Manaaki Whenua
Landcare Research

Remote sensing for monitoring invasive weeds and evaluating impacts of introduced natural enemies in Pacific Island countries and territories

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Remote sensing for monitoring invasive weeds and evaluating impacts of introduced natural enemies in Pacific Island countries and territories

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Manaaki Whenua – Landcare Research

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Summary

Background

Introducing natural enemies to control invasive weeds in Pacific Island countries and territories (PICTs) is often the only practical solution to this growing problem. Current climate change scenarios predict more disruption to biodiversity, ecosystem services, primary production, and human health and safety in the future as the speed of weed invasions across the PICTs increases. While natural enemies of weeds have an excellent weed control track record, monitoring weed populations and evaluating impacts following introductions is challenging especially for large tree species or vines that grow in canopies.

Approach and methods

We tested various remote sensing monitoring and evaluation techniques including consideration of scale, spectra, timing, and texture, to develop a practical solution for PICTs wanting to assess their own weed control projects. The method we recommend after testing these techniques includes flying 10 cm resolution aeroplane imagery over target areas and using artificial intelligence deep learning approaches developed by Manaaki Whenua – Landcare Research (MWLR) in QGIS (commonly used free GIS software) to map distinctive target species.

Results

- We have made maps of African tulip tree (*Spathodea campanulata*) and tamaligi/albizia (*Falcataria moluccana*) occurrence in Rarotonga as an example of the types of baseline maps that can be produced and used for future comparisons. In addition to this, we used high-resolution (1–4 cm) imagery captured at a selection of smaller drone test sites within this area to collect tree-scale statistics for detailed future comparisons and for evaluating the impacts of natural enemies of weeds. Preliminary drone footage from Niue showed the potential for mapping taro vine (*Epipremnum pinnatum*) using unique spectral signatures.
- To help detect natural weed enemy presence and density we captured very high-resolution (< 0.5 cm) drone imagery over individual tree canopies at the same test sites to look for damage on an individual leaf scale. We also trialled a drone-based canopy sampler to collect vegetative material from tall trees, but it proved difficult to operate and would not be suitable for collecting large numbers of samples by an inexperienced operator.

Recommendations

For ongoing monitoring and evaluation of natural enemies to control invasive weeds in Rarotonga and other PICTs we recommend the following (see Section 6 for more detail).

- Rarotongan National Environmental Service to support re-flying island-scale and drone site imagery in 5–10 years' time to assess natural enemy impacts. To do this the practicality of managing image acquisition and assessment work locally versus external

contracting needs to be determined. Tools and skills then need to be acquired for locally managed work and external contractors sourced for remaining tasks.

- Rarotonga National Environmental Service to consider the potential for mapping additional invasive weed species from the existing aeroplane imagery.
- Other PICTs to consider the collection of similar baseline imagery where information on invasive weed spread distribution and impacts of control efforts is required.

1 Introduction

Invasive non-native plants (henceforth ‘invasive weeds’) threaten biodiversity, ecosystem services, primary production and human health and safety in Pacific Island countries and territories (PICTs) and are expected to become more problematic under predicted climate change scenarios. This is because invasive weeds are likely to grow faster under elevated CO_2 levels and because storms are predicted to be more severe in the future creating greater disturbance that further promotes weed invasions.

Since 1911, 69 biological control agents (henceforth ‘natural enemies’) have been released against 28 invasive weeds in 18 PICTs. A renewed effort by Manaaki Whenua – Landcare Research (MWLR) since 2016 has been responsible for 13 of these releases against 12 invasive weeds in 5 PICTs (Cook Islands, Vanuatu, Tonga, Tuvalu, and the Marshall Islands). Assessing impacts of these natural enemies on invasive weed populations in the Pacific is critical to evaluating the costs and benefits to communities but has not been done well in the past. First, it is vital to know the initial extent of invasive weed problems so that baseline distribution and density maps can be produced prior to releasing natural enemies. This information is usually lacking. Second, tools to determine establishment success and impacts of natural enemies need to be developed.

To determine invasive weed distribution, techniques must uniquely distinguish the target from other species in ways that are independent of topographical and geological factors and may include spectral, textural and phenological approaches (Bradley 2014). These techniques can also be scale- and time-dependent and may even require a combination of approaches (Müllerová et al. 2017, 2023).

This report describes an investigation into the application of remote sensing to help map invasive weeds and monitor establishment success and direct impacts of natural enemies imported to control invasive weeds in the PICTs. The aim of this work is to provide Pacific Island communities with tools and knowledge that will allow weed control projects to be fully (or at least partially) monitored and assessed locally.

1.1 Approaches using satellite and other imagery

Previous attempts to map weeds in the Pacific have used satellite imagery to identify canopy composition and/or vegetation types (Pouteau et al. 2013, 2015; Meyer et al. 2015) but there are problems associated with this broad-scale approach. For example, Matepi et. al. (2010) mapped invasive vines in Rarotonga by visiting sites on foot where invasive vines were growing and recording GPS locations. They then identified spectral bands (reflected light) from these locations and made a map of the island by extrapolation.

Matepi et al’s mapping did help to show the broad magnitude of the vine distribution in Rarotonga but the image resolution was only ≥1 m meaning that species identification and subsequent changes due to control efforts will be difficult to interpret. Image resolution refers to the size of the pixels that make up an image and for a target to be identified it needs to span several pixels. This problem is particularly relevant to vines or other targets, where different species can form a heterogenous canopy and cannot easily be distinguished from one another. Vines for example tend to be lumped together (sometimes both exotic and native) and controlling one species can lead to an increase in another. However, this can occur with tree species as well.

In this pilot study we trialled satellite imagery but also tested the use of higher resolution imagery to detect individuals of our target species. For the purposes of this study, we refer to low-resolution imagery as ≥50 cm (satellite), medium-resolution as 10 cm (aeroplane), high-resolution as 1-4 cm (drone 30-100 m above canopy level [ACL]), and very high–resolution as <0.5 cm (drone 10-30 m ACL). Low- and medium-resolution imagery has potential for large-scale mapping of weeds but requires ground truthing to map weeds accurately. Measuring subtle impacts of natural enemies will require even more detailed ground truthing. Ground truthing can be done on foot but there is also potential to use high-resolution imagery to identify different weed species and detect subtle impacts of natural enemies. To detect establishment and damage to vegetation caused by natural enemies even higher resolution may be required.

1.2 Other approaches

Techniques like targeting flowering can also be useful to help distinguish target species that have a peak flowering period, while hyperspectral imagery can be used to identify differences in spectral reflectance not obvious to the human eye. Distinctive spectra reflected by different tree species, or by damage caused by natural enemies that disrupt photosynthesis (feeding, galling, or disease) could be detected using hyperspectral sensors. Spectra can consist of visible light or RGB (red, green, blue) which is captured by a standard camera sensor, or non-visible light such as near infrared (NIR) which can be useful for assessing plant health. When plants photosynthesise chlorophyll only absorbs and uses visible light while NIR light is reflected. When plants become stressed or damaged and stop photosynthesising, they absorb NIR light. This change in reflectance can be measure as the Normalized Difference Vegetation Index (NDVI) calculated as (NIR-Red)/(NIR+Red). The NDVI value ranges from –1 to +1. Negative values indicate no vegetation or vegetation that is dead or has no active chlorophyll (i.e. not green), whereas high values indicate healthy leaves containing chlorophyll (i.e. green).

When natural enemies damage invasive weeds, we’d expect to see negative NDVI values in the NIR bands. Light Detecting and Ranging (LiDAR) is another technique worth exploring to help with mapping and impact assessment. LiDAR data can be used to create canopy height models or distinguish different plant species by leaf/canopy texture at very high resolutions.

1.3 Data processing and analysis considerations

Data processing and analysis are other important considerations when mapping weeds in imagery. The approach used whether it be manual or automated, will depend on the scale of the project and required outcomes. Manual image classification is useful when tolerance of false positives (detecting a weed when it’s not actually there) is low or if the target species share distinctive features with another species which are context dependant (Peterson et al. 2024).

Automated methods including Artificial Intelligence (AI) are useful for analysing large areas where the occurrence of false positives is not critical and can be 'taught' contextual constraints if enough training data are available. AI methods include shallow and deep learning algorithms. Defined parameters can be set and optimised manually which prescribe decision-making in shallow learning algorithms and can be spectral or texture/shape based for example. An example of a shallow learning software platform is eCognition.

Conversely, deep learning models simply require exposure to data, which is representative of the imagery to be mapped, and these 'training data' are specified as either target (to be included in mapping) or non-target (to be excluded from mapping). Parameters for deep learning algorithms are not defined and the constituent components of the decision-making process cannot be isolated or identified. The primary form of deep learning used in image processing are convolutional neural networks (CNN) which employ layers of filters to capture and process spatial hierarchies in imagery.

1.4 Practical considerations

In addition to remote sensing methods, testing drone-based canopy sampling tools may help us to detect natural enemy presence and density. It can often be difficult to determine the establishment success of natural enemies early on, especially if they live in tree canopies. However, methods used need to be practical in remote locations and applicable to a range of terrains. The impacts of natural enemies include: direct primary effects on invasive weeds through feeding, galling, or disease; direct secondary impacts including a reduction in vigour, rate of spread or longevity; and indirect impacts including increased biodiversity, ecosystem services, primary production and human health and safety.

In this study we only considered the direct impacts of natural enemies on invasive weeds using remote sensing. A previous report to the Office of the Prime Minister Cook Islands (Paynter et al. 2024) reports on recent monitoring of establishment and impacts of natural enemies released onto invasive weeds in Rarotonga using ground-based data only.

2 Objectives

This study had several objectives. They included the following.

- Carrying out experimental investigations of remote sensing techniques.
- Capturing baseline images by creating maps of invasive species.
- Collecting data to evaluate impacts of natural enemies including damage to tree canopies.
- Developing capacity in the PICTs so that weed control projects can be monitored and assessed locally.

Our approaches to meeting each of these objectives are described in more detail in Sections 2.1–2.4.

2.1 Design experimental projects to monitor invasive weed distribution and evaluate impacts of introduced natural enemies in PICTs

We designed experimental projects to determine the value of remote sensing for monitoring invasive weed distribution and evaluating impacts of natural enemies to assess the importance of scale, spectra, timing, and texture.

Rarotonga and Niue were the two study sites chosen (Figure 1). The plants chosen as the three priority invasive species for this investigation were: African tulip tree *(Spathodea campanulata*; abbreviated in this report to ATT); tamaligi or albizia *(Falcataria moluccana*) (referred to throughout this report as 'Falcataria' because of the wide range of common names for it worldwide); and taro vine *(Epipremnum pinnatum* cv *Aureum*) (Figure 2).

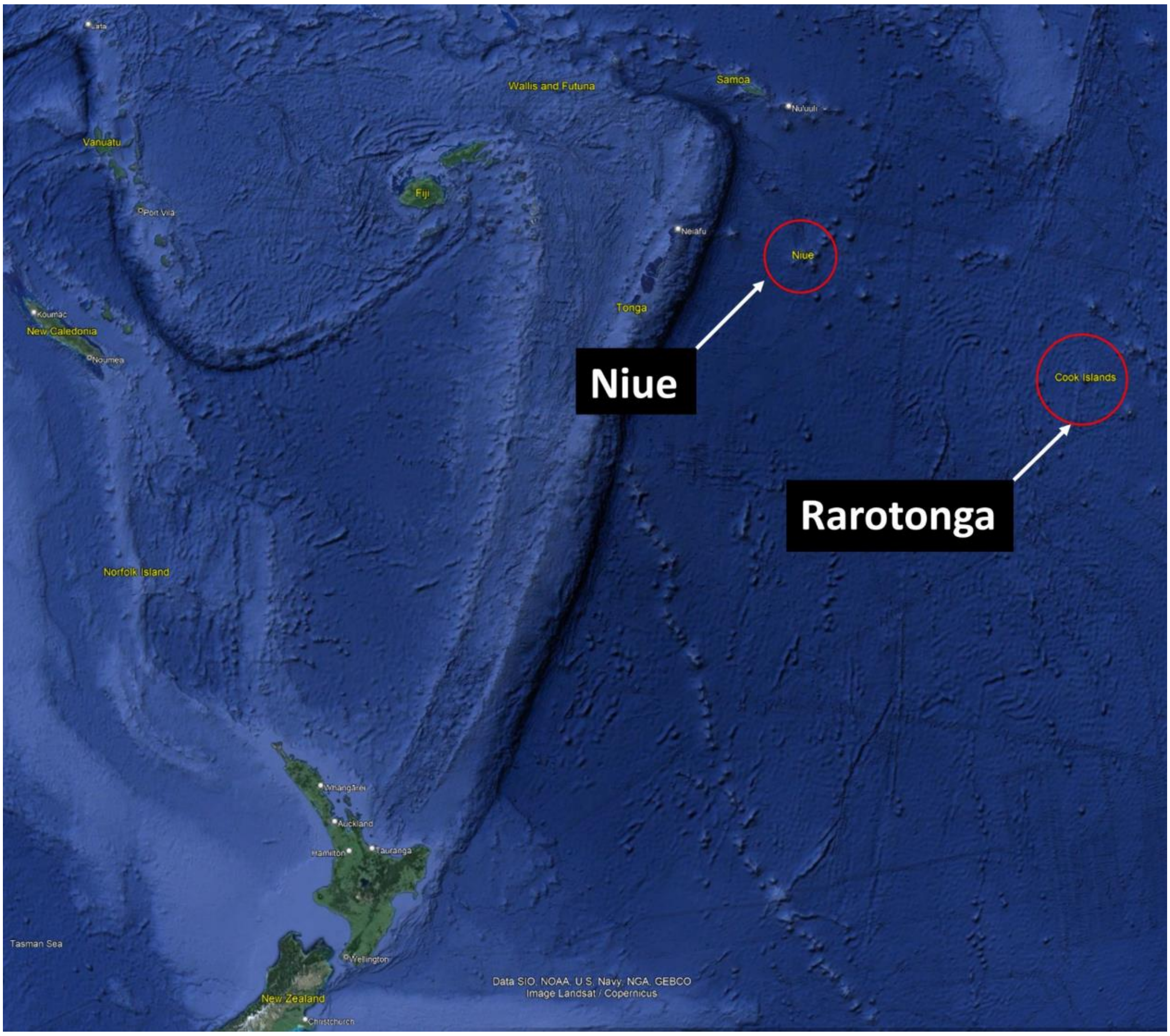

Figure 1. Map showing location of Niue and Rarotonga (Cook Islands).

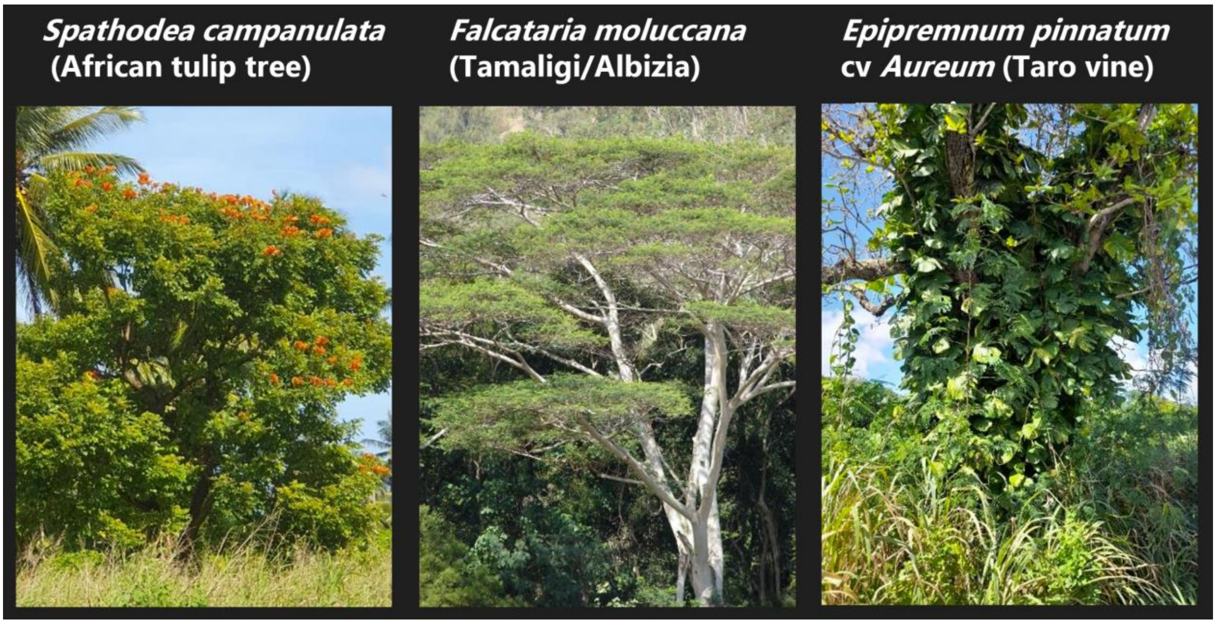

Figure 2. Priority invasive weed species for this investigation.

The Cook Islands and Niue both benefit from the Pacific Regional Invasive Species Management Support Service (PRISMSS). Rarotonga has been one of the most proactive of the Pacific Islands to embrace natural enemies as part of their invasive weed control strategy and has targeted several priority weeds already including: grand balloon vine (*Cardiospermum grandiflorum*), mile-a-minute vine (Mikania micrantha), red passionfruit (*Passiflora rubra*), strawberry guava (*Psidium cattleianum*), ATT and cocklebur (*Xanthium strumarium*). MWLR is currently working with the Cook Island National Environmental Service (NES) to monitor the spread and impacts of these agents and explore the feasibility of conducting biocontrol against additional target weeds. Niue is also considering the use of natural enemies and has several priority invasive weeds including ATT and a rapidly growing taro vine infestation.

Natural enemies have become widespread on most weed species in Rarotonga on which control agents have been released since 2016, but two agents are not yet widespread: the recently released ATT flea beetle (*Paradibolia coerulea*) and the strawberry guava scale insect (*Tectococcus ovatus*). We will investigate the use of remote sensing to help identify and evaluate future damage to ATT populations by the flea beetle and a gall-forming mite (Colomerus spathodeae) which has recently become widespread (Figure 3).

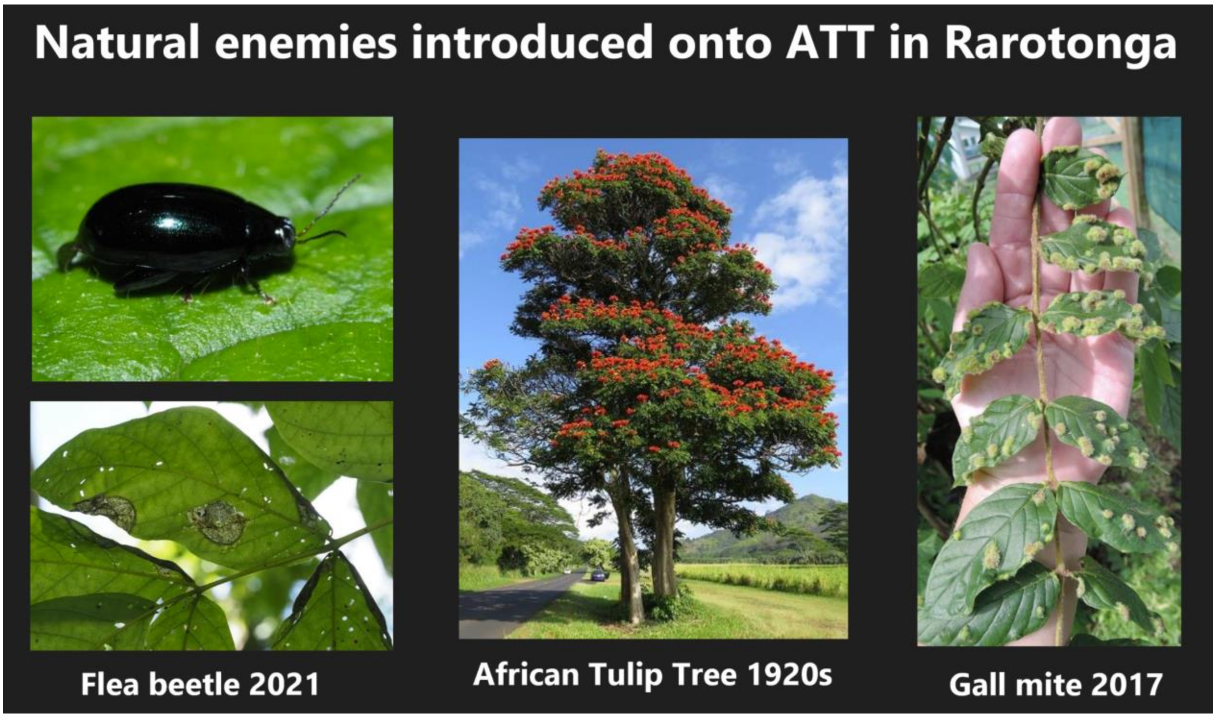

Figure 3. Natural enemies on ATT in Rarotonga and dates of introduction.

2.2 Create baseline maps of two priority invasive weed species

Island-scale satellite and aeroplane imagery of Rarotonga will be captured to determine whether ATT and Falcataria can be mapped, and, if so, which technique provides the best result.

2.3 Develop a natural enemy establishment and monitoring protocol capable of recording tree canopy damage

Drones will be used to photograph and sample invasive weeds to detect natural enemy establishment and damage to tree canopies. Various image resolutions and spectral signatures will be tested to determine what parameters are important for detecting establishment and evaluating impacts of natural enemies. A drone tree canopy sampling tool will also be tested, and other methods considered if this turns out to be impractical.

2.4 Develop capability in the PICTs so that weed control projects can be monitored and assessed locally

In addition to discussing weed monitoring and natural enemy assessment options in Niue and Rarotonga, in-country collaborators will be involved in site visits to test techniques and develop methods that can be used for ongoing monitoring programs. Project objectives and preliminary data will also be presented at a Pacific Island conference.

3 Methods

3.1 Design experimental projects to monitor invasive weed distribution and evaluate impacts of natural enemies introduced in PICTs

To help design and carry out experimental projects we undertook field trips to Niue and Rarotonga in 2023. Trip dates and details are described in detail in Sections 3.1–3.4.

3.1.1 Niue

MWLR staff met with the Niuean Department of Environment (DE) staff including Haden Talagi (Director of Environment) and Huggard Tongatule (Environment Officer), and Elena Procuta (Deputy High Commissioner to New Zealand) on 6 April 2023 to discuss monitoring and control of invasive weeds. Discussions included future steps to improve weed detection and mapping and use of natural enemies as an alternative to manual and herbicide methods currently employed. The trip also included several field site visits to help understand weed issues and fly preliminary drone imagery. High-resolution drone imagery was collected from two sites.

High-resolution imagery – at two sites (2-4 cm)

Huggard Tongatule and other DE staff accompanied Paul Peterson to a site close to Alofi where imagery from an area of forest infested with taro vine was captured using a Mavic 3M multispectral drone at 50 and 100 m ACL (see Figure 4). A trip was also made to Vaiea (an old village site) in Niue where ATT has naturalised but the extent of the infestation was unknown. Images collected from each site were made into orthomosaics (a geographically located mosaic of individual photos).

Figure 4. Drone and camera (left) used to take aerial photograph of light-green coloured taro vine (right) in Niue.

3.1.2 Rarotonga

On 7 August 2023 MWLR staff met with NES staff including Liz Munro (Manager Environmental Stewardship) and Jessie Nicholson (Biodiversity Co-ordinator), Kelvin Passfield (Te Ipukarea Society), and Mike Bowie (Cook Islands Ministry of Agriculture) to discuss the use of natural enemies in the Cook Islands and remote sensing for monitoring weed populations and evaluating natural enemy impacts. During the week-long stay five sites were visited and several remote sensing techniques were tested. In Rarotonga a multi-scale approach was taken including capture of satellite, aeroplane, and drone imagery to help determine the importance of scale, spectra, timing, and texture for invasive weed mapping over large areas, and to help with assessing impacts of natural enemies. A drone sampling tool was also trialled to assess impacts of natural enemies (Figure 5).

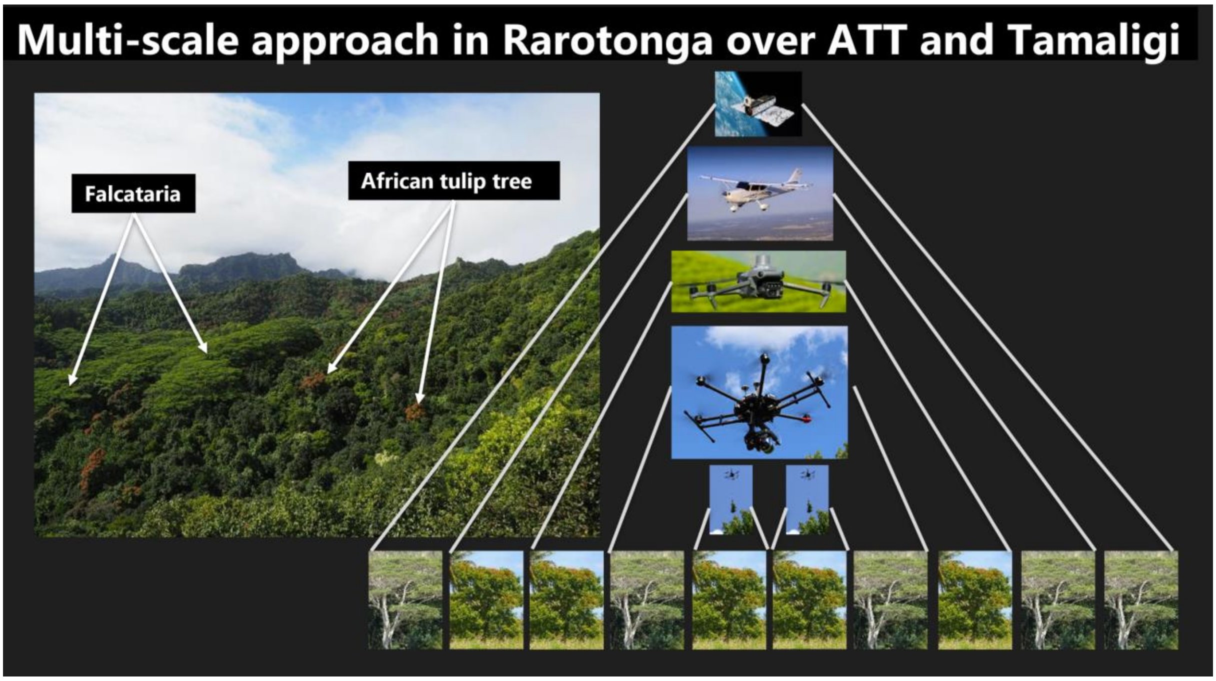

Figure 5. Multi-scale (satellite, aeroplane and drone) approach used in Rarotonga to map ATT and Falcataria.

This work was carried out between 6 and 11 August 2023. Field site visits included NES, Ministry of Agriculture, Infrastructure Cook Islands, Te Ipukarea Society and New Zealand High Commission staff along with MWLR staff and Fijian drone and Geographic Information System (GIS) specialists (Appendix 2).

Low- and medium-resolution RGB imagery – island scale (50–10 cm)

Satellite imagery orthomosaics were purchased from Planet.com (a provider of data and insights about the Earth), and aeroplane imagery was captured by a New Zealand photographer flying with a Rarotongan pilot in an Air Rarotonga Ltd. Cessna 172 to test the importance of scale and timing for invasive weed mapping (Appendix 2). Agisoft Metashape Professional 2.0.1 software was used to create orthomosaics from the aeroplane imagery. Both satellite and aeroplane imagery were captured during peak ATT flowering and a second satellite image was captured when the majority of ATT was not expected to be flowering, so that a multi-seasonal image comparison could be trialled to help detect trees.

High-resolution RGB imagery – at five sites (1–4 cm)

Imagery was flown with a Mavic 3M drone at 30 and 100 m ACL to test the importance of scale, spectra and texture for mapping invasive weeds; and to collect training material for AI mapping with low- and medium-resolution imagery. Orthomosaics of the imagery were made using Agisoft software. We also assessed the ability of high-resolution RGB imagery for quantifying natural enemy impacts.

We developed a workflow to use high-resolution imagery in combination with low- and medium-resolution imagery for island-scale mapping of ATT and Falcataria in Rarotonga (Figure 6).

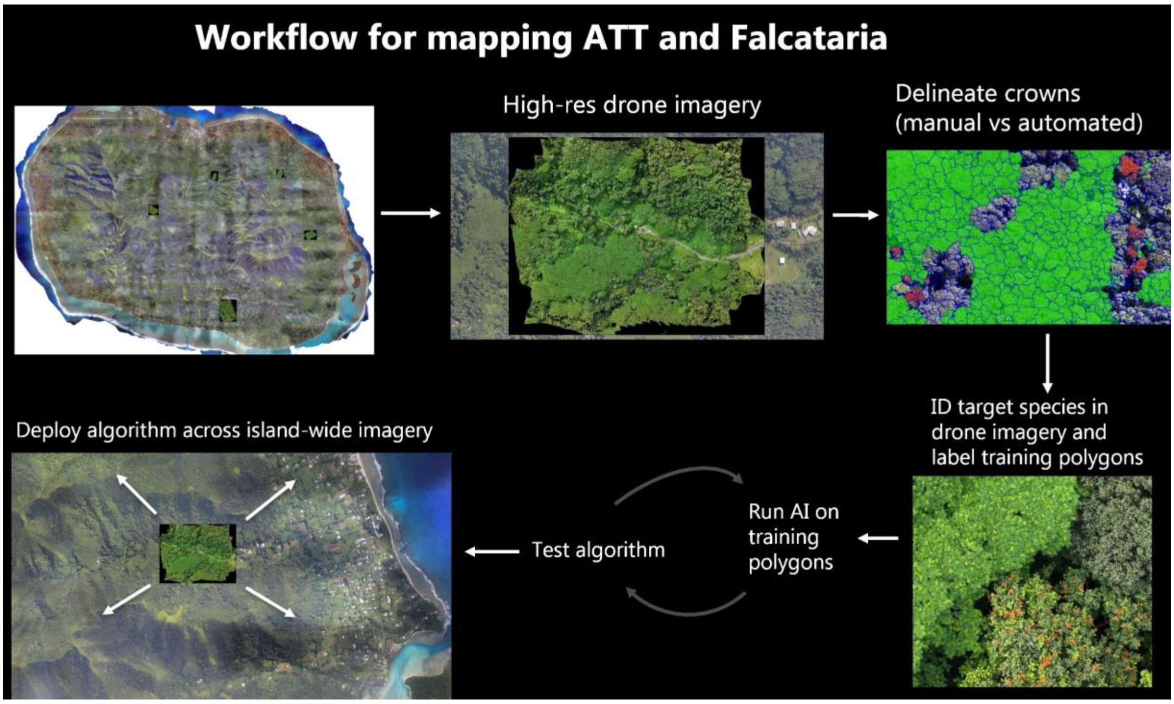

Figure 6. Workflow for mapping ATT and Falcataria in Rarotonga.

Very high-resolution RGB imagery – at one site (< 0.5 cm)

Imagery was flown with the Mavic 3M drone at between 10 and 30 m ACL to assess the importance of scale, spectra, and texture, for natural enemy detection.

Multispectral and hyperspectral imagery – at four sites

Multispectral imagery was flown with a Mavic 3M drone to assess spectral signatures of target versus non-target species in the red, green, blue, RE (red edge) and NIR bands and to test detection methods for measuring direct impacts of natural enemies. The NIR spectral signature of ATT leaves (between 800 and 1200 nm) has been suggested as a possibility for distinguishing ATT from other species for mapping purposes (W. Forstreuter, Consultant and board member of the Pacific GIS and Remote Sensing Council, pers. comm., 26 June 2023). This is potentially useful because not all ATTs flower simultaneously.

LiDAR – at four sites

LiDAR data were collected to assess textural features of target and non-target species for mapping, and to see if a canopy height model would help to map weeds more accurately.

Canopy sampler - at four sites

A drone canopy sampling tool was used to collect material from tree canopies where natural enemies cause damage to foliage which is not visible from the ground.

The three DJI drone platforms used in this project included a Mavic 3M to capture high and very high RGB and multispectral imagery, an M600 to capture hyperspectral imagery and LiDAR data, and an M300 + canopy sampler to collect plant material from tree canopies (Figure 7).

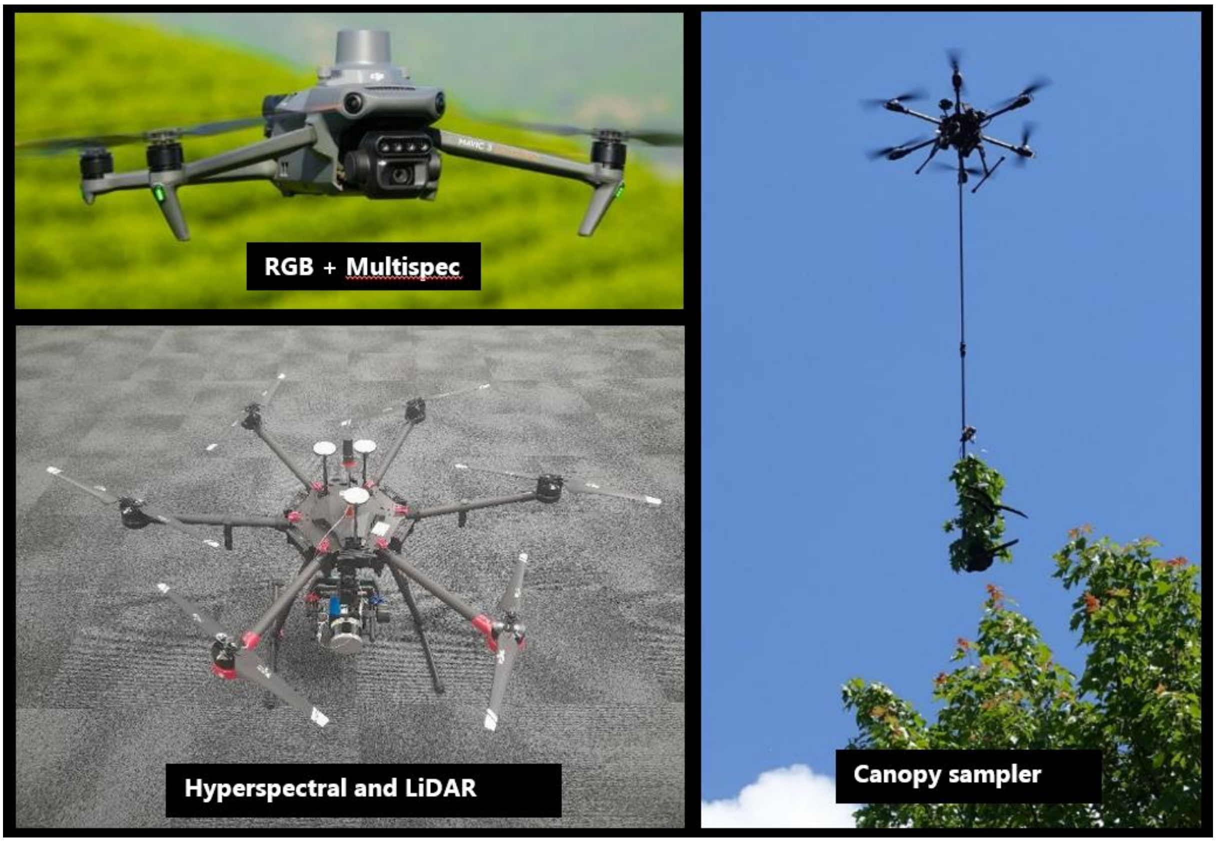

Figure 7. Drone platforms used to collect high- and very high-resolution imagery, LiDAR and tree canopy samples. (**RGB – red, green, blue.)**

3.2 Create baseline maps of two priority invasive weed species

SkySat satellite imagery of Rarotonga from Planet.com was captured from 19 July to 8 August 2023 and from 28 May to 6 June 2024 and aeroplane imagery was captured on 20 July 2023 by Lawrie Cairns (Survey Services, Aerial Photography & Land Information). High–resolution drone imagery taken with a Mavic 3M at five sites in Rarotonga acted as ground truth data and was used for training a deep learning AI model for island-wide mapping of the invasive weeds (Figure 8).

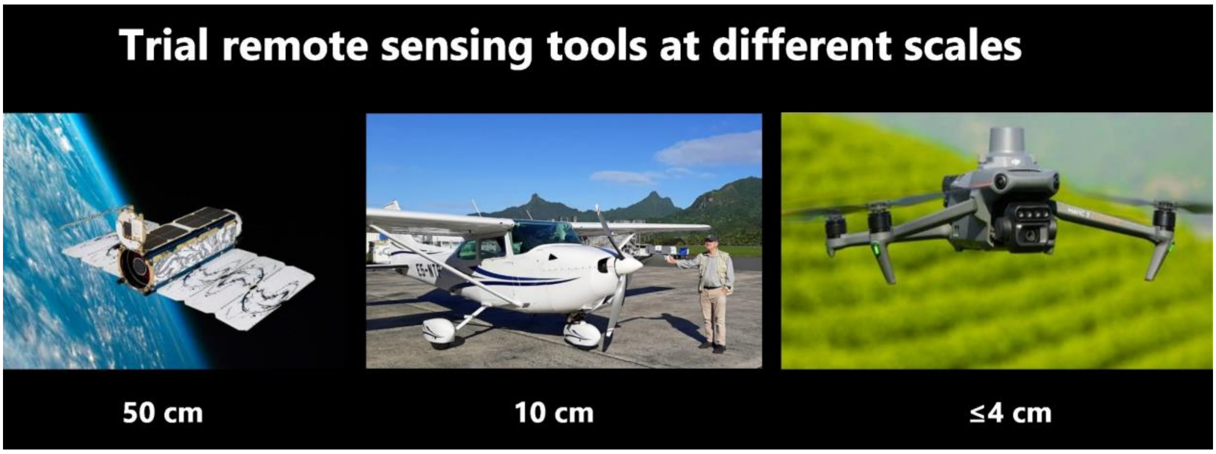

Figure 8. Three methods used to capture imagery in Rarotonga for island-scale mapping.

3.3 Develop a natural enemy establishment and monitoring protocol capable of recording tree canopy damage

In Rarotonga where natural enemies have been released on ATT, very high-resolution imagery was taken to look for galls formed by the ATT gall mite, which has recently become widespread, and feeding damage from the newly established ATT leaf feeding flea beetle. A benchtop spectroradiometer (FieldSpec 4, ASD, Boulder, Colorado, USA) was deployed in the field to determine if galled leaves had a distinctive spectral signature that could be used to detect galling from canopy imagery. At one site we felled a large tree as a comparison to using the tree canopy sampler so that damage to the canopy could be inspected for natural enemy damage by eye.

3.4 Develop capability in PICTs so that weed control projects can be monitored and assessed locally

Visits were made to Niue in April 2023 by Paul Peterson and Rarotonga in August 2023 by Paul, Andrew McMillan and Ben Jolly to discuss invasive weed management problems, trial techniques and gain imagery. Paul also gave presentations at the Pacific Island GIS and Remote Sensing Conference in Fiji in December 2023, and at the Pacific Invasive Learning Network Conference in Rarotonga in August 2024, on how remote sensing might be useful as a tool to map weeds and monitor impacts of weed control methods including the use of natural enemies.

4 Results

4.1 Design experimental projects to monitor invasive weed distribution and evaluate impacts of introduced natural enemies in PICTs

4.1.1 Niue

Imagery from both sites in Niue showed distinctive reflectance signatures from both taro vine and flowering ATT.

High-resolution imagery – at two sites (2-4 cm)

Preliminary drone footage from Niue showed the potential for mapping taro vine using unique spectral signatures. Variegations (i.e. different coloured patches) on taro vine leaves found in Niue reflected in the red band distinguishing it from surrounding vegetation (Figure 9).

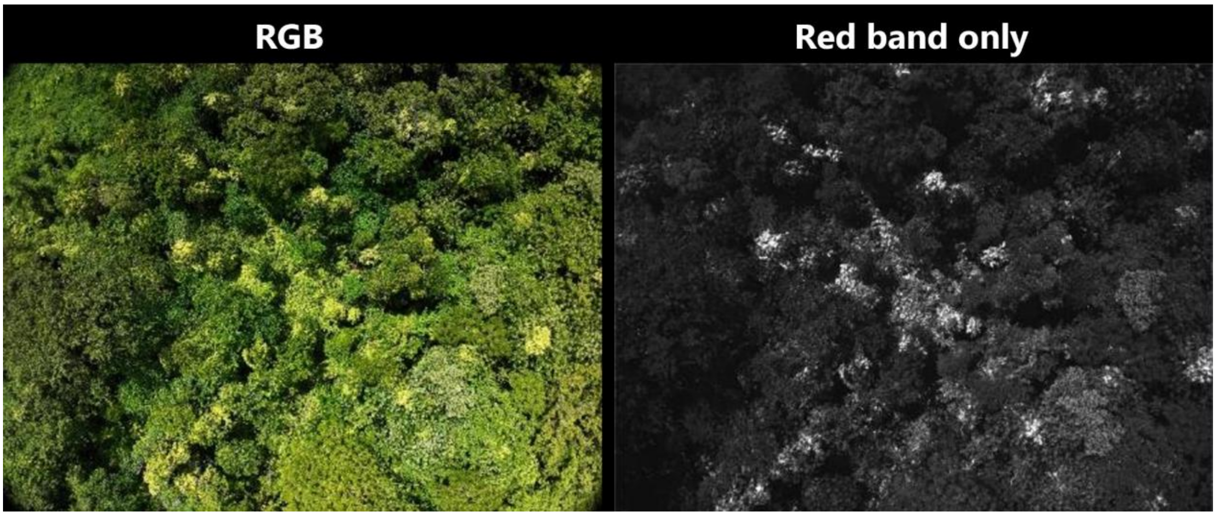

Figure 9. Mavic 3M drone imagery from Niue at 50 m ACL of taro vine – RGB or true colour (left) and red band only (right). Taro vine can be seen as pale green in the left image and white in the right image.

While we only captured imagery of c. 3.5 ha in this trial, experimenting with lower resolution (10 cm) aeroplane imagery may allow for wider mapping using more sophisticated AI techniques (Figure 10) in future.

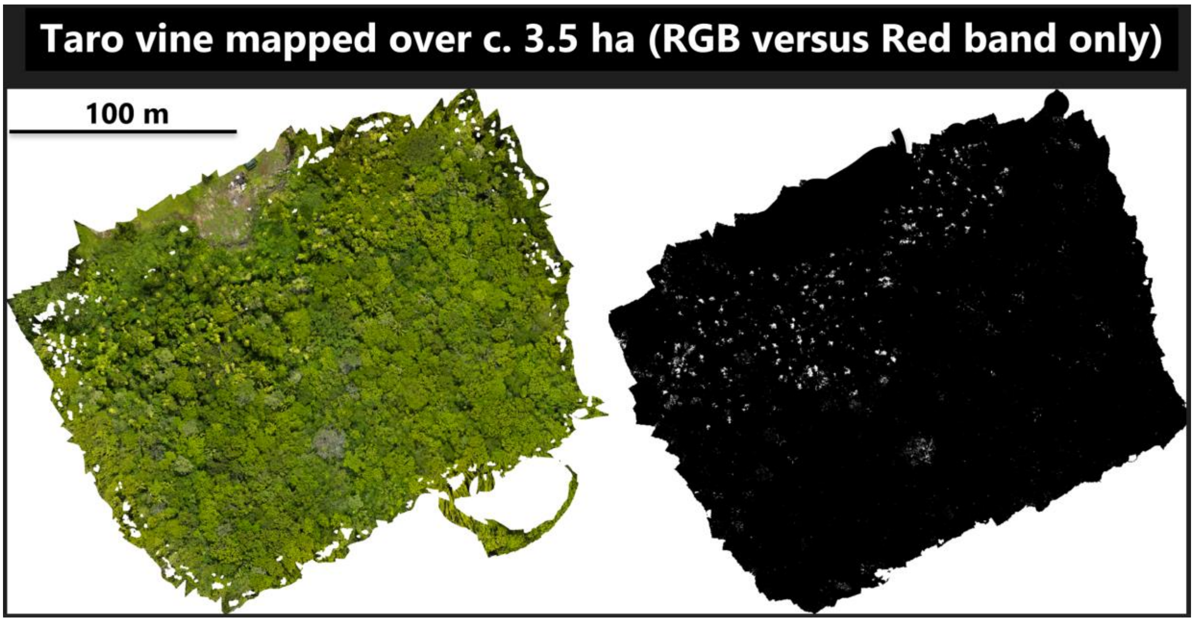

Figure 10. Orthomosaic of taro vine mapped in Niue to test for unique spectral signatures.

At the Vaiea site in Niue, where ATT has naturalised, red/orange flowers and leaf shape were used to detect trees with high-resolution Mavic 3M imagery over a 5 ha area. The multispectral red-band-only imagery helped to detect flowers (Figure 11) and ATT leaf shape and colour was looked for in the RGB to estimate of the invasion size. See Figure 12 for a map of flowering and non-flowering ATTs. Note: it was the wrong time of the year for peak ATT flowering and there was some uncertainty identifying trees based on leaf shape from the 50 cm ACL imagery taken with the Mavic 3M. At this altitude the resolution is 1.3 cm meaning tree identification from leaf shape alone was marginal. Subsequent experience has shown that ≤1 cm resolution is required to identify leaf shape for ATT confidently (see Section 4.1.2), so the estimate needs to be treated with some caution. However, if correct this suggests that eradication of ATT from Niue is still viable based on the 1 ha rule-of-thumb (Rejmánek & Pitcairn 2002). For example, a plant that starts growing in a new environment will generally be very difficult to eradicate if it spreads over more than 1 ha.

Figure 11. Mavic 3M drone imagery from Vaiea, Niue (50 m ACL) of area with ATT in RGB (left) versus red band only (right). ATT flowers are circled in blue.

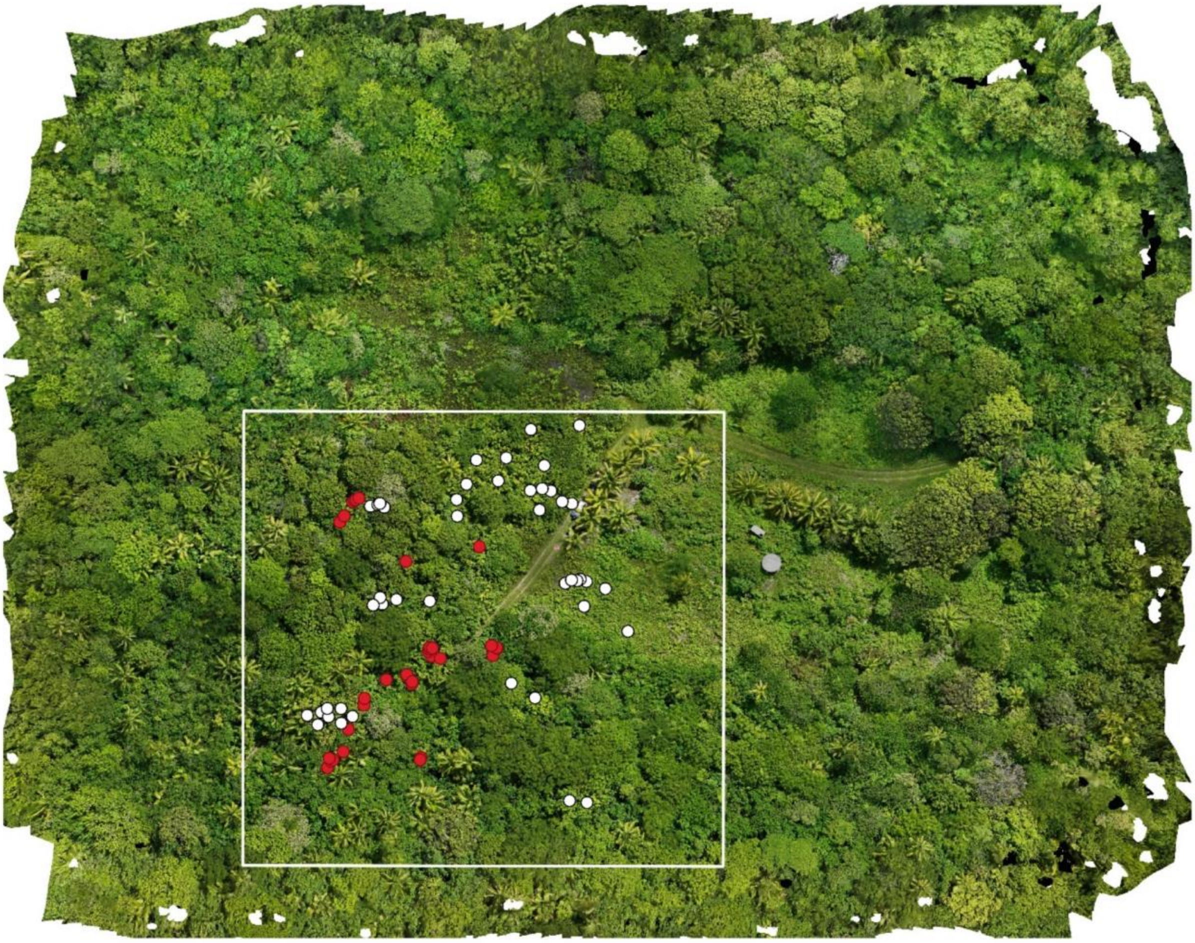

Figure 12. Orthomosaic of flowering (red dots) and non-flowering (white dots) ATTs at the Vaiea site, Niue with a 1 ha white square superimposed for scale.

4.1.2 Rarotonga

Multi-scale imagery and tree canopy samples collected during July and August 2023 were used to develop practical methods for monitoring invasive weed distribution and evaluating impacts of introduced natural enemies in PICTs.

Low- and medium-resolution RGB imagery – island scale (10–50 cm)

See Figure 13 for satellite and aeroplane imagery taken of Rarotonga in July and August 2023 when ATT was at peak flowering and Figure 14 for a zoomed-in scene highlighting differences in resolution.

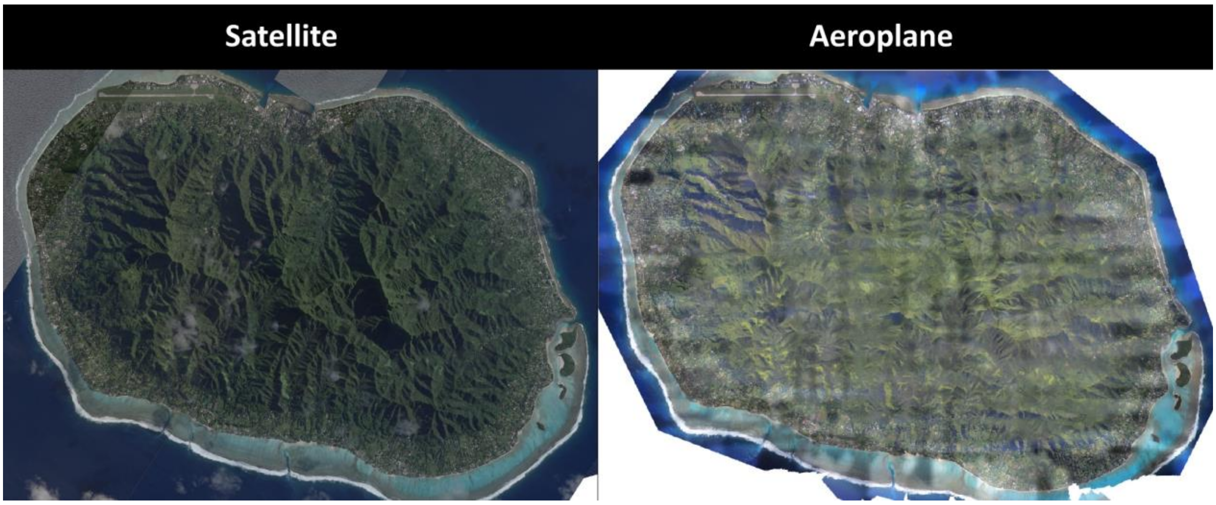

Figure 13 Satellite and aeroplane imagery taken of Rarotonga July and August 2023.

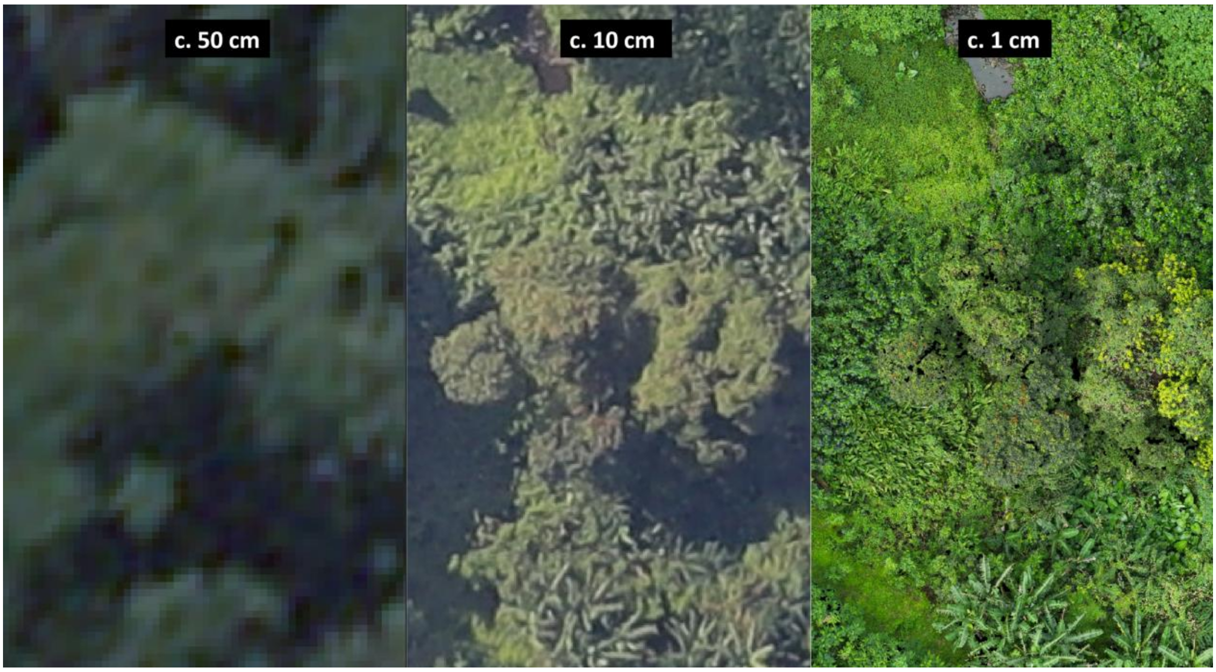

Figure 14. Images from Rarotonga of the same tree from satellite imagery (50 cm resolution), aeroplane imagery (10 cm resolution), and drone imagery (1 cm resolution).

While the target species could be identified in high-resolution drone imagery by leaf shape alone, only flowering trees could be confidently identified in aeroplane imagery by eye, and a combination of tree shape and texture for Falcataria tree crowns (Figure 15).

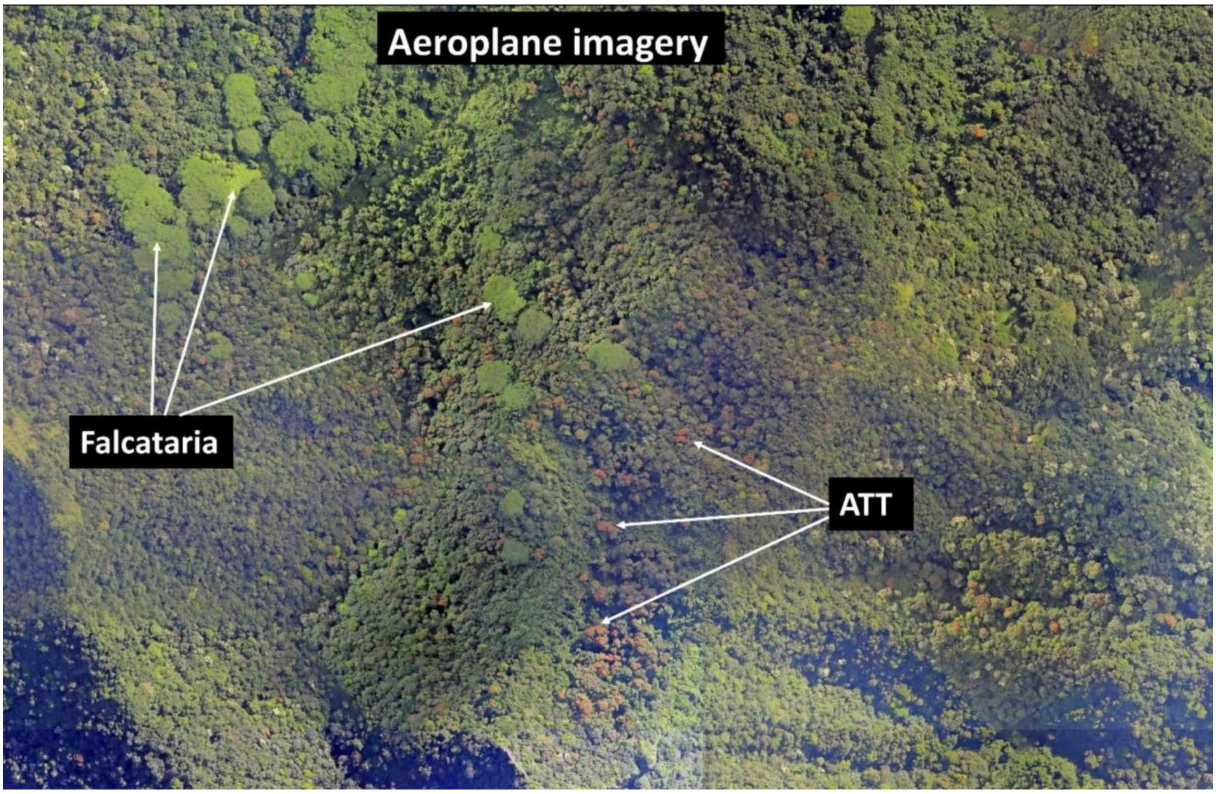

Figure 15. Example of Falcataria and flowering ATT in aeroplane imagery from Rarotonga.

The quality of satellite imagery was poorer than anticipated. It had problems associated with contrast (deep shadows), orthorectification (up to 30 m displacement and misaligned image joins), colour balance (large variation in reflectance in imagery made up from different scenes), and cloud cover (blocked key areas) (Figure 16 and Figure 17).

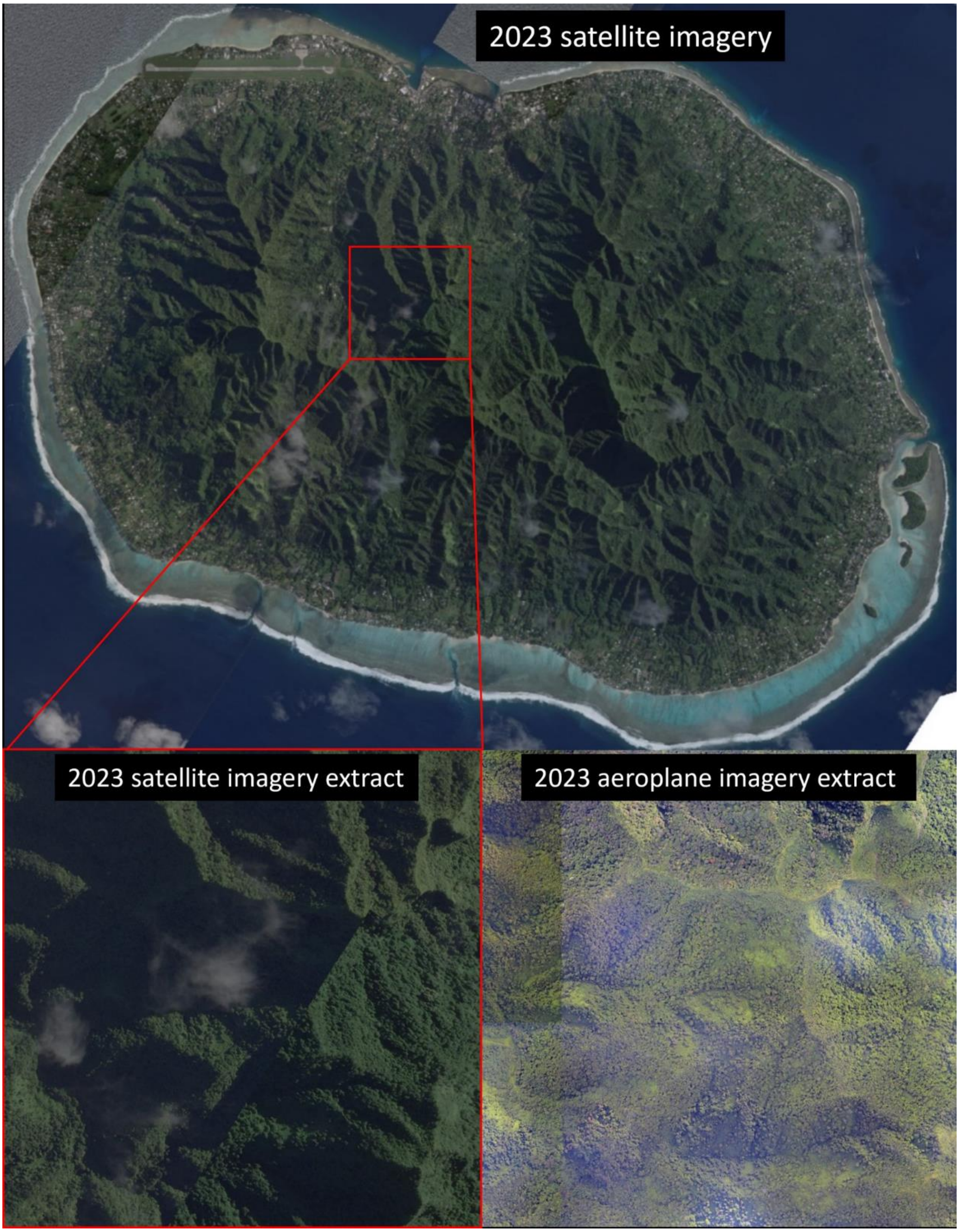

Figure 16. 2023 Satellite image from Rarotonga showing problems with deep shading and orthorectification offsets (top); extract from satellite imagery (left); and aeroplane imagery at the same spot (right).

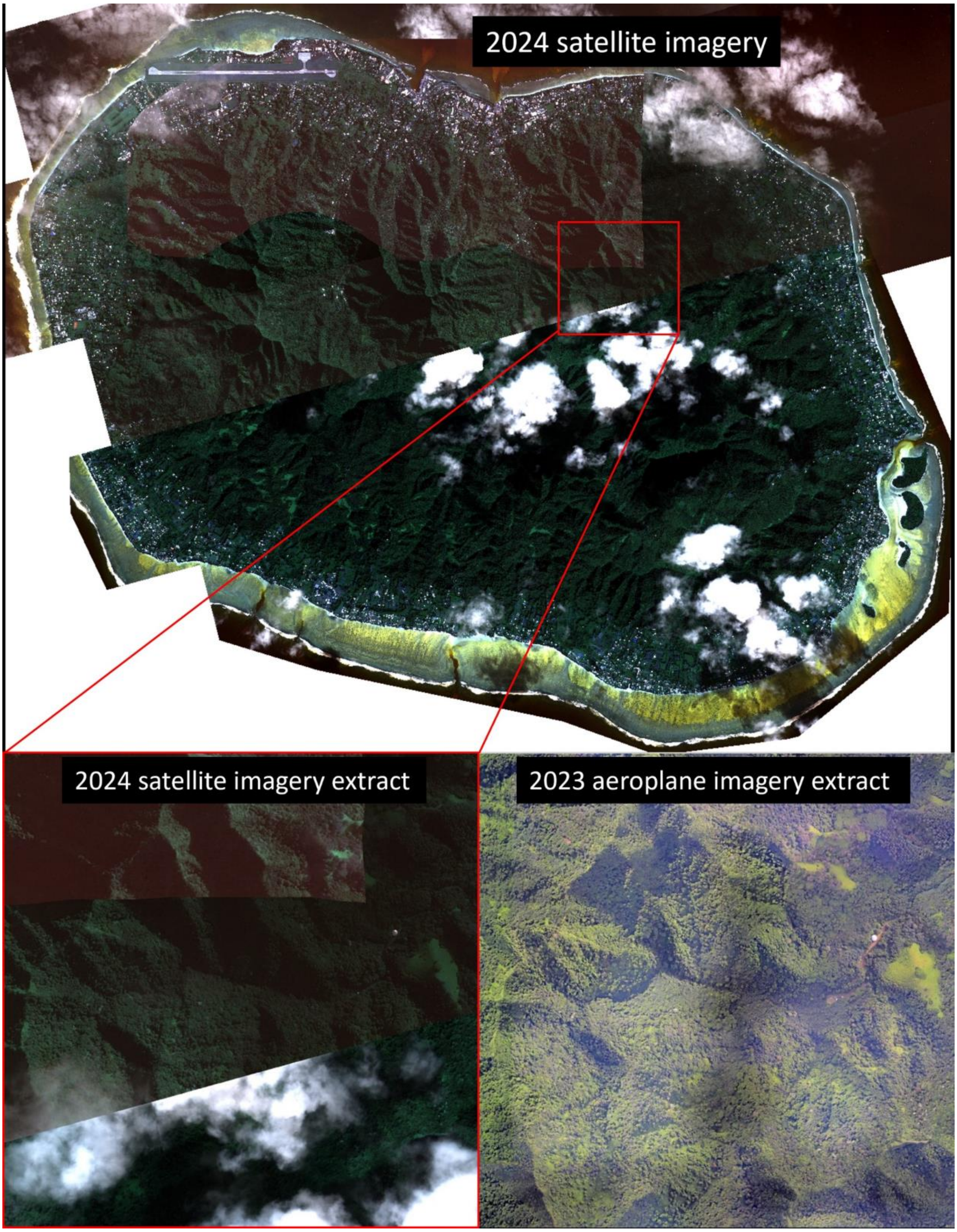

Figure 17. 2023 Satellite image from Rarotonga showing problems with colour balance and cloud cover (top); extract from satellite imagery (left); and aeroplane imagery at the same spot (right).

This meant that ATT and Falcataria tree crowns could not be recognised reliably even when a tree crown vector layer was superimposed from the AI mapping of aeroplane imagery (Figure 18).

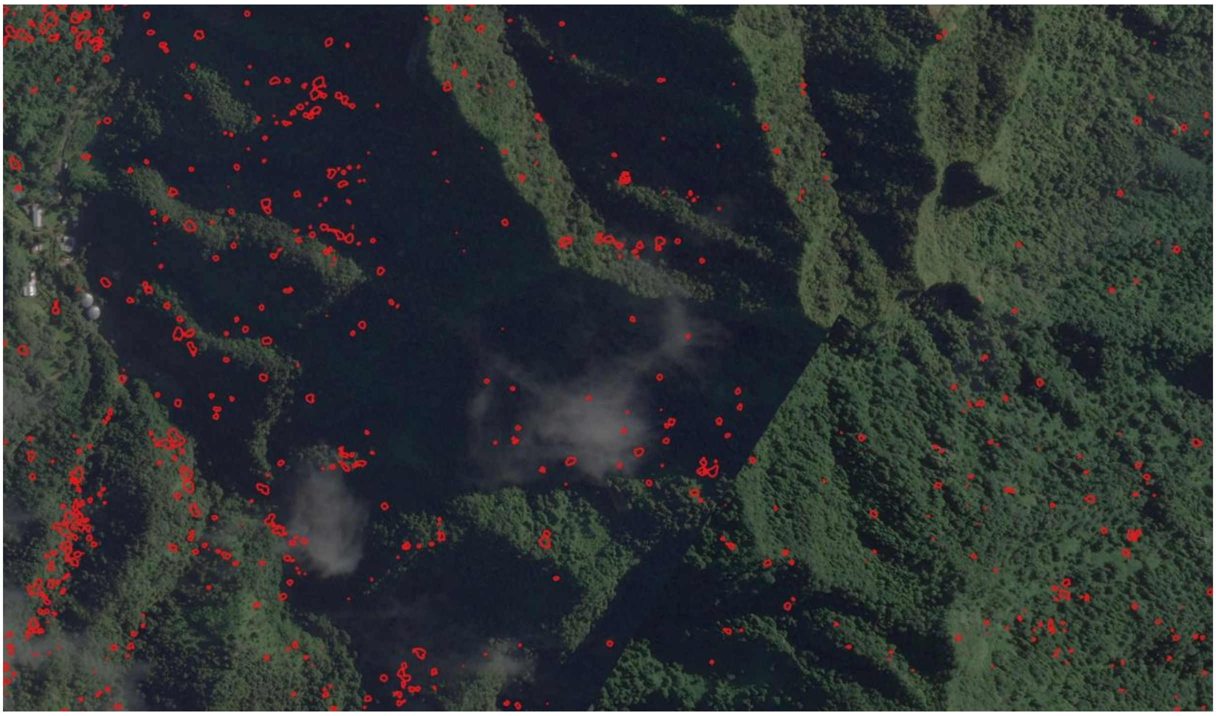

Figure 18. An example from Rarotonga of where ATT trees could not be recognised reliably in satellite imagery, even when a previously derived tree crown vector layer was superimposed from the AI mapping of aeroplane imagery.

High-resolution RGB imagery – at five sites (1–4 cm)

Imagery flown with a Mavic 3M at the five drone sites was used as training data for deep learning–based mapping, to determine flowering rates for ATT, and to assess natural enemy impacts (Figure 19).

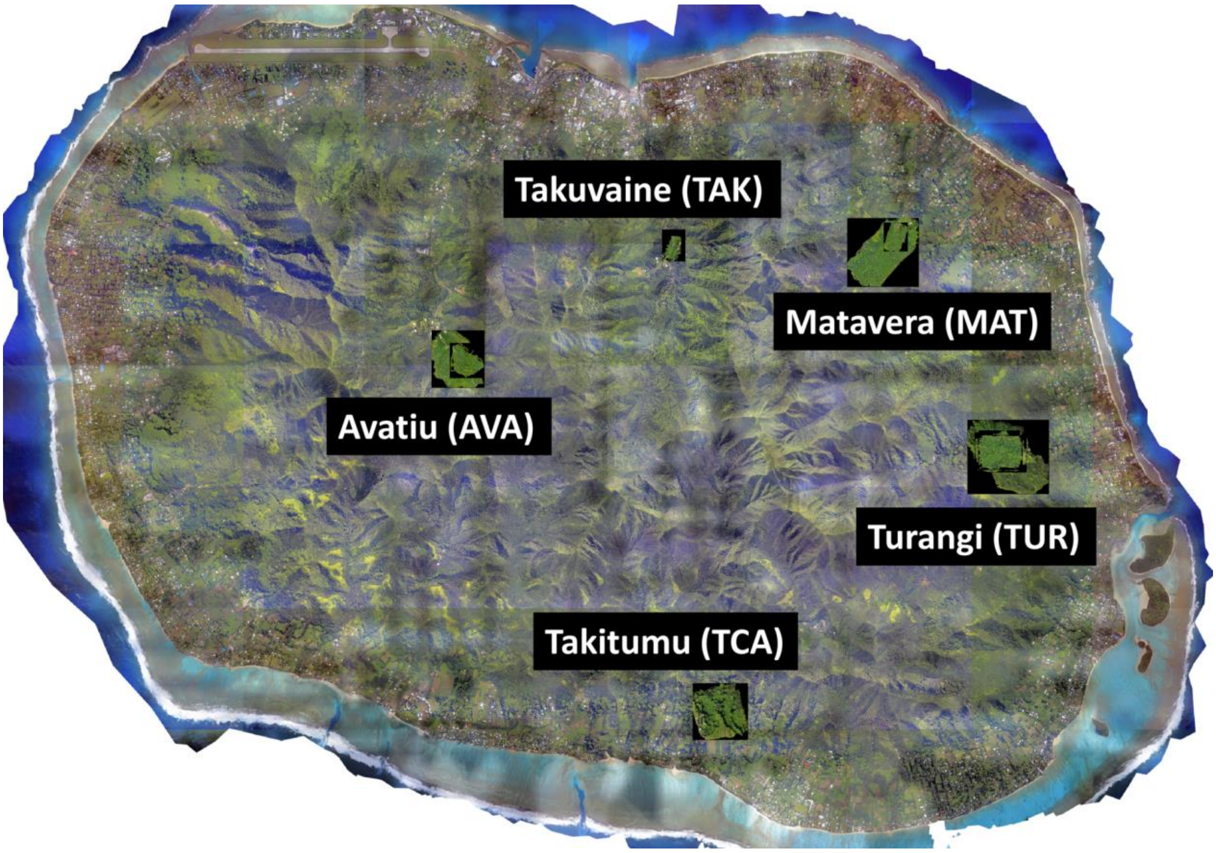

Figure 19. Rarotongan aeroplane imagery with five drone sites superimposed.

Drone imagery showed how critical spatial resolution is for the ground truthing stage of mapping invasive weeds. While some spectral and textural features can be seen in low- and medium-resolution imagery, high-resolution imagery provides the ground truth detail required to *confirm* species identifications. At ground truth sites high-resolution (1 cm) RGB imagery flown at 30 m ACL with the Mavic 3M drone was sufficient to identify and digitise all ATT and Falcataria in and amongst surrounding vegetation by leaf shape alone (Figure 20). See Figure 21 and Figure 22 for examples of tree crown digitising in high-resolution drone imagery at the Turangi site using leaf shape to distinguish Falcataria from other species that had a similar colour and texture in lower-resolution aeroplane imagery.

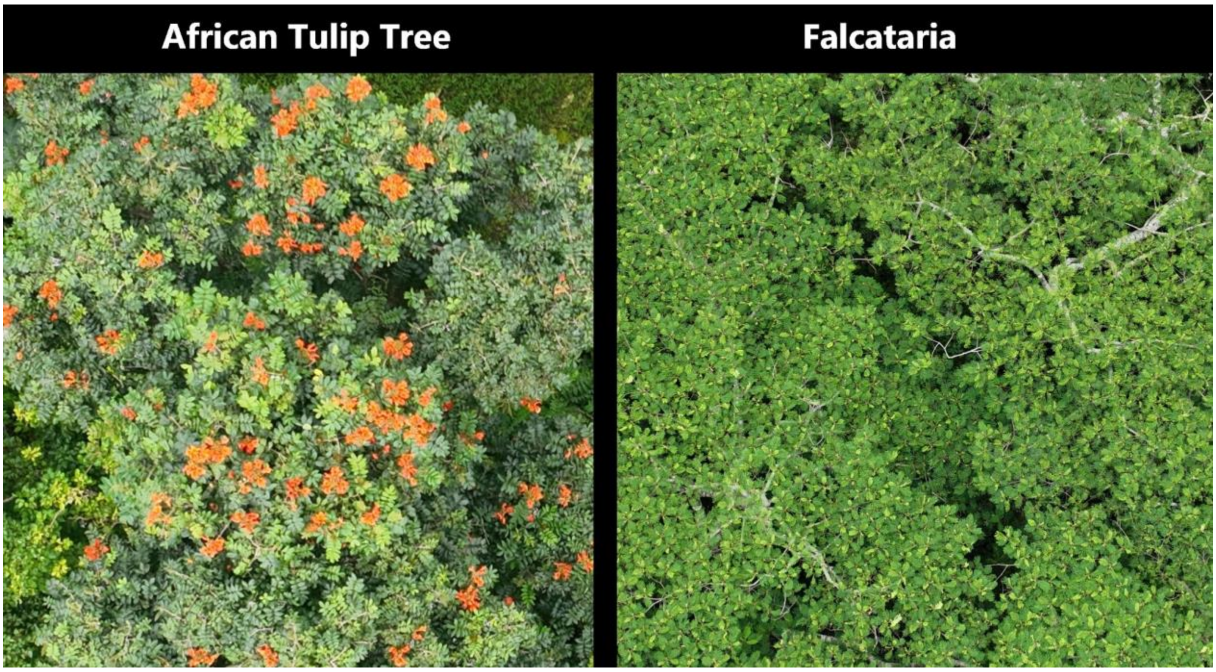

Figure 20. Difference in leaf shape between ATT, Falcataria, and other surrounding vegetation can be seen in high-resolution (1 cm) drone imagery from Rarotonga.

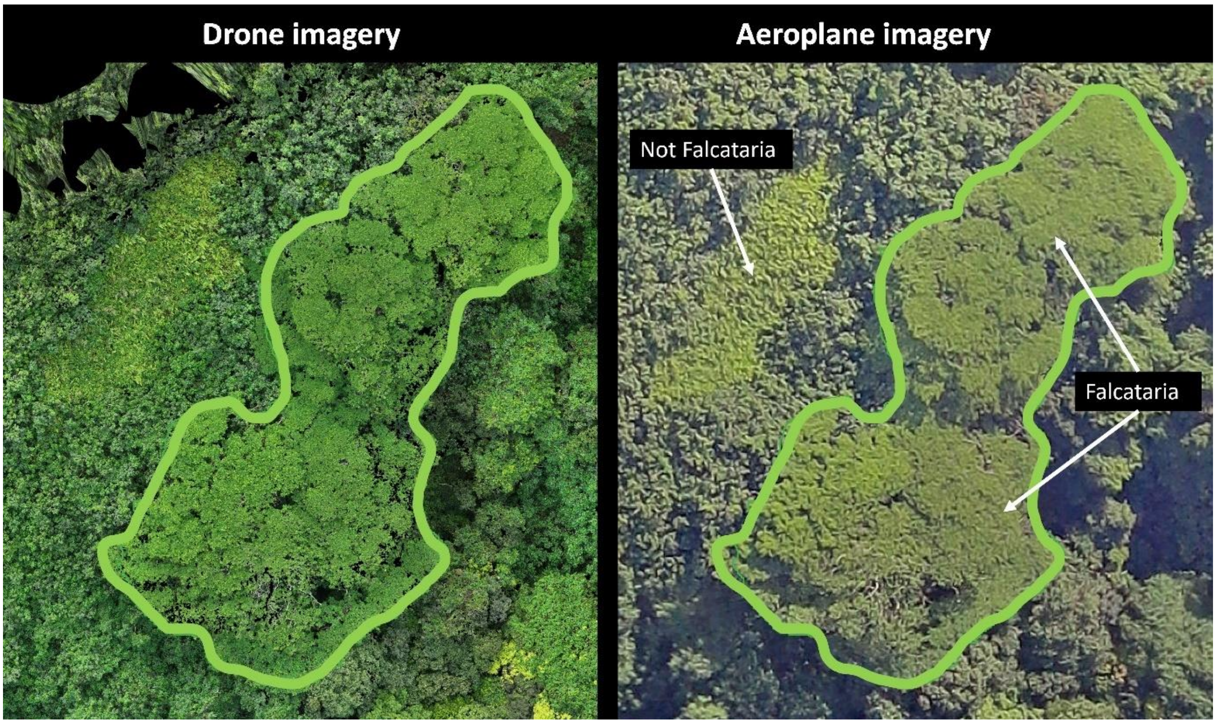

Figure 21. Example of a tree crown polygon digitised (green outline) from high-resolution drone imagery at the Turangi site Rarotonga (left) using leaf shape to distinguish Falcataria from a species with similar colour and texture in the lower-resolution aeroplane imagery (right). See Figure 22 for a zoomed-out image with red box showing location of images above.

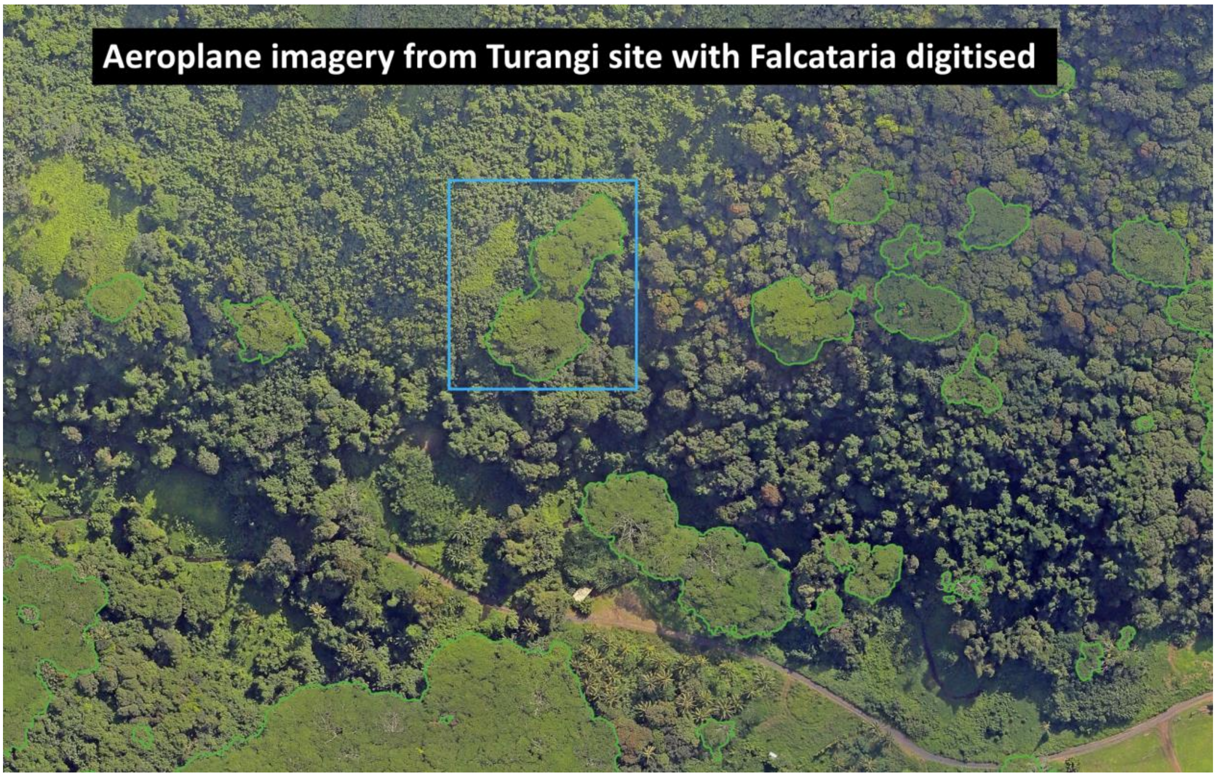

Figure 22. Zoomed out image showing the results of manual digitisation (green outlines) of Falcataria tree crowns at the Turangi drone site Rarotonga. The blue box shows the example in Figure 21.

Non-flowering Falcataria training data transferred from drone-derived tree crown polygons to lower resolution aeroplane imagery was sufficient to run an island-scale mapping model. However, ATT training data required the use of flowering trees because non-flowering trees were too similar to the surrounding vegetation at lower resolutions for the AI model to map them reliably. While not all ATT trees flower at the same time, the high-resolution data allowed us to estimate the proportion of trees that were flowering in island-scale aeroplane imagery. We calculated this by identifying flowering ATTs within drone training areas in the aeroplane imagery and then dividing this number by the total number of ATTs within drone training areas as identified by leaf shape. See Table 1 for results showing that on average 48% of ATTs were flowering when the aeroplane imagery was flown.

Very high-resolution RGB imagery – at one site (<0.5 cm)

Very high-resolution drone imagery (< 0.5 cm) was sufficient to detect ATT gall mite infestations (Figure 23). Although galls were easier to spot in imagery flown at 10 m ACL, galls were still visible in imagery flown at 20 m ACL without the risks associated with flying close to tree canopies (Figure 24).

Table 1. Number and proportion (%) of ATTs flowering and not flowering at five drone sites in Rarotonga. (Sites shown in Figure 19; AVA – Avatiu; MAT – Matavera; TAK – Takuvaine; TCA – Takitumu; TUR – Turangi.)

SITE	Flowering	Not flowering	Total	Flowering (%)
AVA	93	88	**181**	51.4
MAT	195	116	**311**	62.7
TAK	4	8	**12**	33.3
TCA	30	32	**62**	48.4
TUR	108	215	**323**	33.4
TOTAL	**430**	**459**	**889**	**48.4**

Figure 23. Very high–resolution Mavic 3M drone imagery flown at 20 m ACL (< 0.5 cm resolution) showing galls from the ATT gall mite – from Turangi, Rarotonga.

Figure 24. Images from Turangi, Rarotonga, of galled leaves in ATT treetops showing that very high-resolution imagery taken at 10-20 m ACL with the Mavic 3M drone are sufficient to reliably spot galls.

Multispectral and hyperspectral imagery – at five sites

Multispectral imagery flown with a Mavic 3M drone showed that ATT flowers were distinctive in the red wave band as expected (Figure 25).

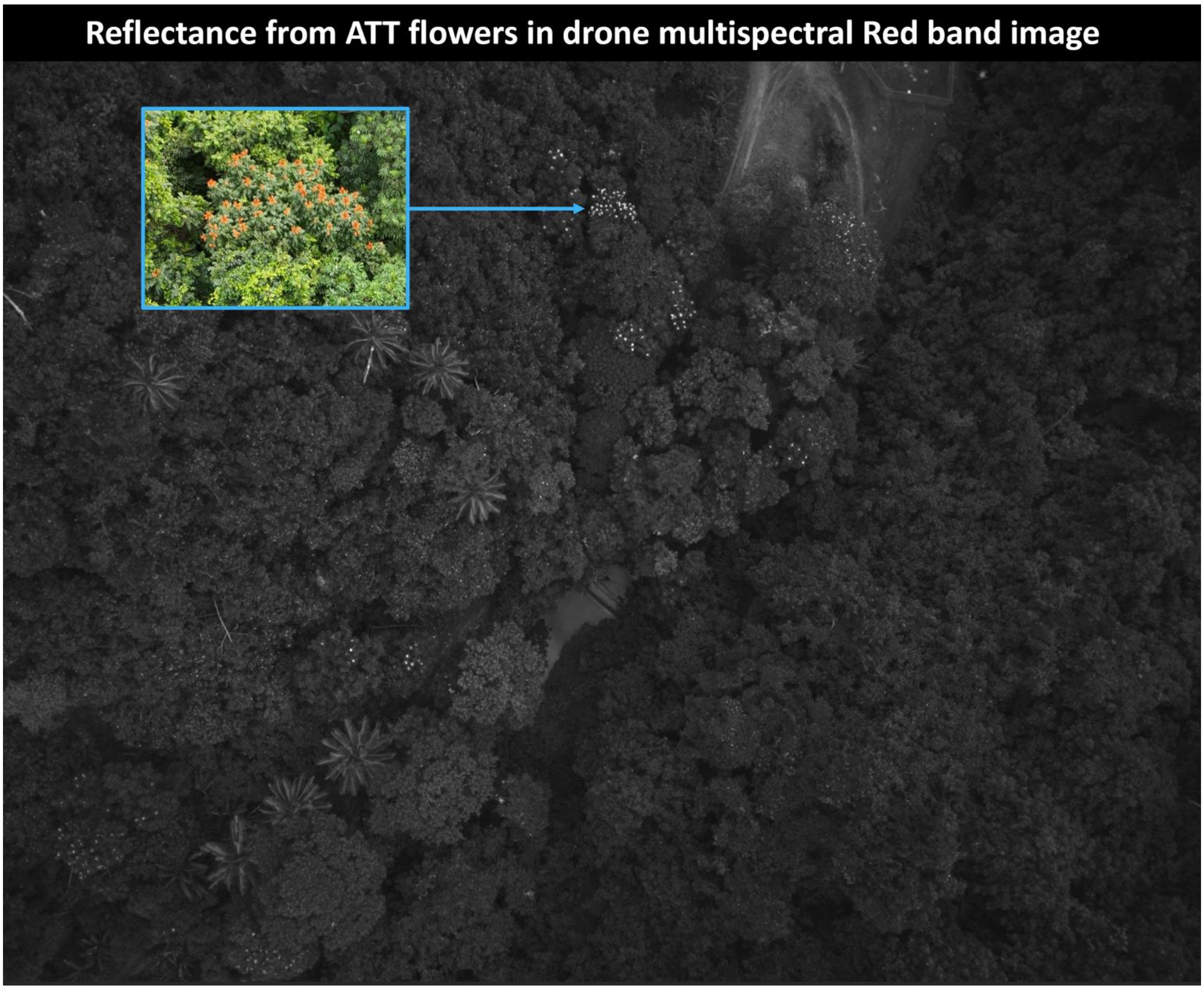

Figure 25. Reflectance in the red band from ATT flowers at the Avatiu drone site Rarotonga.

Figure 26 shows ATTs growing in amongst Falcataria in imagery taken with the Mavic 3M multispectral camera in a colour-stretched NIR band image. The colour stretch in this image is achieved by setting the blue channel to display the NIR band (860 nm); the green channel to display the green band (560 nm) and the red channel to display the red band (650 nm).This is an indication that hyperspectral imagery may be able to at least differentiate ATT and Falcataria leaf spectral signatures in the NIR spectrum.

Figure 26. A false colour image of ATTs (purple) and Falcataria (turquoise) obtained from the multispectral camera on the Mavic 3M drone in Rarotonga.

However, despite this, data from the airborne hyperspectral data didn’t show any clear differentiation between ATT and Falcataria in the NIR spectrum. Futher investigation will be needed to determine whether these data can contribute in any way to producing a more accurate map of ATT non-flowering trees (Figure 27).

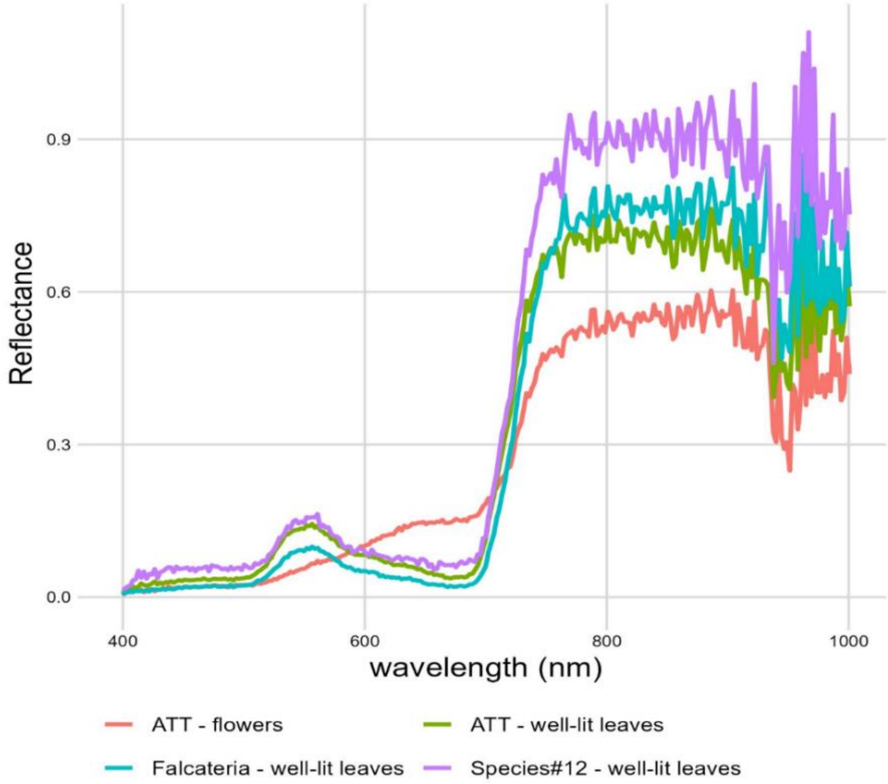

Figure 27. Airborne hyperspectral data showing no differentiation between ATT and Falcataria leaves but some indication that there may be differentiation between other species (see species#12 in plot).

The ASD spectroradiometer showed some unique spectral band responses in the 500 to 800 nm wavelength range for ATT gall mite galls, but again, further investigation will be needed to determine whether there is a practical application for these data (Figure 28).

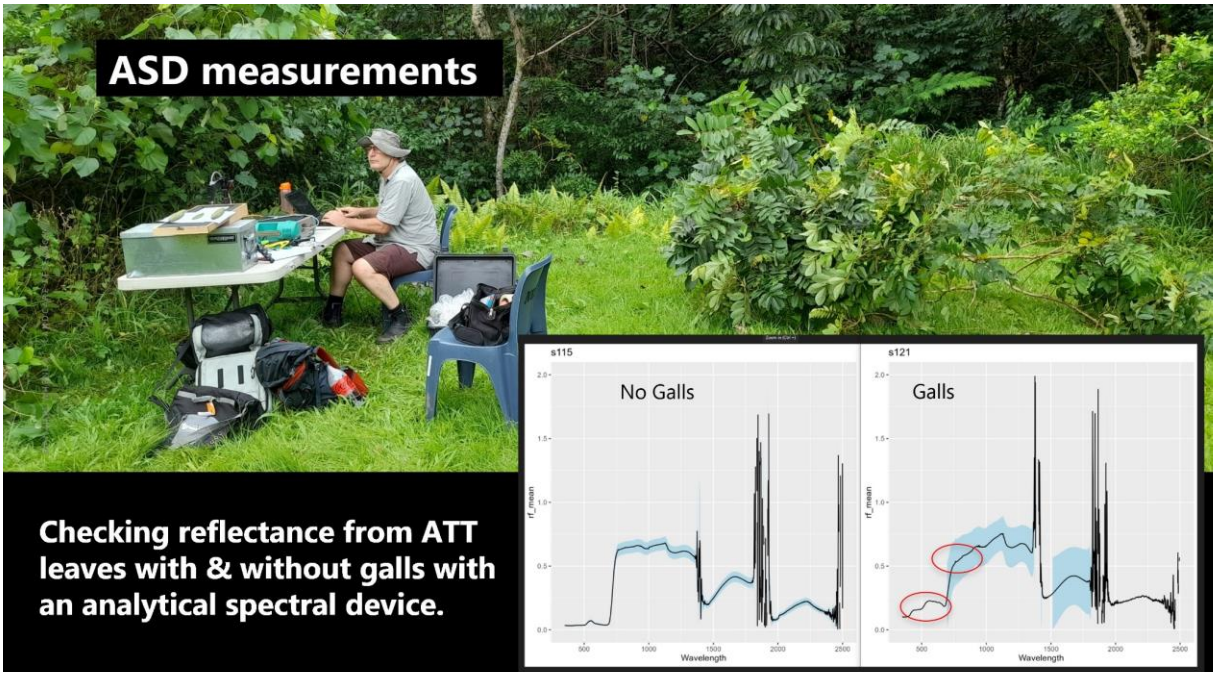

Figure 28. ASD spectoradiometer reflectance plots with red circles highlighting spectral differences in leaves with and without galls.

LiDAR

We collected LiDAR data to assess textural features on target weeds and to see if a canopy height model would help mapping accuracy. Time constraints meant that no formal analysis has been completed on these data to date. However, if funding can be found to publish this report in a scientific journal further analysis will be completed on LiDAR and hyperspectral data.

Canopy sampler

Galls were found on leaves collected from ATTs with the tree canopy sampler attached to the M300 drone. Flowers and seed pods were also collected and inspected. (Figure 29). While the tree canopy sampler did provide us with samples it was a tricky skill to master and is probably not practical for collecting large amounts of sample material in a short space of time. At the Matavera site we felled a mature ATT with a chainsaw providing a large amount of material (Figure 30). Alternative methods not trialled here may be more practical. For example, long-handled loppers have been used to collect ATT vegetation in Cameroon (Q. Paynter, MWLR, pers. comm., 1 August 2024).

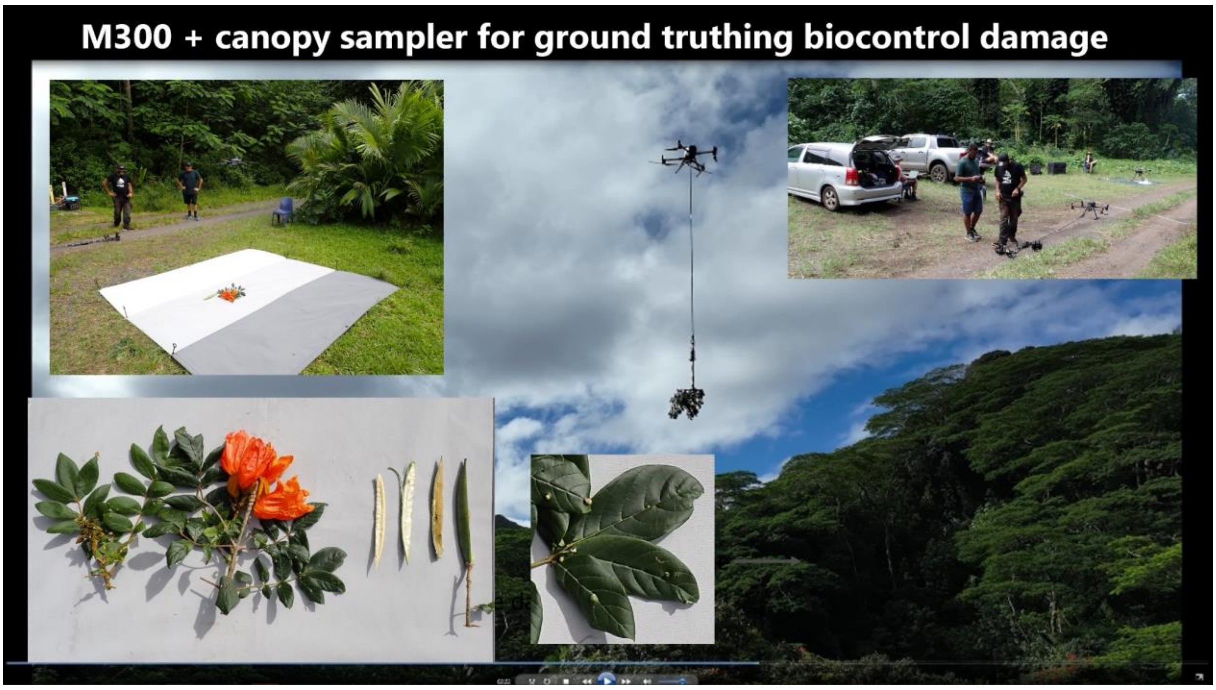

Figure 29. ATT leaf, flower and seed pod samples collected with the tree canopy sampler attached to the M300 drone in Rarotonga.

Figure 30. ATT felled at the Matavera site in Rarotonga so that canopy foliage could be inspected.

4.2 Create baseline maps of two priority invasive weed species

We used high-resolution imagery to digitise tree crowns at the five drone sites. A tree crown vector layer was then used for each target species as a guide to map tree crown outlines on aeroplane imagery within areas where the drone imagery was captured (see Section 4.1.2). Only flowering tree polygons were included for ATT mapping as non-flowering trees could not be distinguished from surrounding vegetation in the aeroplane imagery. A deep learning model was trained using these data and used to generate a preliminary island-scale map of flowering ATT and Falcataria. Technically, the deep learning model used can be described as a U-NET convolutional neural network with a ResNet 101 backbone (He et al. 2015; Ronneberger et al. 2015). Several additional areas outside the original drone ground truthing zones were then selected (Figure 31) and re-digitised to correct errors in the first iteration of the model by including missed trees, removing false positives, removing polygons with area less than 4 m^2 and by reshaping polygons to help refine model predictions (Figure 32). Training the AI mapping model on areas without the target species was also done to help remove additional false positives. Subsequent iterations of tree crown predictions were run until model predictions matched visual assessments over the range of selected test sites. We also trialled mapping flowering ATT and Falcataria using an image segmentation and classification software package called eCognition (https://optron.com/trimble/portfolio/ecognition/), which used a similar workflow except that pixel and shape-based parameters were prescribed by a user-defined ruleset rather than 'learned'. However, the eCognition-based approach struggled to deal with illumination and colour balance variations across the aerial imagery and problems were also encountered with software licensing, so the deep learning model was preferred.

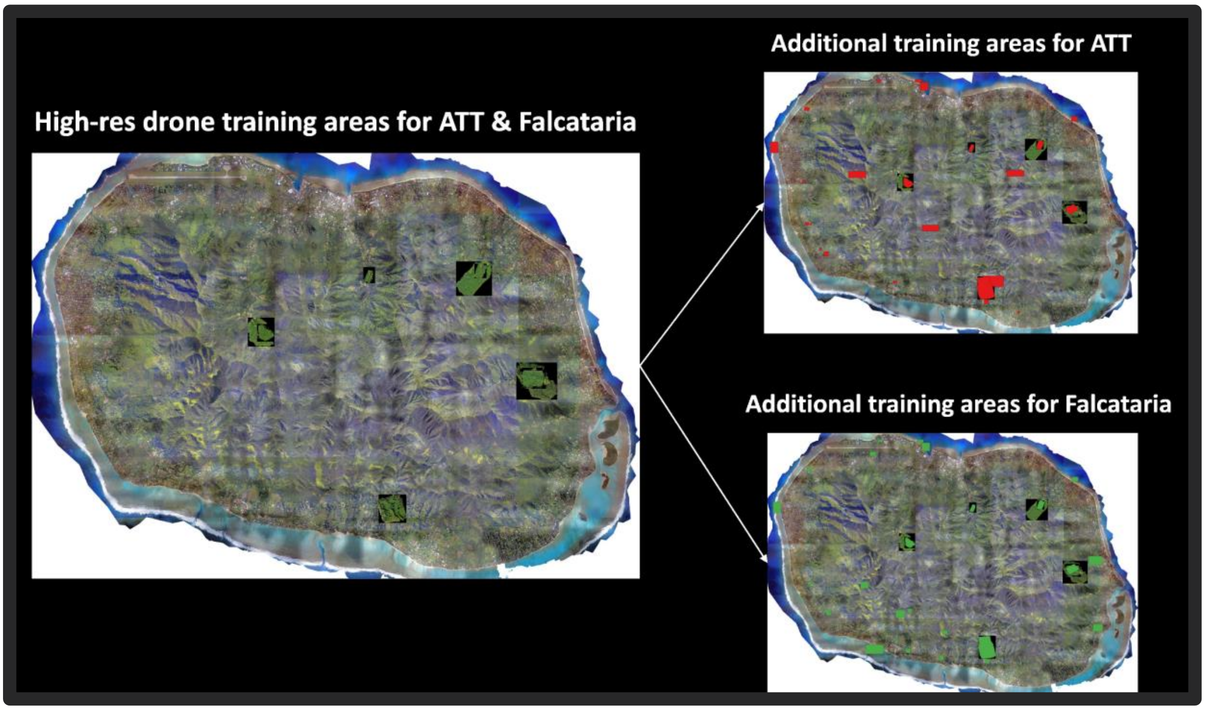

Figure 31. Five drone sites on Rarotonga (left) used for initial training and additional red (top right) and green areas (bottom right) chosen to modify training data for subsequent iterations of flowering ATT and Falcataria mapping of tree crowns via deep learning.

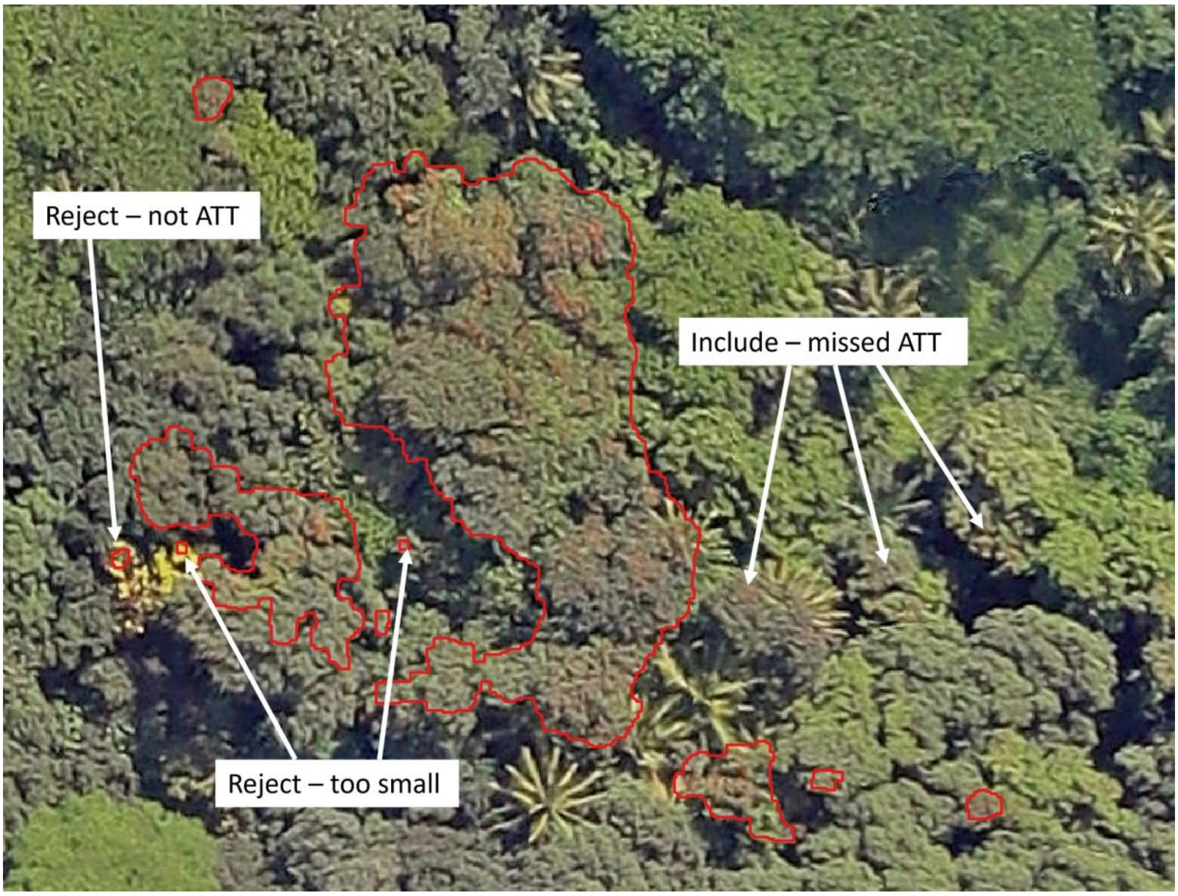

Figure 32. Correcting errors by eye in the Rarotonga flowering ATT canopy AI layer (polygons outlined in red) by including missed flowering trees, removing false positives and polygons < 4 m^2 to help refine AI model predictions.

The tree crown vector layers for flowering ATT and Falcataria from the final iteration of the AI mapping on aeroplane photography are shown in Figure 33 and Figure 34.

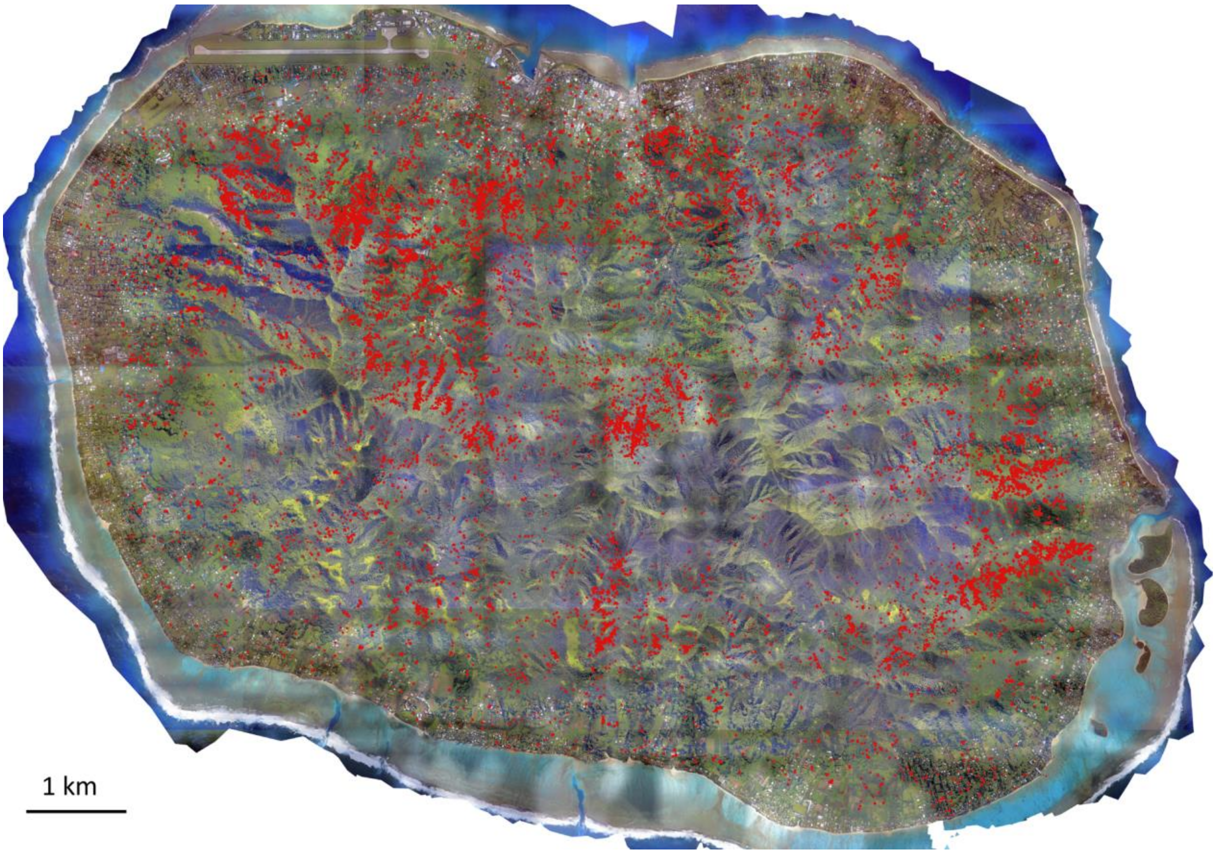

Figure 33. AI map of flowering ATT based on island-scale aeroplane imagery of Rarotonga (70 square km) (red areas are tree crown outlines).

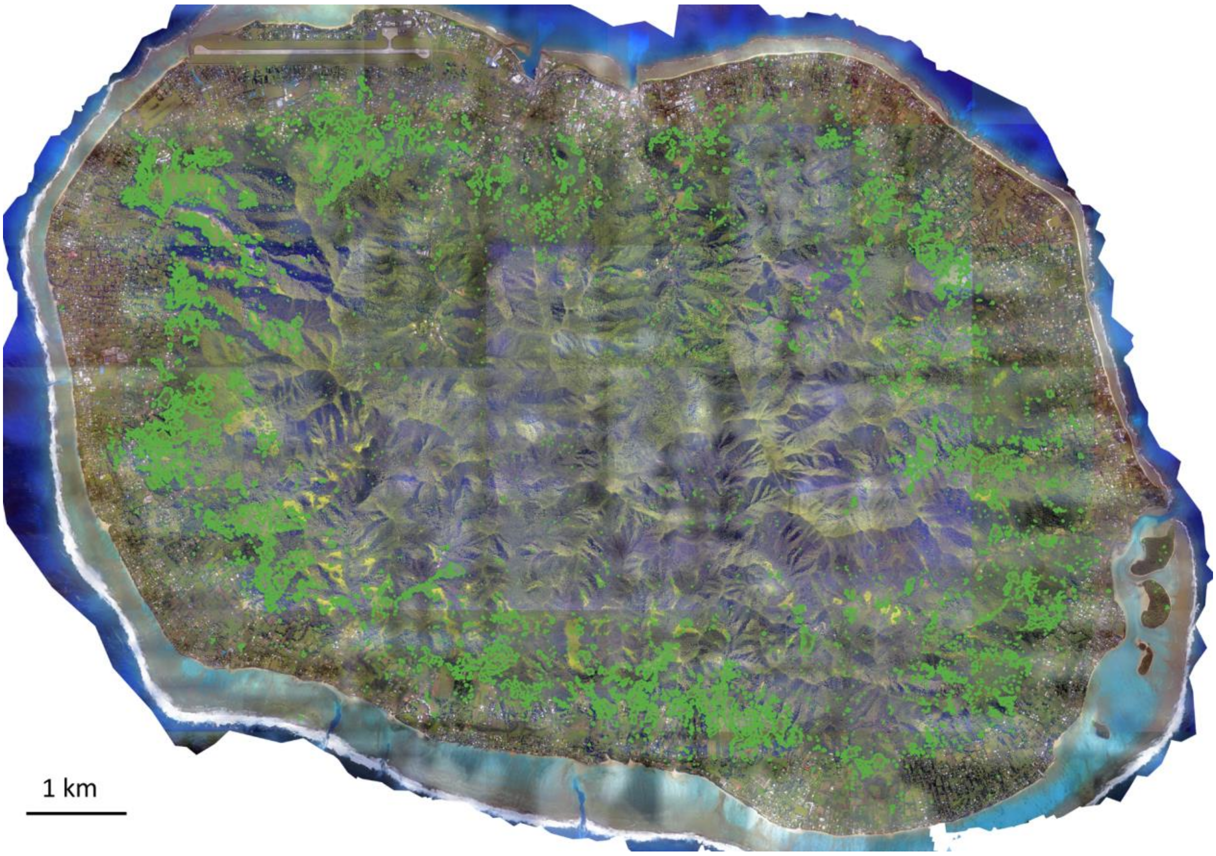

Figure 34. AI map of Falcataria based on island-scale aeroplane imagery of Rarotonga (green areas are tree crown outlines).

Flowering ATT and Falcataria AI mapping layers from aeroplane imagery were then overlaid onto the satellite imagery and attempts made to adjust polygons to fit onto flowering ATT and Falcataria tree crowns in training areas. However, poor image quality meant that neither image could be used for mapping either flowering ATT or Falcataria as tree crowns could not be reliably identified (see Section 4.1.2).

Calculations from the deep learning–based tree crown mapping show that 54 ha of Rarotonga (0.8% of the land area) was occupied by 10,654 flowering ATTs when the aeroplane imagery was taken, and 347 ha (5.1% of the land area) was occupied by 12,357 Falcataria trees. Analysis of the high-resolution drone imagery indicated that 430 of the 889 ATTs were flowering across all the drone sites when the aeroplane imagery was taken (Table 1). Using this ratio (889/430 = 2.07) we estimated the total area occupied by ATTs (flowering and non-flowering) to be 112 ha (1.6% of the land area) and the total number of ATTs to be 21,947. These calculations used average tree crown area estimates of 51m² for ATT and 281 m² for Falcataria. The maps of ATT and Falcataria were surprising because of the extent of weed spread.

4.3 Develop a natural enemy establishment and monitoring protocol capable of recording tree canopy damage

High-resolution (1 cm) drone imagery allowed for ATT identification by leaf shape so that all trees within drone areas could be mapped whether flowering or not (see Section 4.1.2). Base statistics including trees per hectare (trees/ha) and the percentage of the area of drone sites covered by trees were calculated for ATT from five sites (Table 2) and Falcataria from three sites (Table 3). Note that Falcataria was not present at all the sites. Drone site mission plans will be shared with NES staff so that the same flights can be programmed into another drone in the future to re-fly areas to help assess canopy damage from natural enemies over time.

Table 2. Baseline ATT statistics derived from the five drone sites in Rarotonga. (AVA – Avatiu; MAT – Matavera; TAK – Takuvaine; TCA – Takitumu; TUR – Turangi.)

SITE	Trees/ha	Area of trees (m^2)	Area of site (m^2)	Tree area as proportion of site (%)
AVA	28.3	4,826	63,957	7.50%
MAT	67.1	7,190	46,324	15.50%
TAK	4.7	217	25,617	0.80%
TCA	1.9	2,466	318,325	0.08%
TUR	42.5	6,036	76,080	7.90%
TOTAL	**16.8**	**20,735**	**530,302**	**3.9%**

Table 3. Baseline Falcataria statistics derived from three drone sites in Rarotonga. (MAT – Matavera; TCA – Takitumu; TUR – Turangi.)

SITE	Trees/ha	Area of trees (m^2)	Area of site (m^2)	Tree area as proportion of site (%)
MAT	0.2	211.3	46,324	0.50%
TCA	13.8	123,715	318,325	38.9%
TUR	7.1	15,139	76,080	19.9%
TOTAL	**35.6**	**139,065.5**	**44,0728.5**	**31.6%**

Imagery at even higher resolution (< 0.5 cm) enabled the identification of galls formed by the ATT gall mite (see Section 0). Imagery captured at this resolution could also be re-flown and used to monitor natural enemy presence and changes in density over time by comparing the number of galls per unit area. Despite recent establishment of ATT flea beetles (a second natural enemy introduced to control ATT) populations were present in numbers below levels required to cause detectable damage to leaves using remote sensing methods during this project.

4.4 Develop capability in the PICTs so that weed control projects can be monitored and assessed locally

We developed a method for monitoring and assessing weed control projects in PICTs. There are opportunities to partially or fully manage this method locally depending on availability of aircraft, pilots, photographers, drone operators, drones and cameras, GPS and computer hardware. To demonstrate an example of how the steps to this method could be broken down and either managed internally or contracted out we will provide options for repeat data collections in Rarotonga.

The method includes three jobs.

1 Re-photographing Rarotonga in 5–10 years from an aeroplane, creating an orthomosaic, and using AI models developed by MWLR to re-map ATT and Falcataria.

2 Re-flying high-resolution (1 cm) imagery at drone sites to re-calculate tree density and area statistics as shown in Table 2, and to look for canopy damage from natural enemies. Drone site mission flight plans from the 2023 image capture can be used again to re-fly exact areas.

3 Re-flying very high-resolution (< 0.5 cm) imagery over individual trees at drone sites to detect natural enemy presence and density. Some collection of canopy vegetation may also be required.

Logistics and cost estimate details for each job are shown below.

1 For local operators to manage this, a pilot and photographer need to be found to take imagery from Air Rarotonga Ltd's Cessna 172 aeroplane complete with camera hatch. Henry Le Grice (Rarotongan commercial pilot now living in New Zealand) has flown the flight paths for this project with Lawrie Cairns (New Zealand photographer) and may be able to either pilot future missions or train up another local pilot. The cost to re-fly Air Rarotonga Ltd's Cessna 172 aeroplane over the same flight path is approximately NZ$7 K; the cost of a photographer will vary depending on where they come from. Lawrie Cairns used a Canon EOS 6D MkII camera (NZ$5 K) to capture 10 cm resolution imagery on a custom-built camera mount (>NZ$1.5K), and a combination of a Garmin AERA600 GPS (NZ$2 K), inbuilt camera GPS, and GPS navigation/mission planning software on a tablet for flight path guidance and to geotag photos. More modern systems are available that connect to the camera for automatic GPS tagging: such as those provided by https://www.aerosci.info/. Mission planning software can be purchased from several suppliers and some drone software programs could be adopted. Software used in this project was purchased from AeroScientific (https://www.aerosci.info/) at a cost of US$500. Photos were sorted and an orthomosaic made using Agisoft software (pay-per-use licenses are available see: https://www.agisoft.com/buy/saas/service-provider-license/). Photo control points visible on the ground were also used to help locate images. Image processing in Agisoft does require a powerful computer. The current imagery was processed using a Ryzen 7 5800X with 64GB RAM and a 3060 Ti video card. The total cost of taking the aerial imagery and creating the orthomosaic for this job was NZ$23 K including travel and accommodation for Lawrie and Henry. Larger commercial operators with more modern systems like those from Aerial Surveys or Action Aviation (see https://www.aerialsurveys.co.nz/ or https://actionaviation.co.nz/) will probably cost

another NZ$10–20 K to commission with additional costs to orthomosaic imagery. Applying the existing AI model to new imagery and creating a map could be done locally with some training or would cost NZ$5–10 K for MWLR to run.

2 Local staff could be trained to capture high-resolution imagery at drone sites in 5–10 years' time, as suggested above. Drone flying costs include training for the qualifications required to operate drones commercially which can be provided by qualified operators such as Salmendra Chand of Drone Works Consultancy (https://droneworksconsultancy.com/) with rates starting at NZ$5.5 K depending on the type of training (online versus face-to-face) and the number of people attending. Salmen is a qualified drone pilot and trainer based in Fiji who is experienced with working in PICTs. Despite trialling a multispectral DJI Mavic 3M drone during this work, it appears that high-resolution RGB imagery will be sufficient to identify natural enemies in tree canopies and provide imagery for before and after impact assessments. Therefore, a DJI Mavic 3 Pro Fly More Combo (DJI C) kit currently priced at NZ$5K (https://store.dji.com/nz/product/dji-mavic-3-pro-combo?vid=137721) would be sufficient for repeat drone flights. Labour costs associated with flying the drone and putting imagery together into orthomosaics would also need to be factored in. Both the re-flying of drone sites and the creation of orthomosaics could be done within a few weeks (weather dependent) but would also require subscription to software such as Agisoft as described above for processing aeroplane imagery. Alternatively, a qualified drone operator like Salmen could be commissioned to complete flights and provide orthomosaics at a cost of NZ$520/day excluding travel and accommodation. Once orthomosaics have been made they can be viewed with free software such as QGIS. Specific methods would need to be developed to quantify damage caused by natural enemies using before and after photos after both sets of imagery have been collected. Further advice from MWLR may be required.

3 Capture of very high–resolution drone imagery would be included in the logistics and costs estimates shown above (Job 2), but canopy vegetation inspection may also be required to confirm natural enemy presence. Because of the drone flying skill level required to operate the canopy sampler effectively we recommended that trees either be felled to sample canopy foliage or long-handled loppers used instead. Alternatively, if contracted to re-fly drone sites, Salmen can also operate the canopy sampler which can be shipped to Rarotonga from NZ for use. However, a second operator (local) would be required to activate the canopy sampler claw.

Table 4 summarises job cost estimates to re-map invasive ATTs, and Falcataria, over Rarotonga in future. Given that completing these jobs locally would depend on numerous considerations including inhouse experience, knowledge, existing hardware and software, we have only attempted to summarise cost estimates for contracting out remote sensing work to experienced operators. We have also attempted to provide estimates for doing this work on different sized islands, see Table 5.

Table 4. Cost estimates for contracting out repeat remote sensing work to monitor invasive weeds and evaluate impacts of natural enemies

Re-run of Rarotonga aerial imagery and mapping (70 sq. km)		
Job	**Task**	**Cost NZD**
1	Re-capture island-scale aerial imagery and orthomosaic (10 cm)	$25 - 60K
	Mapping using AI model (existing model)	$5 - 10K
2	Re-capture 1 cm drone imagery at selected sites	$5 - 15K
	Analyse tree area data	$5K
3	Re-capture <0.5 cm drone imagery over a selection of trees + canopy samples	incl. in job 2
	Analyse natural enemy establishment/abundance	$5 - 10K
4	Landcare Research - Manaaki Whenua project administration	$5-$10K
	Total	**$50 - 110K**

Table 5. Cost estimates for contracting out remote sensing work to monitor invasive weeds and evaluate impacts of natural enemies on different-sized islands

Fly aerial imagery and mapping (1st time)		**30 sq. km**	**70 sq. km**	**260 sq. km**
Job	**Task**	**Cost NZD**	**Cost NZD**	**Cost NZD**
1	Capture island scale aerial imagery and orthomosaic (10 cm)	$20 - $55K	$25 - 60K	$30 - 65K
	Mapping using AI model	$10 - 20K	$10 - 20K	$10 - 20K
2	Capture 1 cm drone imagery at selected sites	$10 - 30K	$10 - 30K	$10 - 30K
	Analyse tree area data	$5K	$5K	$5K
3	Capture <0.5 cm drone imagery over a selection of trees + canopy samples	incl. in job 2	incl. in job 2	incl. in job 2
	Analyse natural enemy establishment/abundance	$5 - 10K	$5 - 10K	$5 - 10K
4	Landcare Research - Manaaki Whenua project administration	$5 - 10K	$5 - 10K	$5 - 10K
	Total	**$55 - 130K**	**$60 - 135K**	**$65 - 140K**

NB. Proportion of fixed costs for flying imagery is high so different sized islands do not change the cost much. Island accessibility/remoteness and access to aircraft are likely to have a much larger impact on costs.

The presentation to the Pacific Islands GIS and Remote Sensing Users Conference in Fiji from 27 November to 1 December 2023 (on day 3) can be viewed at https://pgrsc.org/2023-conference-resources/. The conference had 250 participants from 22 countries including 16 PICTs. Newspaper (Cook Islands News) and television (CITC News) media coverage was also generated in Rarotonga to share project objectives. Paul Peterson also presented results from this work at the Pacific Invasive Learning Network meeting 12-16 August 2024 (https://www.sprep.org/invasive-species-management-in-the-pacific/piln) in Rarotonga.

5 Discussion

The imagery we captured at multiple scales from Niue and Rarotonga during this project has provided data to assess the importance of scale, spectra, timing, and texture for mapping and monitoring invasive weed species distribution and evaluating impacts of natural enemies introduced to PICTs. Medium-resolution aeroplane imagery (10 cm) was sufficiently detailed to produce two baseline maps of ATT and Falcataria in Rarotonga and demonstrated the potential to map others. The use of remote sensing to evaluate the establishment and impact of natural enemies introduced into PICTs Islands was also demonstrated using high-resolution (1 cm) and very high–resolution (<0.5 cm) drone imagery. Satellite imagery (50 cm) was less expensive to capture but its poor image quality excluded it as a reliable mapping option. Problems associated with contrast, orthorectification, colour balance and cloud cover meant that target species could not be reliably identified across Rarotonga.

Despite aeroplane imagery providing good tree-scale detail, the use of high-resolution drone imagery (1 cm) was an integral part of the weed mapping workflow because non-target species with similar spectral and textural characteristics could be more reliably identified in high-resolution imagery and excluded from the lower resolution AI training data.

AI was preferred over manual (by-eye) mapping for this project because it was faster, and some false positives could be tolerated. The AI model can also be re-run on imagery collected in the future by local assessors using identical parameters for comparison with baseline maps. High-resolution (1 cm) imagery also allowed for collection of target species statistics at each of the drone sites because target species could be identified accurately by leaf shape alone. This was particularly relevant to ATT because wider island-scale mapping could only be done on flowering trees.

Statistics collected from drone areas such as number of trees per hectare and the percentage of the area covered by trees can be re-run in future, if more high-resolution imagery is taken, to see if the presence of natural enemies is associated with weed species decline. To monitor presence and density of natural enemies on a finer scale very high-resolution (< 0.5 cm) imagery was also captured at the drone sites to detect subtle impacts of natural enemies like leaf galling. Despite not quantifying galling at each drone site in this report, photos can be analysed later, and comparisons made, with imagery collected in future.

We also collected data using other (more expensive) specialist remote sensing equipment such as hyperspectral imagery and LiDAR, but we have only made a preliminary analysis of these data and would require more funds to assess these options fully. Similarly, the tree canopy sampler was trialled at each drone site but was found tricky to operate by one of our experienced pilots and is not practical for collecting large numbers of samples without considerable practice. Alternative methods such as felling sample trees or using long-handled loppers may be a more practical method for collecting canopy samples if these are required to identify natural enemies/damage in future. Long-handled loppers have been used successfully to collect plant material from large ATTs recently in Cameroon (Q. Paynter, MWLR, pers. comm., 1 August 2024).

The method we developed to monitor invasive weeds and evaluate the impacts of natural enemies is practical and minimises the use of specialist equipment. However, the method is only practical for complete coverage of small islands. High-resolution aerial photography (10 cm) is seldom collected over areas larger than several hundred square kilometres. Therefore, for larger islands we would need to focus on areas of interest. A relatively unique high-resolution mapping project for broom (*Cytisus scoparius*), gorse (*Ulex europaeus*), and tree lupin (*Lupinus arboreus*) currently under way in New Zealand covers an area of 230 km^2 (Peterson et al. 2024).

Previous mapping attempts over similar areas in the PICTs have relied almost exclusively on satellite imagery (≥ 50 cm) from which associated uncertainties can lead to incomplete mapping and difficultly with distinguishing between species in a heterogenous canopy (Matepi et al. 2010; Pouteau et al. 2013, 2015; Meyer et al. 2015). These factors will probably contribute to unreliable before and after weed control assessments. This is particularly relevant when assessing damage from natural enemies which might break down the homogenous canopy cover of invasive species allowing for some native regeneration. While impacts from natural enemies can sometimes be spectacular, they never completely remove weeds from the environment they are released into, and subtle but significant reductions in weed densities are not uncommon. The work we report on in this study is the first of its kind in the PICTs, as far as the authors are aware, where aeroplane and drone imagery has been used in tandem to map invasive weeds in detail, using multiple scales, to help assess a range of impact outcomes from weed control programmes.

6 Recommendations

Our recommendations for future use of remote sensing for monitoring invasive weed distribution and evaluating natural enemy impacts locally in PICTs are summarised below (also see Section 4.4 for logistics and costings).

1 In Rarotonga we recommend the following.

- Rarotongan National Environmental Service re-fly island-wide aeroplane and drone site imagery again in 5–10 years' time to monitor spread of ATT and Falcataria and evaluate natural enemy impacts on ATT distribution.
- Consider the practicality of managing future image acquisition and assessment work locally versus external contracting.
- If managing aerial imagery locally, find a local pilot and photographer and utilize Air Rarotonga Ltd.'s Cessna 172 (complete with a camera hatch) to re-capture 10 cm resolution imagery of Rarotonga. A camera mount, camera and GPS unit will need to be purchased, otherwise contract work to an offshore service provider.
- If managing drone imagery locally, purchase a drone and train drone operators to re-fly imagery at the five established drone sites using existing drone site mission flight plans to evaluate natural enemy establishment and impact. Otherwise contract an offshore qualified drone operator.
- If processing aerial and drone imagery locally, purchase Agisoft software and train NES staff to create orthomosaics, with input from MWLR if required. A powerful computer will also be required. Alternatively have imagery processed externally by MWLR or another commercial provider.

- If maps are to be produced locally, test and become familiar with running the AI model in QGIS with guidance from MWLR to map ATT and Falcataria. Also consider mapping additional species of interest from existing imagery.

2 In other PICTs we recommend the following.

- Consider adapting the method developed in Rarotonga (67 km^2) for use in other PICTs to monitor invasive weeds and evaluate natural enemy impacts. In larger countries, such as Fiji (18,300 km^2), representative target areas not more than several hundred square kilometres will need to be identified to acquire and manage data in a practical way.

7 Acknowledgements

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The Pacific Regional Invasive Species Management Support Service (PRISMSS) is a coordinating mechanism designed to facilitate the scaling up of operational management of invasive species in the Pacific. PRISMSS brings together experts to provide support within the Pacific region with a focus on protection of indigenous biodiversity and ecosystem function and provides a comprehensive suite of support services in a cohesive, effective, efficient, and accessible manner to Pacific Island countries and territories. Manaaki Whenua is the technical lead for the PRISMSS Natural Enemies - Natural Solutions (NENS) Programme.

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Appendix 1 – Inventory of imagery collected from Rarotonga as part of the MWLR MISCCAP Project 2023

Inventory of imagery collected from Rarotonga as part of the MWLR MISCCAP Project 2023-24.

Andrew McMillan, Paul Peterson and Ben Jolly.

Manaaki Whenua, Palmerston North, New Zealand

October 2024.

Overview

As part of the 2023 MWLR MISCCAP Project (led by MWLR and funded by MFAT), we collected a variety of remote sensing imagery for the purposes of monitoring the distribution of invasive species, with a particular focus on African Tulip Tree (*Spathodea campanulata*) and Falcataria (*Falcataria moluccana*).

The imagery was collected from a variety of platforms that included:

- The Planet constellation of SkySat satellites.
- An aeroplane survey at 1200 m of the entire island.
- A drone survey at 5 sites using a DJI Mavic 3M Multispectral Drone.
- A drone survey at 4 sites using a DJI M600 drone equipped with a hyperspectral camera and LiDAR equipment.
- We also collected hyperspectral spectra from leaves of African tulip trees (either hand-picked or collected with a drone-based vegetation sampler) with a portable analytical spectral device (ASD).

Satellite imagery

The Planet SkySat satellite imagery was ordered through Interpine Innovation Ltd who are Aotearoa NZ agents for Planet. SkySat is a constellation of ~20 satellites that can be tasked to view.

Aerial Imagery

An aerial survey of Rarotonga took place on 20/7/2023. This imagery was collected at 1200 m with a RGB camera (Canon EOS-6D). The resolution of the imagery is ~10 cm/pixel.

The photos were taken with substantial spatial overlap and the collection of photos were ingested into the structure-from-motion photogrammetry software package Agisoft Metashape, which constructed an orthomosaic.

During the construction of the orthomosaic, a digital surface model of the island was also developed.

The orthomosaic was georeferenced using control points that were obtained from the Mavic drone imagery (which was positioned using RTK-GPS referenced to a Trimble R10 base station). In areas outside of the drone study sites, the orthomosiac was georeferenced by control points from separate imagery.

Mavic Drone Imagery

We collected high resolution RGB and multispectral imagery using a DJI Mavic 3M drone at five sites: Turangi, Matavera, Takitumu Conservation Reserve, Takuvaine and Avatiu.

The Mavic was equipped with a highly accuracte RTK GPS system so the positioning of the photographs should be very accurate.

The raw still photographs were processed into an othomosaic as described above.

At four of the sites (Turangi, Matavera, Takitumu Conservation Reserve, and Avatiu) we captured imagery at 100 m altitude (providing 2 cm/pixel resolution RGB imagery) and at 30m altitude (providing 1 cm/pixel resolution RGB imagery). At Takuvaine, only 1cm imagery was collected. Imagery with a resolution of <0.5 cm/pixel was also collected at the Turangi site to determine whether evidence of natural enemy damage could be seen.

The multispectral camera on the Mavic 3M drone collects imagery at slightly lower resolution but in four spectral bands:

- Near Infrared: 860 nm ± 26 nm
- Red: 650 nm ± 16 nm
- Red Edge: 730 nm ± 16 nm
- Green: 560 nm ± 16 nm

The near-infrared and red edge bands are in the part of the electromagnetic spectrum called the near-infrared region. This is beyond the visible spectrum. The bands from this region can be used in combination with the red and green bands to construct spectral indices (mathematical combinations of individual band values, such as NDVI) that can provide valuable information about the surface vegetation.

Hyperspectral Drone Imagery

At the four main sites (Turangi, Matavera, Takitumu Conservation Reserve, and Avatiu), hyperspectral imagery was also collected.

Hyperspectral imagery is similar to multispectral imagery in that it contains bands from both the visible and the near-infrared part of the spectrum. However, in hyperspectral imagery there are many more bands and the bands are much narrower.

We used a Headwall Nano Hyperspec camera of which the images contain 269 bands ranging from 400 nm (at the blue end of the visible spectrum) to 1200 nm (at the upper end of the near-infrared spectrum).

Due to time constraints most of the hyperspectral imagery could not be processed in the current project.

LiDAR Drone Imagery

At the four main sites (Turangi, Matavera, Takitumu Conservation Reserve, and Avatiu), LiDAR imagery was also collected (on the same drone platform as the hyperspectral camera)

The LiDAR instrument is a Velodyne VLP-16 Puck Lite. This is a 16-channel laser with a 360° horizontal field of view and a 30° vertical field of view, and generates approximately 300,000 points per second, resulting in a point density well in excess of 20 points per square metre. It is integrated with the GPS and inertial measurement unit that is used with the hyperspectral camera so that they can be spatially co-registered.

Due to time constraints the LiDAR imagery could not be processed in the current project.

Viewing this imagery – software and image formats

We suggest the use of either QGIS or ArcGIS to view

The imagery is stored in two types of geospatial raster formats:

- Geotiff files
- kea Files

geotiff files are a common format that can be read by mapping software such as QGIS and ArcGIS. However, very large geotiff files can overwhelm the memory of the computer unless the files carefully generated with appropriate tiling, compression and overviews (pyramids).

The *.kea format was developed at Manaaki Whenua to overcome these issues. A *.kea raster file (with overviews) of any size can be displayed in QGIS or ArcGIS without overloading the memory. To be able to use *.kea files with QGIS or ArcGIS, particular libraries must be installed. We are happy to provide guidance on how to do this.

Inventory of imagery

Platform	Imagery type	Sensor	Site	Date	Altitude	Resolution (cm/pixel)	Filename
Aeroplane	Aerial RGB Orthomosaic	Canon EOS-D6 RGB Camera	Rarotonga	20 July 2023	1200 m	~10 cm	Raro-ortho-v3.kea
	Aerial DEM	Canon EOS-D6 RGB Camera	Rarotonga	20 July 2023	1200 m		Raro_Mesh_DSM_2023.kea
Planet Satellite	Surface-Reflectance Orthomosaic	Skysat	Parts of Rarotonga in 2023	8 dates between 19 July 2023 and 8 August 2023.	450 km	50 cm	20230808_193818_ssc15_u0001_analytic_SR.kea 20230808_190708_ssc16_u0001_analytic_SR.kea 20230807_194428_ssc2_u0001_analytic_SR.kea 20230724_001146_ssc7_u0001_analytic_SR.kea 20230724_001117_ssc7_u0001_analytic_SR.kea 20230719_222638_ssc19_u0002_analytic_SR.kea 20230719_222638_ssc19_u0001_analytic_SR.kea Data from 7-8 Aug 2023 mosaiced to form whole island image: skysat_pansharpened_230807-230808_mosaic_modified.kea
			Parts of Rarotonga in 2024	3 dates between 27 May 2024 and 3 June 2024.	450 km	50 cm	Data from 27 May 2024 to 3 June 2024 mosaiced to form whole island image: skysat_pansharpened_240527-240531-240603_mosaic.kea
Mavic 3M Drone	RGB Orthomosaic	20MP wide camera RGB Camera	Avatiu	9 Aug 2023	100 m	2 cm	230809-AVA-avatiu-100m-10mDEM.tif
			Matavera	10 Aug 2023	100 m	2 cm	2308010-MAT-matavera-100m-10mDEM.tif
			Takitumu	8 Aug 2023	100 m	2 cm	230808-TCA-takitumu-100m-10mDEM.tif
			Turangi	7 Aug 2023	100 m	2 cm	230807-TUR-turangi-100m-10mDEM.tif
			Turangi	11 Aug 2023	100 m	2 cm	230811-TUR-turangi-pt2-100m-10mDEM.tif
			Avatiu	10 Aug 2023	30 m	1 cm	230809-AVA-avatiu-30m-10mDEM.tif
			Matavera	10 Aug 2023	30 m	1 cm	2308010-MAT-matavera-30m-10mDEM.tif
			Takitumu	8 Aug 2023	30 m	1 cm	230808-TCA-takitumu-30m-10mDEM.tif
			Turangi	7 Aug 2023	30 m	1 cm	230807-TUR-turangi-30m-10mDEM.tif
			Turangi	11 Aug 2023	30 m	1 cm	230811-TUR-turangi-pt2-30m-10mDEM.tif
	Multispectral	5 MP – 4 band	Avatiu	9 Aug 2023	100 m	2 cm	230809-AVA-avatiu-100m-MultiSpec-10mDEM-MS.tif
			Matavera	10 Aug 2023	100 m	2 cm	2308010-MAT-matavera-100m- MultiSpec-10mDEM-MS.tif
			Takitumu	8 Aug 2023	100 m	2 cm	230808-TCA-takitumu-100m- MultiSpec-10mDEM-MS.tif

			Turangi	7 Aug 2023	100 m	2 cm	230807-TUR-turangi-100m- MultiSpec-10mDEM-MS.tif
			Turangi	11 Aug 2023	100 m	2 cm	230811-TUR-turangi-pt2-100m- MultiSpec-10mDEM-MS.tif
			Avatiu	0 Aug 2023	30 m	1 cm	230809-AVA-avatiu-30m- MultiSpec-10mDEM-MS.tif
			Matavera	10 Aug 2023	30 m	1 cm	2308010-MAT-matavera-30m- MultiSpec-10mDEM-MS.tif
			Takitumu	8 Aug 2023	30 m	1 cm	230808-TCA-takitumu-30m- MultiSpec-10mDEM-MS.tif
			Turangi	7 Aug 2023	30 m	1 cm	230807-TUR-turangi-30m- MultiSpec-10mDEM-MS.tif
			Turangi	11 Aug 2023	30 m	1 cm	230811-TUR-turangi-pt2-30m- MultiSpec-10mDEM-MS.tif
Drone-based hyperspectral imagery	Hyperspectral Orthomosaic	Headwall Nano Hyperspec	Turangi	11 Aug 2023	80 m	4 cm	multi_or_TUR_20230811_2BYTE_32704.kea
	Unprocessed	Headwall Nano Hyperspec	Avatiu	10 Aug 2023	80 m	4 cm	Orthomosaic to be created
	Unprocessed	Headwall Nano Hyperspec	Matavera	10 Aug 2023	80 m	4 cm	Orthomosaic to be created
	Unprocessed	Headwall Nano Hyperspec	Takitumu	8 Aug 2023	80 m	4 cm	Orthomosaic to be created
Drone-based LiDAR	Unprocessed	Velodyne VLP-LITE	Turangi	11 Aug 2023	80 m	>20 points per square m (unknown point density until processed)	Point cloud *.las file to be created
	Unprocessed	Velodyne VLP-LITE	Avatiu	10 Aug 2023	80 m		Point cloud *.las file to be created
	Unprocessed	Velodyne VLP-LITE	Matavera	10 Aug 2023	80 m		Point cloud *.las file to be created
	Unprocessed	Velodyne VLP-LITE	Takitumu	8 Aug 2023	80 m		Point cloud *.las file to be created

Appendix 2 – Summary of project team who contributed to this work

The project team consisted of:

- Andrew McMillan, Ben Jolly, Paul Peterson – Experience with assessing natural enemy impacts on invasive weeds and drone pilots with experience in drone mission planning, hyperspectral sensing and LiDAR (MWLR).
- Waisale Rakusanavanua – Drone pilot (School of Agriculture, Geography, Environment, Oceans & Natural Sciences, Laucala, Fiji).
- Salmendra Ratnesh Chand – Drone pilot (Drone Works Consultancy, Fiji).
- Lawrie Cairns – Aerial photographer (Survey Services & Land Information, NZ).
- Henry Le Grice – Rarotongan commercial aeroplane pilot (now living in NZ) who flew a local Cessna 172 diesel-powered aircraft owned by Air Rarotonga Limited.
- James Shepherd, Jan Schindler, Harley Betts and Brent Martin (MWLR) – image analysis including AI experience.