et al* 2013)
- A wheat field in Spain was used to explore the use of UAVs for precision agriculture, finding that visible spectral indices derived from images acquired using a low-cost camera onboard a UAV flying at low

[1] http://www.itnews.com.au/News/363484,queensland-deploys-drones-to-kill-weeds.aspx

[2] RMCG has made contact with Melbourne Water project officers and intends to meet to discuss the potential for cost-sharing with other agencies and jurisdictions.

[3] http://www.enviroinfo.com.au/robots-help-save-rainforests-from-invasive-weeds/?utm_source=EnviroInfo%20Subscribers&utm_campaign=b521614420-Enviro%20Info%20Newsletter&utm_medium=email&utm_term=0_e6009c686b-b521614420-69423145#.U_1IfFbfLTM

altitudes are a suitable tool to discriminate vegetation in wheat fields in the early season (Torres-Sanchez 2014).

Of the 15 peer-reviewed international studies explored for this literature review, the majority focussed on potential agricultural uses (e.g. fertiliser application, crop observation) and all focussed on the technical capacity of the technology rather than genuinely exploring the cost-effectiveness of the application in the field.

Where studies have considered the cost-effectiveness of the application, it has been compared against manned helicopter flights, not current practice by the agricultural or weed management industry.

Similarly, exploration of both the practical effectiveness and the cost-effectiveness of incorporating UAV technology into weed management activities appears to be a gap in the Australian and international literature.

Conceptualising an economic framework

Development of an economic framework for assessing the costs and benefits of incorporating UAV technology into NIWAC weed management activities requires three key steps:

1. An understanding of the economic costs and benefits of weeds and weed management to an economy
2. An understanding of how the incorporation of UAV technology will change the weed management activities and effectiveness of NIWAC; and lastly
3. Quantification of the impact of these changes to the economy in cost-benefit terms.

Steps two and three will be developed subsequent to this literature review, building on inputs from NIWAC and Professor Sukkarieh. As such, we focus the literature review on relevant assessments of economic costs and benefits of weed management.

Weeds affect an economy through impacts on productivity, amenity values, lost recreational values and biodiversity among other impacts. In response, weed management activities are undertaken to mitigate these impacts, requiring the investment of time and resources.

Jones *et al* (2000) outlined the trade-off between losses caused by weeds and expenditure on weed management activities. As expenditure on weed management increases, reductions in costs caused by weeds can be expected to fall.

Two approaches have been used to quantify the costs of weeds to an economy:

- The loss-expenditure method quantifies losses due to weeds and adds the management costs that have been incurred to control weeds; and
- The economic surplus approach measures the lost economic surplus in affected markets when supply shifts due to increased costs of production and reduced availability of product in the market place.

In theory, both methodologies should produce similar results. The economic surplus approach includes estimated changes in agricultural prices due to weeds and thus may not be perfectly suited to this CBA, which focuses on a policy change affecting a smaller geographic region which is unlikely to produce price changes. The loss-expenditure method is therefore recommended for this analysis.

Estimates of weed impact – agricultural productivity and weed management costs

There is a significant body of literature that has estimated the annual economic impact of weeds in Australia. Studies have focussed on national costs of all weeds, others on jurisdictional analyses, and others have focussed on the impact of specific weeds. Almost all analyses have focussed on the impacts on agricultural productivity, and expenditures to mitigate these impacts by public and private land managers.

For example, Lloyd (2005) estimated the annual cost of Paterson's curse to Australia at $240M, focussed largely on lost productivity, control costs and wool contamination to sheep and cattle producers. The Weeds CRC (2006) estimated the cost of blackberry control and lost production across Australia at $70M per year.

Ireson *et al* (2007) estimated production losses and herbicide costs to produce a total annual economic cost of weeds to Tasmania of $58M.

Sinden *et al* (2005) estimated the total annual cost of weeds in Australia, using loss-expenditure analysis and an estimate of the total change in economic surplus caused by weeds in agriculture. This study estimated total annual cost at an average of $4,039M.

An earlier estimate by Combellack (1987) considered control costs and gross losses in agricultural production, as well as direct weed management costs in national parks, railways, forestry establishment, aquatic areas and industrial buildings. Total annual costs were estimated at $2,096M.

Several studies have explored the impact of weeds on the NSW economy.

Most recently, Gordon (2014) estimated the annual economic costs of weeds to the NSW economy, which totalled $1,797M. This comprised $1,733M of lost economic surplus (largely to agricultural land) and $64.6M in public expenditure on agricultural and non-agricultural land. This estimate focussed on agricultural land (80% of NSW land), and did not consider the economic cost of biodiversity loss or expenditure by private landholders of non-agricultural land. It can therefore be considered a conservative estimate.

Previously, Montoya (2012) estimated the combined annual economic cost of weeds on the NSW economy at $1,200M.

ABS (2007) estimated that the total herbicide expenditure on agricultural lands in NSW totalled $475M.

Keller (2007) estimated the economic cost per invasive species due to the ornamental plant trade based on the Sinden (2004) estimate of total annual economic cost of weeds ($4,039M) and attributing a share of this to the ornamental plant industry (70% of this value, or $2,800M). Dividing this by the number of invasive species (1,366) gives the average annual cost per invader ($2,068,100).

Gordon (2014) notes that almost the entire literature on the costs of weeds has focussed on losses to agricultural systems. This is unsurprising given the sheer scale of agricultural land as a proportion of total land (80% of NSW land).

A useful breakdown of weed costs to agriculture in NSW can be found in **Table 1**, which shows the land area per major agricultural activity and the three major cost types to agriculture (lost production, chemical and machinery, and labour). From this data we can derive an 'average' cost per hectare of weed management by cropping, grazing and horticulture. Of relevance to the NIWAC, if it can be established that UAV technology can reduce this cost per hectare, this can be used as a basis for estimating a benefit in the CBA.

Table 1: Agricultural cost of weeds in NSW

Land use	Area (million ha)	Value of lost production ($M)	Chemical and machinery cost ($M)	Labour cost ($M)	Total cost ($M)	Cost per hectare ($/ha)
Cropping	8.57	117.85	364.17	31.26	513.28	$59.89
Grazing	54.66	454.93	325.64	178.7	959.27	$17.55
Horticulture	0.15	0.82	6.33	0.33	7.48	$49.87

Source: Land use data from DPI, weed cost data adapted from Gordon (2014)

Economic cost of weeds to biodiversity

Invasive weeds are recognized as one the five most serious factors causing the loss of global biodiversity (Vitousek, et al 1996). As noted by Adair and Groves (1998):

Environmental weeds threaten nearly all biological communities in Australia. Although weeds appear to degrade many natural ecosystems, quantitative measures of their impact on those systems are relatively rare.

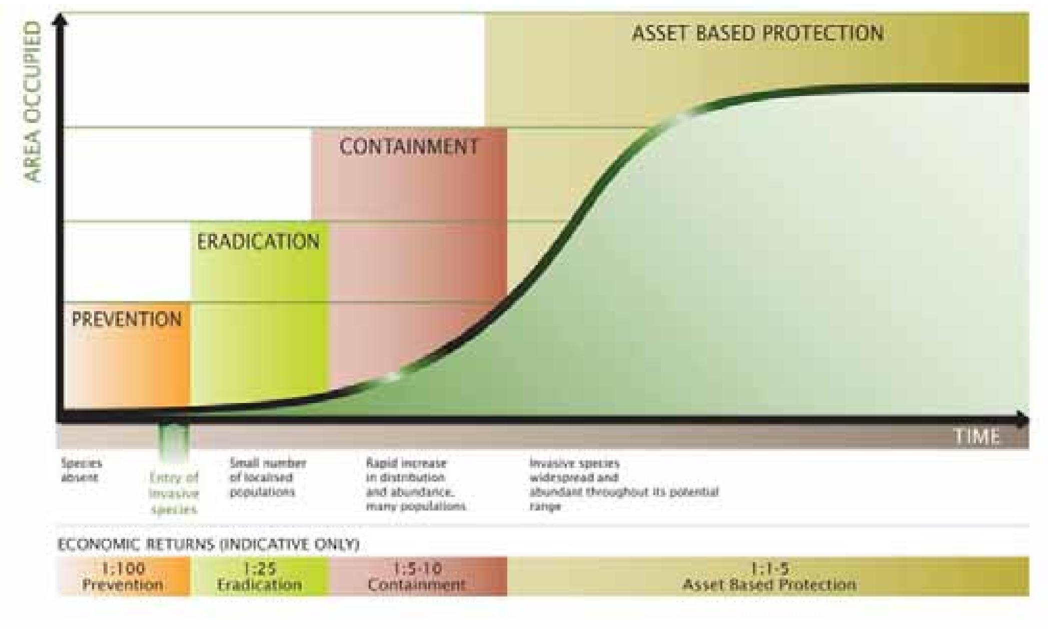
While often acknowledged as significant, no studies appear to have appropriately quantified the impact of weeds on biodiversity and environmental assets. This is due to difficulties in isolating the impact of weeds on biodiversity, and appropriately quantifying the loss in dollar terms due to weed invasions.

It appears unlikely that this project could meaningfully quantify the benefits to biodiversity of using the UAV technology. However, avoided costs to national park managers can be included if expected to change as a result of this technology.

The cost of a weed incursion and the benefits of early detection

The literature agrees that the costs of a weed incursion increases exponentially as the weed spreads. **Figure 1** shows a much-used representation of area covered by a new weed over time accompanied by the recommended stages of management: prevention, eradication, containment and asset based protection. Below the curve are the indicative economic returns of investment at each stage, showing declining cost-effectiveness at latter stages and the clear benefits of prevention, eradication and containment.

Figure 1 : Generalised weed invasion curve[4]



This indicative representation is supported by the literature in this area, however actual costs incurred both by weed managers and private landholders at different stages of a weed invasion are not recorded in the literature. This may be because individual weeds and their impact will differ significantly by weed type, geographic location and time period.

Discussion with John Virtue[5] and Dr Cheryl Kalisch Gordon[6] suggests that case studies of weed incursions with associated costs may be best developed in consultation with NIWAC. This could be based on actual costs incurred by NIWAC for new weed incursions, and added to industry averages for private weed management costs that would be incurred by landholders if a new weed invasion were to occur.

The 'avoided cost' of preventing a weed from becoming established in the NIWAC region might be established. When combined with the change in likelihood of this occurring due to the UAV technology, quantification of this benefit can be established.

We will develop this concept further once we have a better understanding of the proposed options for incorporating UAV technology into NIWAC activities.

[4] Source: http://www.depi.vic.gov.au/agriculture-and-food/pests-diseases-and-weeds/protecting-victoria-from-pest-animals-and-weeds
[5] Senior Weed Ecologist, Animal and Plant Control Group, Department of Water, Land and Biodiversity Conservation (South Australia)
[6] Senior Economist, GrainGrowers Limited

Consideration of broader or flow-on benefits

It has been identified by NIWAC and others that there is potential to generate broader benefits from the use of UAV technology in multiple ways. Our initial consultation and literature review suggests the following possibilities:

- Multiple stakeholders could benefit from the aerial imagery used in the trial, including landholders themselves. Discussion with Dr Gordon of GrainGrowers revealed that they have an online farm management tool called ProductionWise which is GIS linked into soil, weather/forecasting and historical use data. Linking it with GIS Weed identification and control data would be a great additional tool for grain producers
- Collaboration with other agencies within and outside of NSW could generate more value from the technology. For example, the Victorian Department of Environment and Primary Industries (DEPI) has been trialling similar technology, and has developed algorithms for two weeds with Professor Sukkarieh.[7] The potential to share this information could significantly reduce overall costs to agencies
- Other land management agencies may be interested in sharing the visual imagery data, reducing the costs to a single agency in securing the data.

These potential flow-on benefits will be explored in more detail in the analysis.

National parks

Preliminary discussion with Stuart Boyd-Law[8] revealed that there is potential to use the UAV technology to assist the National Parks service in prioritising their spending on weed management in the NIWAC region. Available budget allocated to weed management is considered minimal, resulting in the undertaking of specific actions that are commensurate with available funds.

RMCG will discuss this further as a potential 'flow-on' benefit of the UAV technology, or an opportunity to cost-share with other agencies.

Consideration of a CBA framework for NIWAC

This literature review confirms a number of facts for the NIWAC use of UAV technology, including:

- The cost of weeds is significant both to landholders and agencies charged with managing weed infestations
- The major burden of weed costs is on reduced agricultural production, with smaller but important costs to public and private weed managers (e.g. herbicides, labour, control costs, and
- The costs to biodiversity and environmental assets are likely to be significant, but have rarely been appropriately quantified.

Considering the impact of UAV technology on weed management in the NIWAC region, a number of potential benefits are apparent:

- Cost savings to NIWAC by increasing the efficiency of weed surveillance and response actions

[7] RMCG intends to meet with DEPI to discuss their experiences with the technology. We also intend to meet with Melbourne Water which has also trialled the use of UAV technology.
[8] Pest Management Officer, National Parks (Glen Innes)

- Improvements in the effectiveness of weed management activities by NIWAC, leading to a reduction in the likelihood that a new weed incursion moves beyond the eradication stage to containment, and/or from containment to asset based protection. This would have benefits to private landholders from reduced weed management and productivity losses, and
- Flow-on benefits for other agencies and private landholders from using the technology or the data outputs.

To quantify the increased weed management effectiveness benefit of incorporating the UAV technology, we would need the following inputs:

- The number of new incursions that occur in the NIWAC region in a given time period (through discussion with NIWAC)
- The increased likelihood of eradicating or containing a weed incursion due to the technology
- Quantification of the saved costs to NIWAC from eradicating or containing the weed incursion (through discussion with NIWAC), and
- Quantification of the saved costs to private landholders of eradicating or containing the weed incursion due to the technology (NIWAC may be able to provide weed management costs per hectare for use in this analysis).

This data could be used to calculate the present value of the technology in increasing the effectiveness of weed management in the region. This concept appears possible to quantify (with the use of some necessary assumptions) but will be developed further in consultation with NIWAC.

Building on this literature, we have prepared a preliminary economic framework to consider the incorporation of UAV technology into NIWAC activities. This framework is illustrated in **Figure 2**.

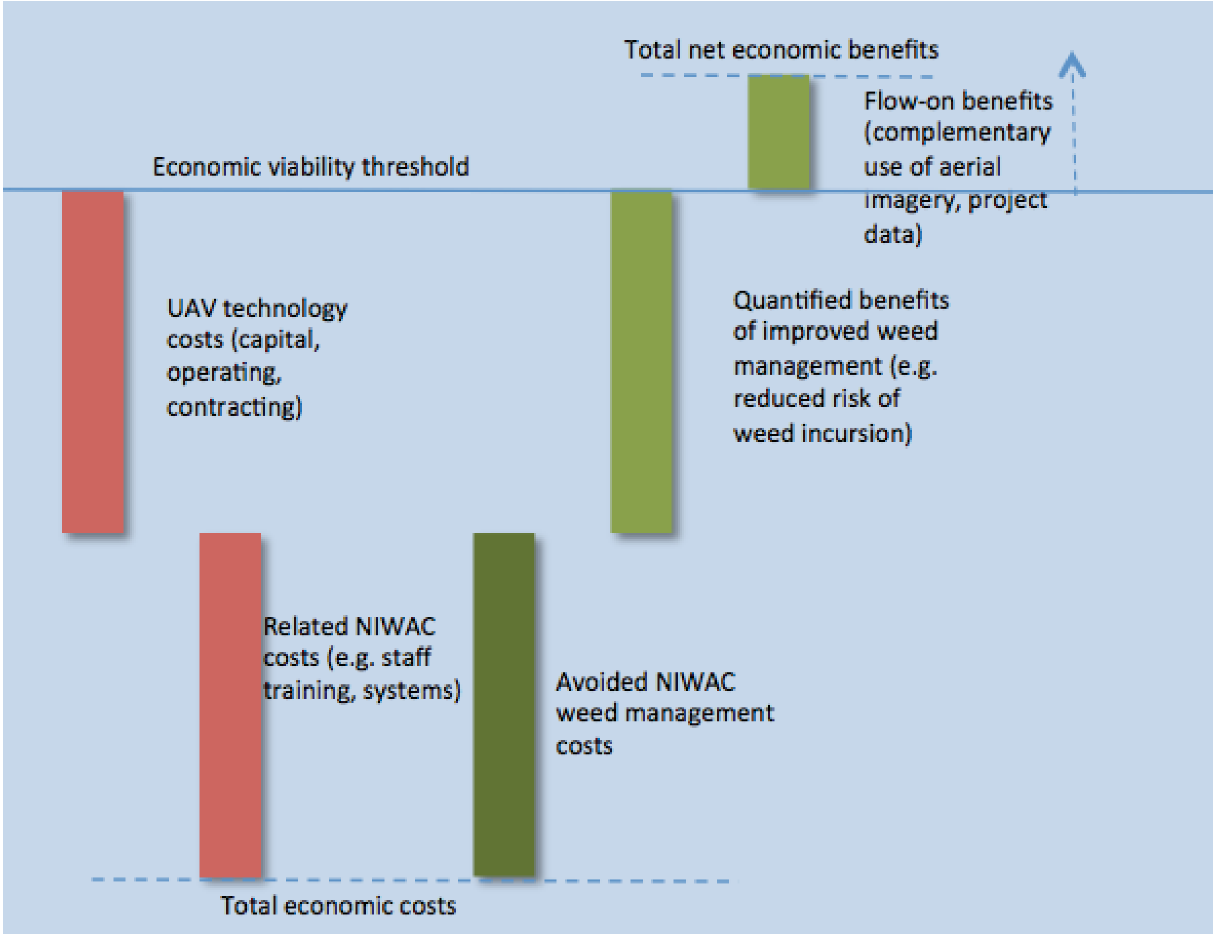
Relevant costs are represented in the red bars that add downward to the ‘total economic costs’. These include all those direct and indirect costs associated with the use of UAV technology as part of NIWAC activities, including capital and operating costs of the technology, any algorithm development costs, training and purchase of any services. For this study, these costs will be developed in collaboration with Professor Sukkarieh and NIWAC.

Benefits are represented in green bars and broadly involve three types:

1. Avoided weed management costs for NIWAC or other weed managers where the technology replaces the need for other types of weed management expenditures
2. Reduction in the economic costs of weeds due to increased effectiveness of weed management (quantified impacts on agricultural productivity, amenity and recreational values and biodiversity values), and
3. Flow-on benefits that the technology may bring, such as flow-on benefits to other data users (such as farmers who may find compatible uses for high resolution photos, or other land managers). This may involve quantifiable benefits (e.g. other agencies may be willing to pay for analysis data outputs) and unquantifiable benefits of information sharing.

Where the project benefits add to exceed the project costs (the ‘net economic benefits’ exceed the economic viability threshold), the investment has positive net benefits and can be justified for implementation.

Figure 2 : Economic framework for costs and benefits of UAV technology to NIWAC[9]



This framework will be further developed through the course of the project.

[9] Source: RMCG analysis. Note, this is conceptual only – bars do not reflect actual scale of benefits and costs

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