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Remote Sensing Guides Management Strategy for Invasive Legumes on the Central Plateau, New Zealand

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Abstract: Remote sensing was used to map the invasion of yellow-flowered legumes on the Central Plateau of New Zealand to inform weed management strategy. The distributions of *Cytisus scoparius* (broom), *Ulex europaeus* (gorse) and *Lupinus arboreus* (tree lupin) were captured with high-resolution RGB photographs of the plants while flowering. The outcomes of herbicide operations to control *C. scoparius* and *U. europaeus* over time were also assessed through repeat photography and change mapping. A grid-square sampling tool previously developed by Manaaki Whenua—Landcare Research was used to help transfer data rapidly from photography to maps using manual classification. Artificial intelligence was trialled and ruled out because the number of false positives could not be tolerated. Future actions to protect the natural values and vistas of the Central Plateau from legume invasion were identified. While previous control operations have mostly targeted large, highly visible legume patches, the importance of removing outlying plants to prevent the establishment of new seed banks and slow spread has been underestimated. Outliers not only establish new, large, long-lived seed banks in previously seed-free areas, but they also contribute more to range expansion than larger patches. Our *C. scoparius* and *U. europaeus* change mapping confirms and helps to visualise the establishment and expansion of uncontrolled outliers. The power of visualizing weed control strategies through remote sensing has supported recommendations to improve outlier control to achieve long-term, sustainable landscape-scale suppression of invasive legumes.

Keywords: adaptive weed management; aerial photography; invasive legumes; outlier control

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1. Introduction

Invasive weeds cause environmental, social, cultural and economic issues around the world, and the problem is accelerating [1,2]. Plants invading new environments become problematic when they outcompete resident native flora and, in some cases, alter nutrient budgets, which disrupts natural ecosystems [3,4]. They can also alter the character and appearance of iconic landscapes [5] to the detriment of tourism as well as spiritual and aesthetic values. Management interventions can be driven by a variety of goals and strategies [6]. Goals might include weed eradication, weed suppression to prevent infestations from getting worse or minimal control if intervention is deemed too expensive. Long-term management can be costly and logistically challenging, and outcomes need to be measurable so that sustainable adaptive management can be deployed over time. Relationships between ecologists and stakeholders and an understanding of commitments required are key to achieving these outcomes [7]. Without good planning and reporting, it is difficult to maintain stakeholder motivation and investment over the long time frames required to achieve good weed management.

It is vital to know the extent of the distribution of an invasive weed to manage it. Moreover, in ecologically sensitive environments, accurate locations are required to minimise impacts of non-target damage from interventions like herbicide control. Ground-based surveys can be laborious and difficult to implement on landscape scales. Recent advances in the quality and affordability of remote sensing technology provide an opportunity for rapid landscape-scale assessments of weed distribution and abundance. Indeed, remote sensing is emerging as a valuable approach to not only map weeds but also model and predict invasion processes to help inform management strategies [8–10]. However, current mapping of weeds uses either low-resolution imagery over large areas, which is not capable of outlier plant-level detection, or high-resolution imagery over smaller sub-management-scale areas [11–18]. Exceptions to this include studies by the authors of [19,20], where considerable efforts went into the early detection of wilding pines over large areas, and the authors of [21], who flew over a 10 km stretch of riverbed using high-resolution aerial photography. There are also few examples of operational programs that routinely use remote sensing to inform weed biosecurity programs [8,22].

While remote sensing through image acquisition and mapping appears cost-effective, limitations need to be acknowledged and methods must be tailored to the target species. 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 [23]. These include using an appropriate scale or a multi-scale approach, and timing is also often important [8]. Techniques like 'rocking' between imagery taken at different times of the year can help distinguish target species when using spectral analysis, for example [24]. Data processing and analysis are other important considerations. The approach used, whether it be manual or automated, may also depend on the scale of the project and the required outcomes.

New Zealand's (NZ's) indigenous plant communities have a high level of endemicity and are particularly vulnerable to the spread of introduced invasive plant species [25]. *Cytisus scoparius* (broom), *Ulex europaeus* (gorse) and *Lupinus arboreus* (tree lupin) are all invasive legumes that are currently invading NZ, including areas on the Central Plateau of the North Island. The NZ native flora has almost no yellow-flowered species, and the vast vista of the Central Plateau shrubland area would be irrevocably altered if these yellow-flowered leguminous weeds were to become widely established. From an ecological perspective, widescale invasive legumes could irreversibly transform the ecosystem because they not only outcompete native vegetation, but they increase the soil's nutrient status by fixing nitrogen from the atmosphere [26]. This would threaten ecosystems that have evolved on relatively infertile volcanic soils [27].

Seed bank management is a key consideration when controlling invasive weeds [28], and invasive legumes can establish extremely large (>10,000/m^2) and long-lived multi-decadal seed banks which drive persistent, hard-to-manage invasions [29,30]. Low-intensity weed management and monitoring programs have been underway to control invasive legumes on the Central Plateau since the 1980s [31,32], but despite this, the problem has been slowly increasing. Levels of public concern received by regional councils and the Department of Conservation (DOC) increased during the 2010s, and the effectiveness of weed control was questioned because more and more yellow flowering plants were visible from the Desert Road that runs through the Central Plateau.

In this paper, we describe how remote sensing, in combination with weed life history and dispersal theory, guides an adaptive weed management strategy. We develop a remote sensing method that can be routinely used to record and document outcomes of control operations and translate data into practical management solutions for landowners.

2. Materials and Methods

2.1. Site Description

The 23,000 ha area of interest (AOI) for this study is on the Central Plateau, North Island, NZ, and is bisected by the Desert Road/State Highway One (SH1) (39°17′18.81″S, 175°42′33.54″E) (Figure 1). It is made up of land within Tongariro National Park (TNP) and an adjacent area used by the New Zealand Defence Force (NZDF). The Department of

Conservation manages TNP and consults with indigenous stakeholders (iwi), including Ngāti Rangi, Ngāti Tūwharetoa, Ngāti Hikairo ki Tongariro, Ngāti Hāua, Te Korowai o Wainuiārua and Te Pou Tupua on significant management issues. TNP is a World Heritage Park that was established in 1894 and is NZ's oldest national park. It covers nearly 80,000 ha and includes three volcanic craters (Tongariro, Ngauruhoe and Ruapehu). The area has special ecological and cultural significance, with unique flora and fauna shaped by a volcanic history, including montane and subalpine vegetation with extensive areas of red tussock (*Chionochloa rubra*), mixed shrublands and patches of beech forest [33]. Neighbouring land has been used by NZDF for military training exercises since 1939, and there is a strategy in place to promote sustainable management of the natural and physical resources within the 63,000 ha NZDF-managed area [32]. The New Zealand Transport Authority (NZTA), Transpower and Genesis Energy also own and/or administer significant infrastructure within or alongside the AOI.

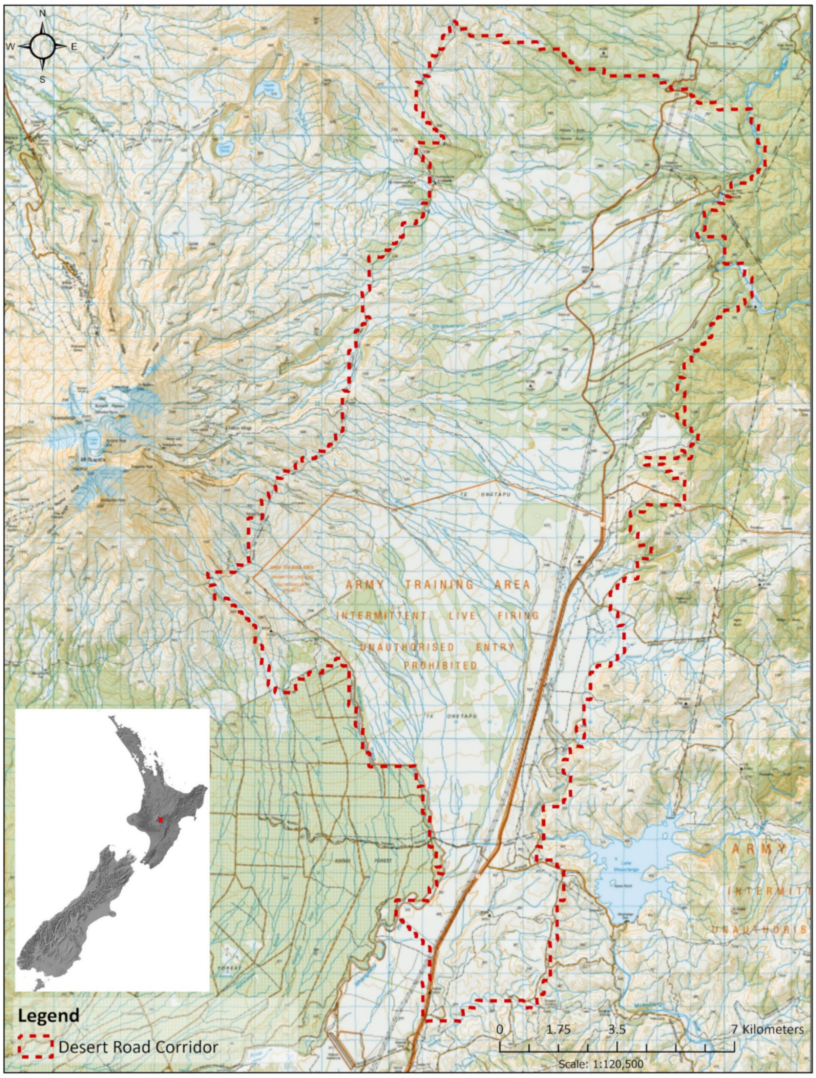


Figure 1. The 23,000 ha area of interest (AOI) for control of *C. scoparius*, *U. europaeus* and *L. arboreus* (dotted red lines) with adjacent map of NZ showing location (red shading).

2.2. Methods

Eight stakeholders formed a consortium in 2012 to discuss the history and future of weed control on the Central Plateau. The parties consisted of two central government agencies (DOC and the NZDF), a crown entity (NZTA), two state-owned enterprises (Transpower and Genesis Energy), two local government authorities (Horizons Regional

Council and Waikato Regional Council) and a local iwi organisation (Lake Rotoaira Forest Trust). In addition, a crown research institute (Manaaki Whenua—Landcare Research [MWLR]) was engaged to advise on weed management strategy based on its experience with the target weeds' life history and dispersal information.

Following a meeting on 31 October 2012, the stakeholder consortium arrived at a shared vision with the aim that "The unique values and vistas of the Desert Road environments are protected from invasive legumes". The eight signatories agreed to work collaboratively to protect the Desert Road landscape from the adverse effects of three legume pest plants over the AOI until 2025. The key objective was to reduce *C. scoparius*, *U. europaeus* and *L. arboreus* to near-zero density in sparse/low-density areas and to measurably reduce and contain populations in moderate- and high-density areas, respectively. Tools to carry out control operations and provide for future assessment of the project's success were also discussed, including aerial photography and mapping at 3-year intervals. A commitment to annual meetings was made so that progress towards the stated objectives, upcoming control, mapping and adaptive management plans could be discussed. Outcomes were documented in a Memorandum of Understanding (MOU), along with project principles, objectives and methods (see the 'Project Yellow' website in Results section).

Before this initiative, landowners independently conducted weed control programs without comprehensive mapping tools, using a combination of aerial and ground-based operations. Northern areas were checked annually and southern areas on a 3-year rotation. As part of the newly formed consortium objectives, high-resolution photographs were taken from 2012 to 2023 by Lawrie Cairns (Survey Services, Aerial Photography & Land Information) from a CESSNA 172 at a flight height of 4000–6000 feet above ground level over the entire AOI. Photographs of each of the three target plants were taken during peak flowering because non-flowering plants could not be distinguished from the surrounding vegetation. Each species was photographed during a different year to spread costs. The camera used and ground sample distance (GSD) improved over time (Table 1).

Table 1. Summary of photography captured.

Date of Photography	Species	Camera	Ground Sample Distance (GSD)
10 December 2012 to 15 December 2012	*C. scoparius*	Hasselblad 500ELM (Victor Hasselblad AB, Gothenburg, Sweden)	0.40 m
9 November 2013 to 3 December 2013	*U. europaeus*	Hasselblad 500ELM	0.25 m
17 December 2014 to 11 January 2015	*L. arboreus*	Hasselblad 500ELM	0.25 m
6 December 2016 to 28 December 2016	*C. scoparius*	CANON EOS 6D (Canon Inc., Tokyo, Japan)	0.20 m
18 October 2020 to 14 November 2020	*U. europaeus*	CANON EOS 6D	0.18 m
26 December 2022 to 28 December 2022	*L. arboreus*	CANON EOS 6D MkII	0.15 m

Earlier photos (2012–2015) were orthorectified, and orthomosaics were made manually from scanned film images using aerial triangulation methods by COWI India Private Ltd., Gurgaon, Haryana, India (now Hexagon Geosystems division). More recent digital photos were processed with Agisoft Photoscan Professional 1.2.6 (2016), Agisoft Cloud Beta (2020) and Agisoft Metashape Professional 1.8.4 (2022) to create orthomosaics. All mosaics were divided into approximately 6000 200 $\times$ 200 m grid squares over the AOI. A grid-square sampling tool previously developed by MWLR to help classify large amounts of orthorectified data rapidly was used to classify grid squares. Each grid square was scored as containing zero (no legumes), low-density (<1 plant/ha), moderate-density ($\geq$1 to <10 plants/ha) or high-density legumes ($\geq$10 plants/ha). Colour-coded maps were made by overlaying the grid-square density scores as a vector layer onto New Zealand topographical map sheets. When repeat photography was successfully taken, change maps were also produced, showing grid-square density scores as higher, lower, no change or removed since the original photography was taken.

A selection of sites was visited opportunistically by land managers who had extensive local knowledge to verify the presence of the target species. Imagery from different sampling occasions was also used to verify the presence of the target species by comparing flowering and non-flowering dates and removing false positives during analysis using the grid-square sampling tool. An investigation by NousAI Ltd. tested artificial intelligence (AI) on 2020 *U. europaeus* imagery training data that had already been manually classified by eye using a convolutional neural network (U-NET) to see if the image analysis and mapping could be performed more efficiently.

3. Results

During the assessment period, weed control practice varied between landowners, but efforts were made annually by DOC, Regional Council and NZDF staff and contractors to control legumes in their respective areas, as stated in the MOU. The project description, its extent and a proposed schedule of works were documented on a 'Project Yellow' website hosted by the Waikato Regional Council: www.waikatoregion.govt.nz/services/biosecurity/project-yellow/ (accessed on 19 June 2024). Figure 2a,b show an example of a successful 'before and after' *U. europaeus* control operation.

(**a**) (**b**)

Figure 2. Example of a successful *U. europaeus* control operation between 2012 (**a**) and 2016 (**b**). Red circle shows presence of *U. europaeus*.

Orthorectified aerial photography mosaics and topographical maps with grid-square-density vector overlays were produced to show the distribution and density of *C. scoparius*, *U. europaeus* and *L. arboreus* within the AOI from 2012 to 2022 (Figures 3 and 4a–e). Photography of *L. arboreus* in 2022 was taken too late to capture flowering, so a grid-square-density vector layer could not be produced.

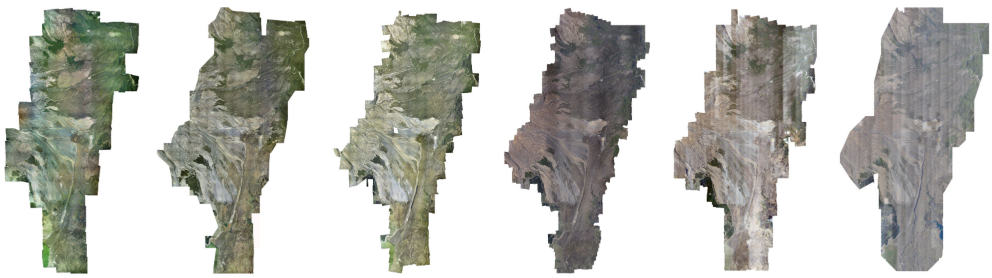


Figure 3. Orthorectified aerial photography mosaics of flowering invasive legumes in the AOI between 2012 and 2022.

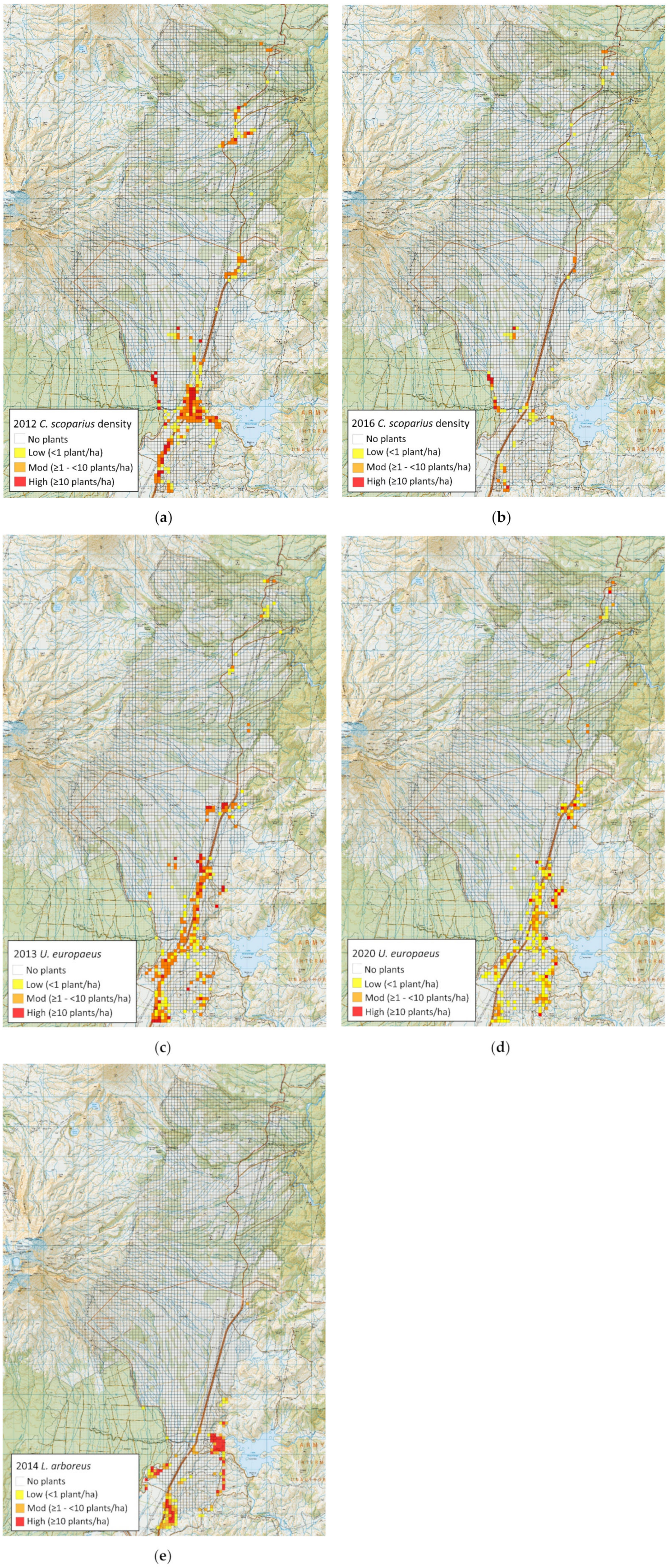
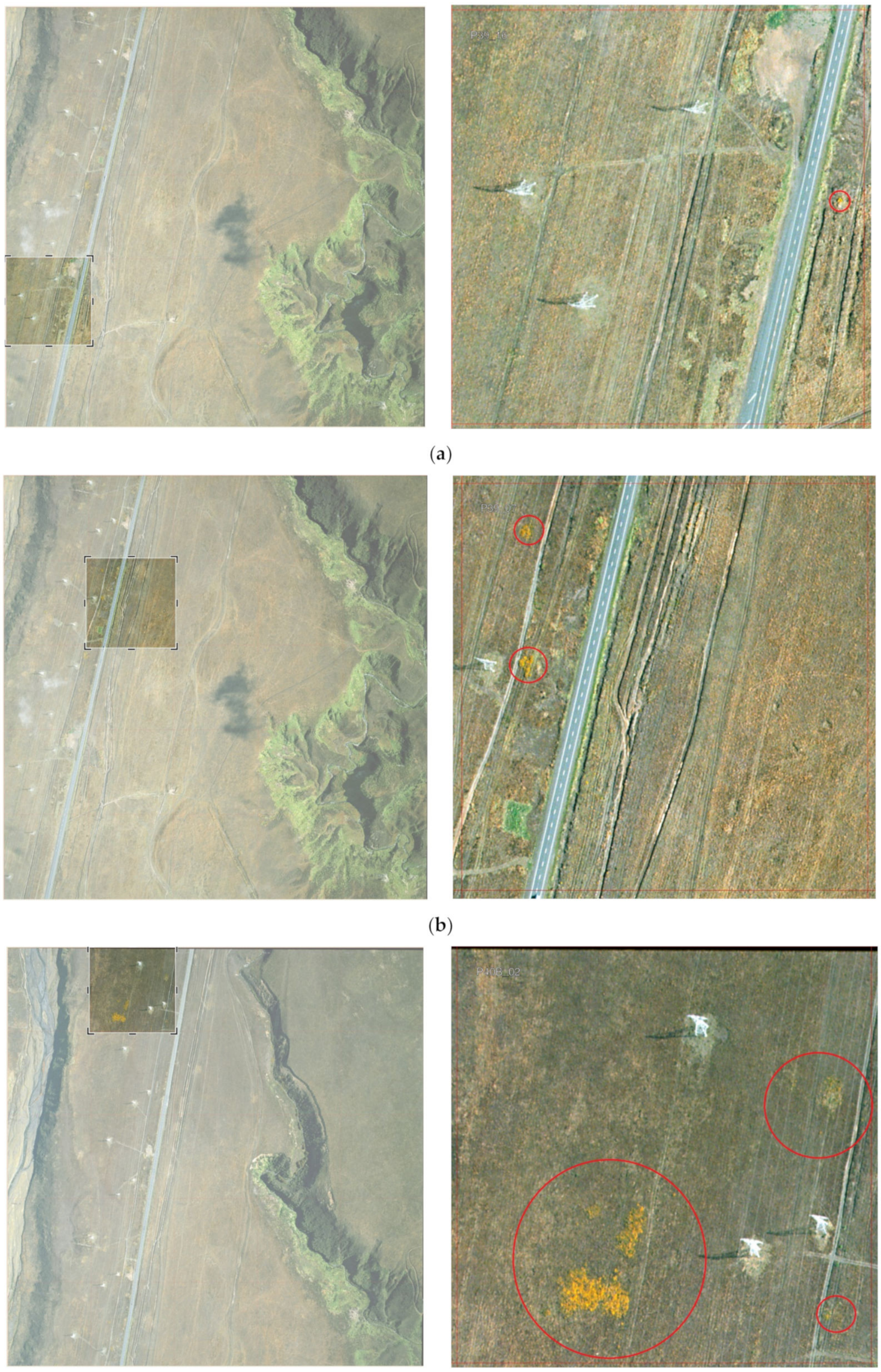


Figure 4. Maps of the distribution and density of *C. scoparius* (**a**,**b**), *U. europaeus* (**c**,**d**) and *L. arboreus* (**e**) in the AOI between 2012 and 2020.

Figure 5a–c show examples of low- (a), moderate- (b) and high-density (c) *U. europaeus* grid squares, and Figure 6a,b show examples of flowering *C. scoparius* and *L. arboreus*.



(**a**)

(**b**)

(**c**)

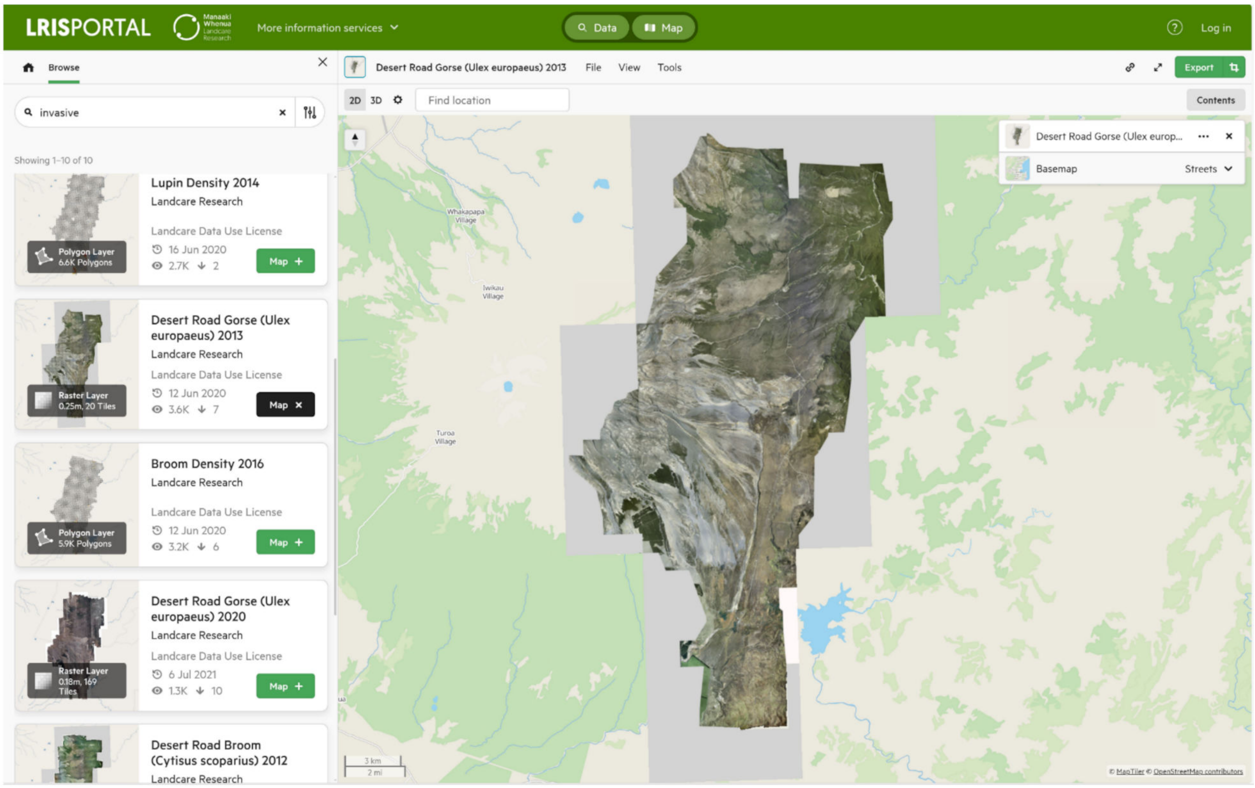
Figure 5. Examples of low- (**a**), moderate- (**b**) and high-density (**c**) *U. europaeus* grid squares. The image on the left shows a 1 km^2 area alongside the Desert Road, and the image on the right is a 200 × 200 m grid square within this area. The red circles highlight *U. europaeus* plants.

(**a**)

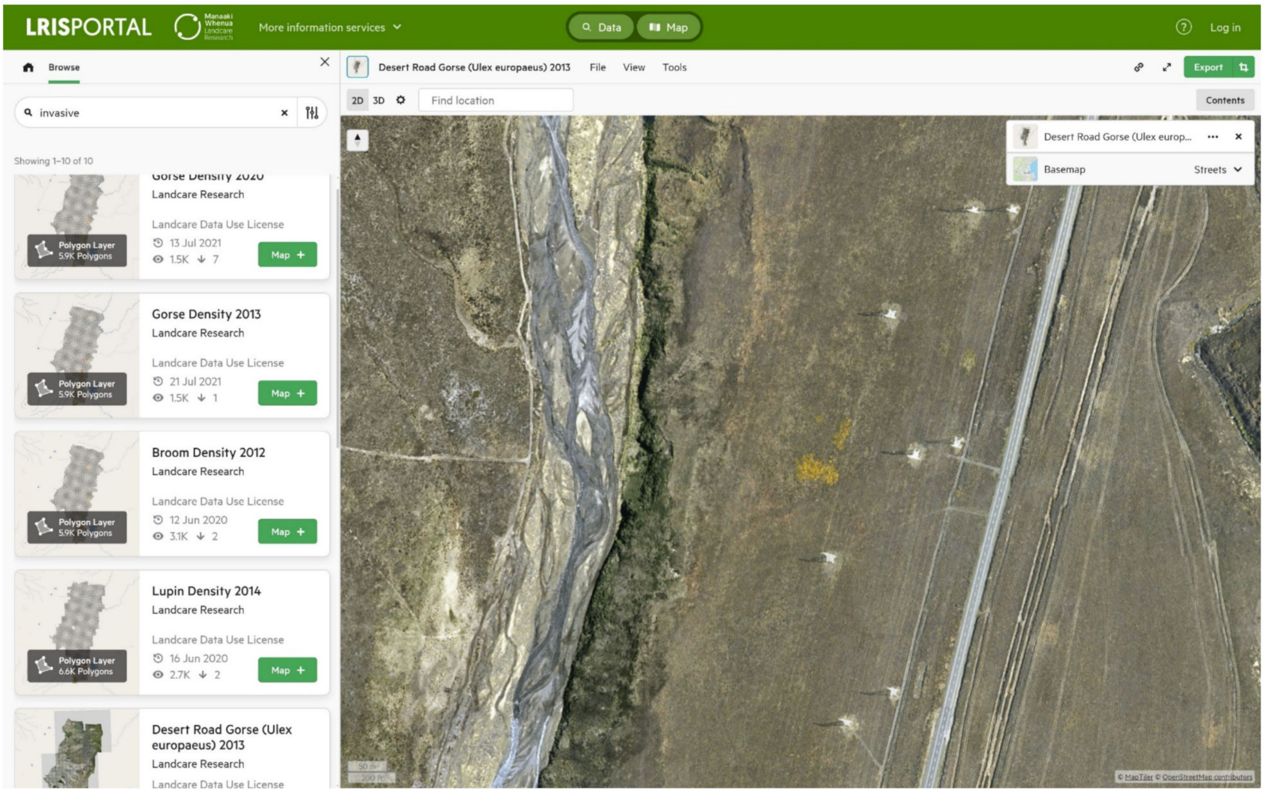
(**b**)

Figure 6. Flowering *C. scoparius* (**a**) and *L. arboreus* (**b**) visible in aerial photography.

Maps, including full-resolution photography and density-grid vector layers, were shared with stakeholders both in person at annual meetings and through MWLR's Land Resource Information System (LRIS) portal: https://lris.scinfo.org.nz/data/?q=legumes (accessed on 19 June 2024) (Figure 7a,b).



(**a**)



(**b**)

Figure 7. LRIS portal screenshot showing orthomosaic of photographs over the entire AOI (**a**) and zoomed-in image of a high-density *U. europaeus* area alongside the Desert Road (**b**).

These maps, along with raw imagery, were designed to flag areas of concern for stakeholders so that they could carry out more detailed investigation of their own. Options include digitizing individual plants or patches within grid squares and/or obtaining GPS coordinates to load into aircraft navigation software to help plan control flight paths. The ability to overlay semi-transparent grid-density vector layers on the photography allows for weed target detection within each grid square (Figure 8).

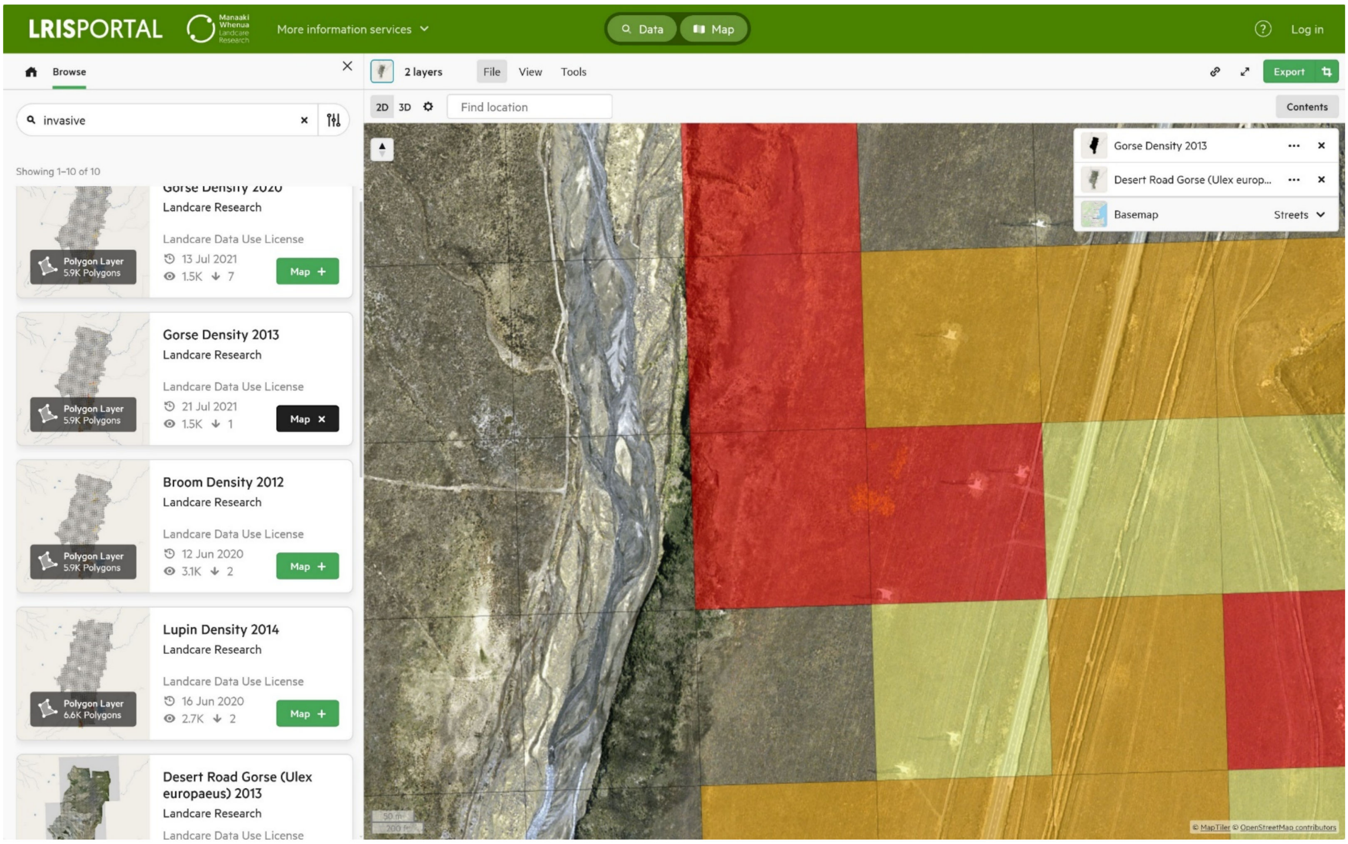


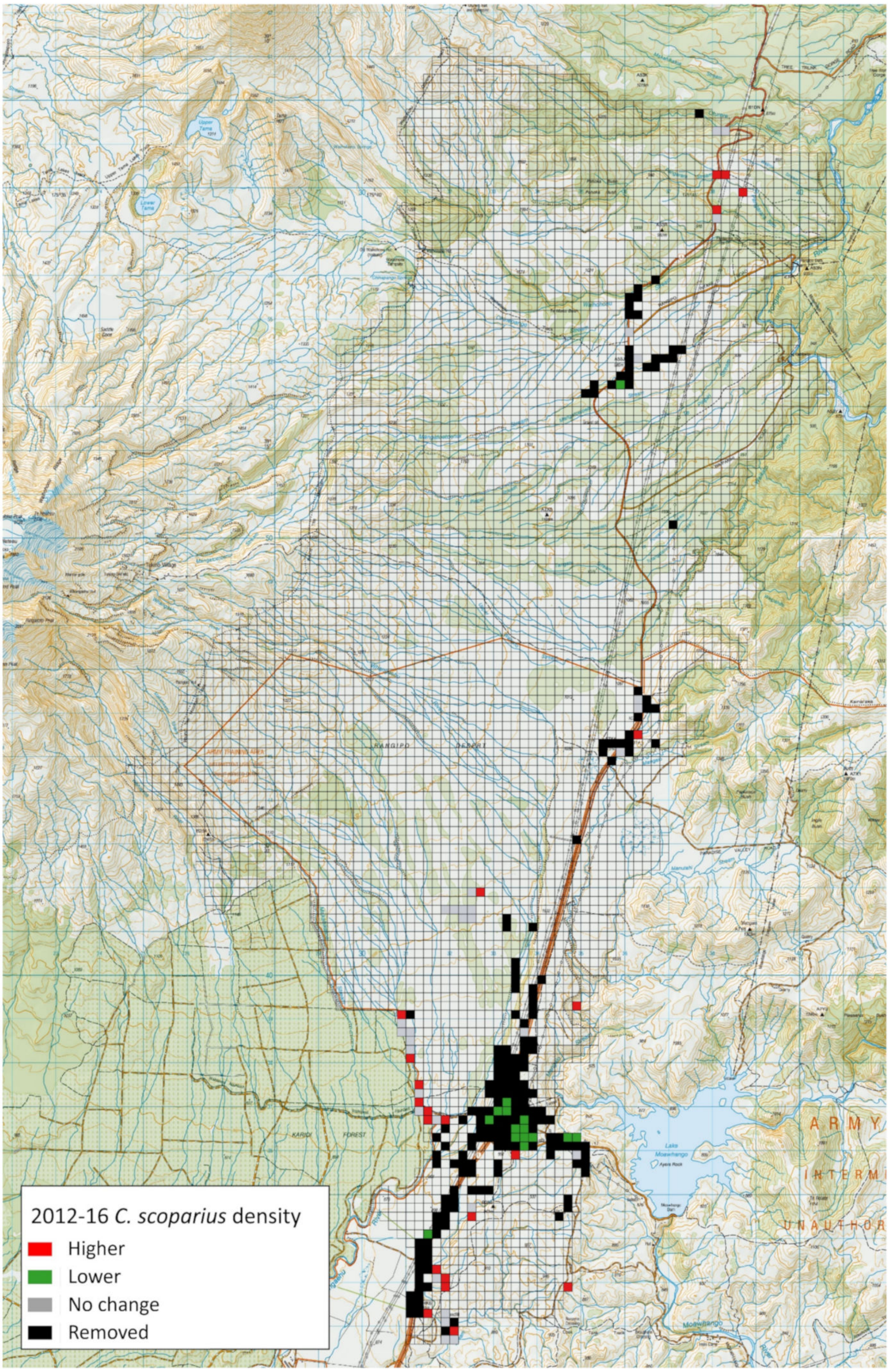
Figure 8. LRIS portal screenshot showing semi-transparent grid-density vector layer on the *U. europaeus* 2013 photography for easy weed target detection (red = high density, orange = moderate density, yellow = low density).

Change maps were made for *C. scoparius* and *U. europaeus* to show where weed density had reduced, increased or stayed the same between aerial photography assessments (Figure 9a,b). A summary of grid-square density scores from the change maps is shown in Table 2.

Figure 10a,b and Figure 11a,b show examples of a new *U. europaeus* outlier that would trigger a new grid square and a control operation that would trigger a grid-square removal.

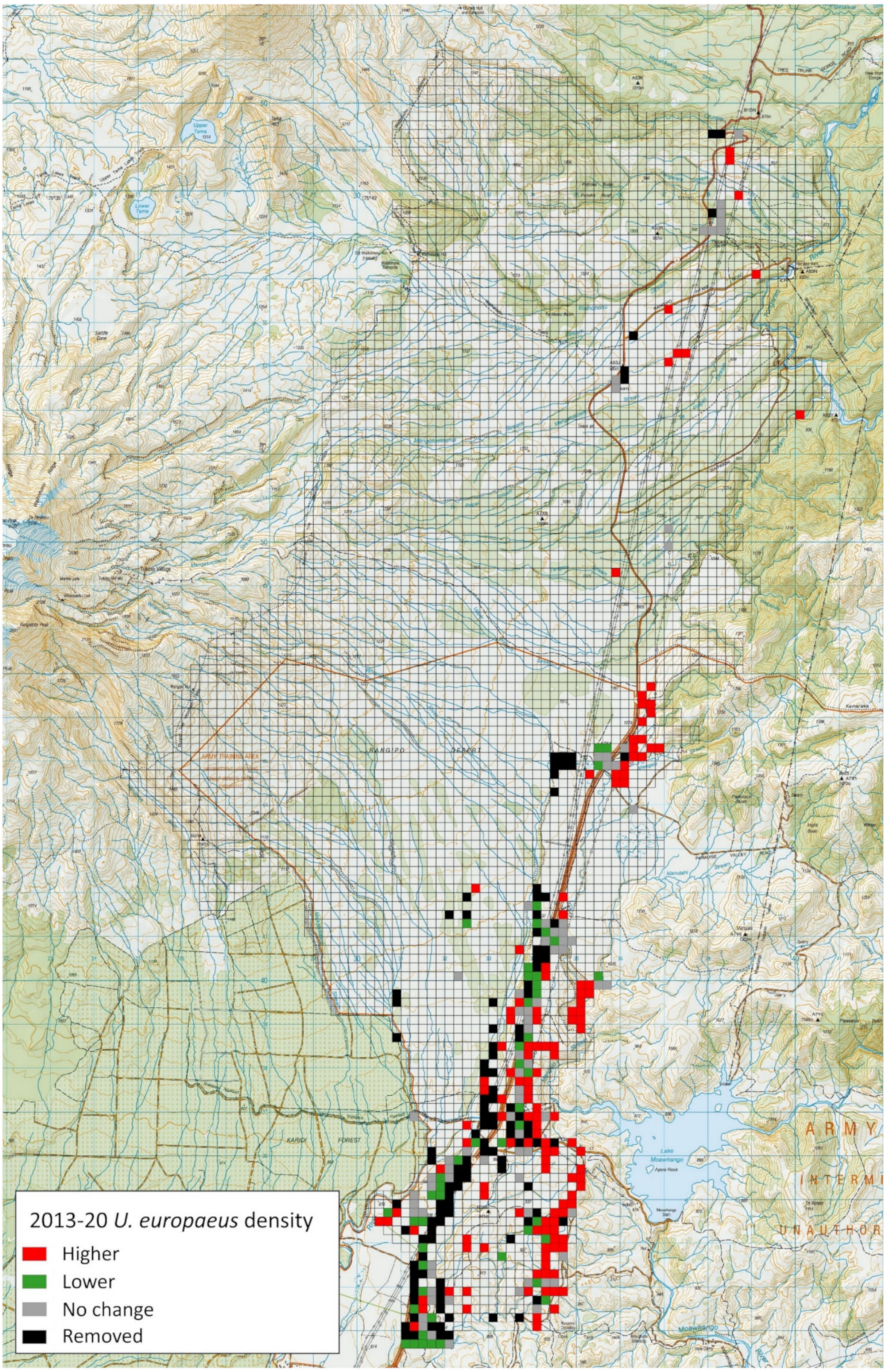
Table 2. Summary of legume grid-square density scores between 2012 and 2023.

Species	Initial Grid Squares Occupied	Final Grid Squares Occupied	Grid Squares Removed	Grid Squares Increased	New Grid Squares
C. scoparius	230	68	177	22	15
U. europaeus	265	256	115	132	106
L. arboreus	150	no data	no data	no data	no data



(a)

Figure 9. *Cont.*

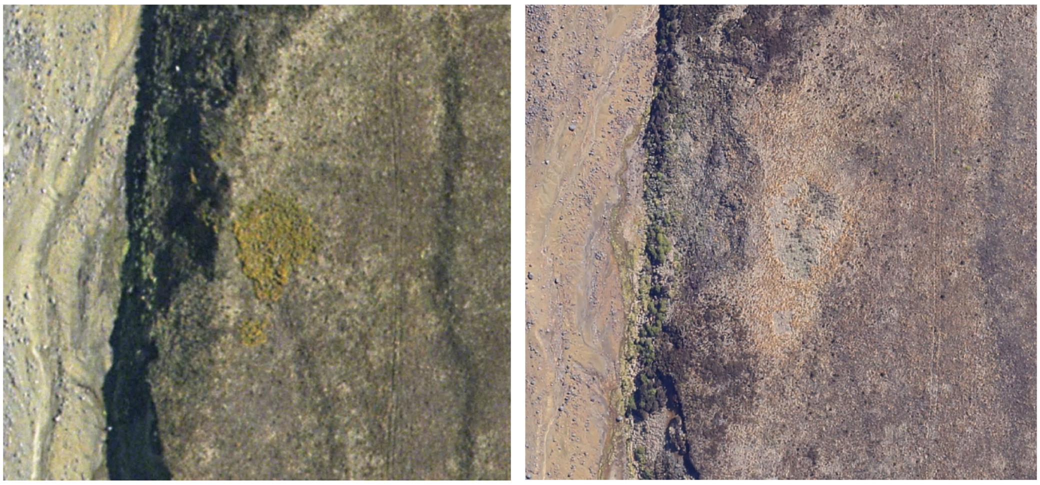


(**b**)

Figure 9. *C. scoparius* 2012–2016 (**a**) and *U. europaeus* 2013–2020 (**b**) change maps showing where weeds increased, decreased, stayed the same or were removed from grid squares.

(**a**) (**b**)

Figure 10. Example of a new *U. europaeus* outlier (red circle) present within a grid square in 2020 (**b**) but not in 2013 (**a**).

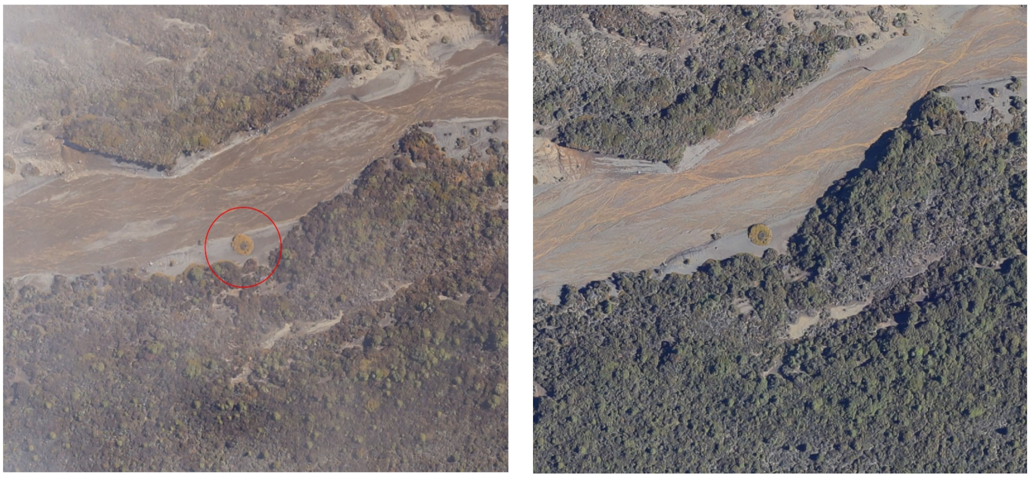


(**a**) (**b**)

Figure 11. Example of a *U. europaeus* control operation conducted between 2013 (**a**) and 2020 (**b**) in a grid square.

It was found that "Opportunistic site visits in 2014 and 2016 verified the presence of the target species in the maps but showed that small flowering plants were not being recorded from the imagery." As a consequence, plants <0.5 m in diameter or younger than 4 years old were not mapped. False positives were also found, including a woody shrub called snow tōtara (*Podocarpus nivalis*). These were identified by comparing imagery from flowering and non-flowering dates with the grid-square sampling tool to rule out the possibility that each was *C. scoparius*, *U. europaeus* or *L. arboreus* (Figure 12a,b).

Moreover, "AI analysis was attempted but had to be abandoned given the time available, due to the large amount of training required to remove false positives (G Harris, pers. comm.)". In addition to *Podocarpus nivalis*, false positives were also found from other plant species, including *Hierochloe redolens* (holy grass/kāretu, a large indigenous grass), as well as inanimate objects, such as muddy puddles.



(a) (b)

Figure 12. An example of yellow reflectance (circled in red) from *Podocarpus nivalis* remaining in imagery taken during (**a**) December 2016 and (**b**) October 2020.

4. Discussion

Analysis of the remote sensing data obtained during this study reinforced the need to take each weed's life history and dispersal theory information into account when carrying out control programs. Initial mapping of *C. scoparius*, *U. europaeus* and *L. arboreus* within the 23,000 ha AOI on the Central Plateau, NZ, in 2012, 2013 and 2014/2015 provided MOU signatories with baseline data for planning future control operations. Despite recommendations to reduce low-density areas to near-zero density while also containing high-density areas, control operations have focussed on removing large, highly visible dense patches, while many small, less-visible outlier patches have not been controlled. As a result, infestations on the periphery of the control area have increased rather than decreased, and new seed banks have been established. All three leguminous weeds can only be controlled if the establishment of new seed banks is prevented by plant removal before significant seeding occurs. For *C. scoparius* at least, this is at approximately 6 years of age ([34], MWLR unpublished data). Established populations already have large seed banks and are of secondary importance.

Density-grid vector layers derived from the high-resolution aerial photography showed that *C. scoparius* control has been more effective than *U. europaeus* control, with a 77% reduction in the number of occupied grid squares compared with just a 43% reduction for *U. europaeus*. Of the remaining grid squares that showed increased weed density, 68% of the *C. scoparius* and 80% of the *U. europaeus* grid squares were previously weed-free, and these new incursions pose a significant threat to the success of the management program.

The exercise of change mapping shows that most of these newly occupied red grid squares (i.e., higher densities) are on the periphery of the legume outbreaks, away from the denser weed infestations near the Desert Road and likely to be the result of recruitment from medium- to long-distance seed dispersal. Isolated outliers can only establish when seeds are transport by human activity, water or animals. Due to the large amount of activity in this area, particularly within the NZDF, consideration should be given to the movement of machinery and personnel on foot, especially when moving from areas of high legume density to low-density areas. Near waterways, control operations should give priority to upstream populations to help remove waterborne seed sources.

Effective control of outliers and reduction in long-distance seed dispersal will not only prevent new seed banks from establishing but will also slow range expansion. Once established, not only can outliers produce large seed banks if left uncontrolled, but they also speed landscape-scale invasion and the probability of further long-distance seed dispersal. While seed banks are the number one driver of the long-term persistence of *C. scoparius*, *U. europaeus* and *L. arboreus* populations, the speed of dispersal from point sources is also an important consideration when trying to achieve sustainable weed control. Legume seeds are ejected explosively from seed pods, and most only fall within metres of the parent plant [29,30]. Moody and Mack [35] were among the first to address weed control strategy when they considered the dynamics of invasive weed spread and how best to allocate resources on a landscape scale. Their simplistic population biology approach showed that in species with predominantly short-range seed dispersal, outliers contribute the most to range expansion compared to larger patches and should therefore be removed first. This is because a higher proportion of plants are surrounded by conspecifics in large patches and seeds fall on already occupied ground, having no further impact on seed banks. In contrast, a large proportion of seeds produced by outliers fall on virgin ground, resulting in further recruitment and seed production. Subsequent studies that include control and damage cost estimates and different patterns of spread have arrived at conflicting conclusions, depending on the details of the invasion [6]. However, [36] showed that a strategy of removing outliers before dense patches took 44% less time to eradicate *Spartina alterniflora* (American spartina), which only throws most seed a few meters from the parent plant. The target species herein all require a combination of seed bank management, prevention of long-distance seed dispersal and priority control of outlier populations to achieve control on a landscape scale.

Lupinus arboreus has spread over a smaller area than *C. scoparius* and *U. europaeus* because it is a more recent arrival. Controlling outlying plants is therefore likely to provide significant future benefits to avoid widespread invasion. The failure to map *L. arboreus* in 2022 and produce a change map highlights the importance of timing to capture flowering. While in previous years, flowering occurred during mid-December to mid-January, in 2022, *L. arboreus* flowering was one month early, meaning it could not be seen in the imagery taken from 26 to 28 December 2022.

Manual interpretation of the photography to produce distribution maps was preferred because every measurement was important, and false positives could not be tolerated, as visits to low-density outliers are relatively expensive. The 23,000 ha AOI was split into approximately 6000 grid squares which could be individually checked and classified with one key press at an average rate of one grid square every 10 s (total time: approximately 17 h). During this study, the GSD of the imagery improved over time, as more advanced camera technology was used—potentially resulting in an overestimate of the spread if small plants were missed in earlier imagery. We accounted for this by rechecking areas where new incursions were found in repeat imagery to make sure small plants were not missed in earlier imagery. The grid-square size of 200 × 200 m was selected as a compromise that allowed for an appropriate resolution for manual classification while providing for a reasonable search area for finding individual or small patches of flowering plants for the aerial search and spray teams. However, smaller search areas may be required if searching and spraying cannot be performed with air support. We think 50 × 50 m grid squares would be more suitable for ground-based searching but would increase the time required to manually classify images by up to eightfold. We also recommend that grid squares adjacent to those mapped should be checked for small outlying plants (<0.5 m diameter) that could not be reliably detected during our mapping. Smaller grid squares would also reduce the ground-based searching required to achieve this goal.

Total mapping costs came to approximately $1 NZD/ha and were split 50:50 between image acquisition and image classification/mapping. Artificial intelligence was trialled to see if classification could be automated and manual classification costs could be cut, but the number of false positives recovered meant it could not provide a viable alternative for this program. NousAI recorded several thousand false positives that would require more data to eliminate. Improvements to the AI mapping might be realised by stacking images from different seasons to capture flowering time and potentially adding other inputs, such as near-infrared- and LiDAR-based products (B Martin, pers. comm.). Improved AI performance could then allow for a reduced grid-square size, making data more suitable for ground search and spray teams. This would probably increase the price of the mapping beyond the current expenditure though, and some manual checking for false positives would still be required.

While spraying large patches of weedy legumes with large volumes of herbicide intuitively seems more effective, spraying individual outliers at a greater per-plant cost will be required to prevent new seed banks from developing and suppress the legume population spread on the Central Plateau in the long term. High-resolution RGB photography can detect new flowering plants before they develop significant seed banks, but this only allows for a short window of approximately 2 years in which control can take place. Sites would also need to be re-visited to check that new plants are not growing if seed banks establish. Convincing land managers to control less conspicuous outliers when faced with larger, more publicly visible patches remains a challenge. In fact, as the goal for this project is to protect the unique natural values and vistas of the Desert Road environment from invasive legumes, maintaining some control of large visible patches may be prudent, as stated in the MOU for this project—but only if efforts remain directed largely toward outlier control. It is also important that the reduced public pressure after roadside cleanups are achieved does not reduce motivation to control weeds in less-visible areas. Despite key objectives being developed to achieve a shared vision for this program in 2013, clear outcomes were not adequately understood at the beginning. However, remote sensing has provided another opportunity to visualise future outcomes of various control strategies. Ongoing communication, including face-to-face meetings between stakeholders, is critical to maintain a common vision and to facilitate the implementation of adaptive management through operational changes that are guided by data obtained from tools like remote sensing.

This study brings a cost-effective, bespoke, remote sensing approach to a specific problem. The solution, intended for application over large areas, uses automated viewing and recording software to manually classify imagery. It provides a tool for land managers to improve long-term weed control outcomes and a mechanism for monitoring and documenting results.

5. Conclusions

This project demonstrates how remote sensing can be used to help inform adaptive management for the control of invasive weeds on a landscape scale. Previous recommendations were based on the life history and dispersal of the weeds, but maps of weed management progress in real time that were created from remote sensing have provided a much more compelling tool for showing land managers the direct consequences of various control strategies and the potential long-term impacts of these decisions. Maps made from high-resolution aerial photography alongside the Desert Road on the Central Plateau show that invasive legume management strategies must change to achieve the long-term goal of reducing weed density across this iconic landscape.

6. Recommendations

Change the invasive legume control strategy on the Central Plateau to focus on outlier plants to prevent new seed bank establishment and slow the spread to achieve long-term weed reduction on a landscape scale. Consideration should also be given to the risk(s) of seed transport during the movement of machinery and personnel from areas of high legume density to low-density areas, and control operations adjacent to waterways should prioritise upstream populations to remove seed sources.

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Data Availability Statement: Data, including aerial photographs and grid-square-density vector layers, are available at https://lris.scinfo.org.nz/data/?q=legumes (accessed on 19 June 2024).

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