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RESEARCH

Ephemeral wetlands in Aotearoa | New Zealand kettle holes: geographic range, botanical biodiversity values and underlying land tenures

Jane L. Gosden[1]*, Dave Kelly[1] and Angus R. McIntosh[1]

[1]Te Kura Pūtaiao Koiora | School of Biological Sciences, Te Whare Wānanga o Waitaha | University of Canterbury, Christchurch, New Zealand

*Author for correspondence (Email: jane.gosden@pg.canterbury.ac.nz)

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Abstract: Ephemeral wetlands are naturally uncommon ecosystems that have become threatened in Aotearoa | New Zealand and include many glacially derived kettle holes (kettles) of the South Island. These kettles can be easily overlooked as wetlands, particularly when in a dry phase, thereby increasing their vulnerability. To aid conservation planning and management of this threatened ecosystem, we identified and mapped all detectable individual kettles in the South Island ($n = 1802$) and used geographic and survey data to evaluate patterns in their distribution, floristic diversity, land tenure, changes in land tenure over time, legal status, and the occurrence of Threatened plants and lichens. Ninety-five percent of kettles were found in Waitaha | Canterbury, mostly in Te Manahuna | Mackenzie Basin, and most were small (< 0.6 ha) and close to other kettles. Altogether, kettles occupy just 0.004% of Aotearoa's land area. Sixty-eight percent of kettles were found on either freehold land or pastoral lease land, with 10% of these protected by conservation or Queen Elizabeth II covenants; 29% of kettles were on public conservation land. Of the 29%, over half (60%) were on Stewardship Land. Therefore, kettles generally have limited protections that are dependent on their land managers. We completed plant and lichen surveys for 269 of the mapped kettles. We recorded 443 plant and lichen taxa; 128 were exotic species, 314 were indigenous, and one had uncertain biostatus. Occurrence of plants in Threatened or At Risk categories did not differ by land tenure or legal status of the kettles, so preservation of these wetlands needs to occur across all land tenures to ensure representative protection of kettles and their botanical values. Pairing desktop mapping with a flora survey shows that kettles are remarkable plant biodiversity hotspots, especially given they occupy such a small land area in Aotearoa.

Keywords: conservation, flora, glacial landscapes, lichens, threatened plants

Introduction

Naturally rare ecosystems (Williams et al. 2007), all wetlands regardless of original rarity, and places that are habitat for threatened species are priorities for protection and management in Aotearoa | New Zealand (hereafter Aotearoa) (Ministry for the Environment 2007). Whilst many naturally rare ecosystems are broadly represented within Threatened Environment Classification maps (Cieraad et al. 2015), most of these occupy small areas and have not been mapped at local scales (Wiser et al. 2013).

Wetlands require particular attention because 90% have already been lost in Aotearoa, and losses continue (Ausseil et al. 2011; Robertson 2016; Dymond et al. 2021; Burge et al. 2023). Ephemeral wetlands are naturally rare ecosystems (Williams et al. 2007) that have become threatened (Holdaway et al. 2012) and are found across Aotearoa. Ephemeral wetlands contain a fifth of Aotearoa's native vascular flora, including a large proportion of Aotearoa's threatened plant species (Johnson & Rogers 2003; Ausseil et al. 2011). Understanding patterns in the distribution of ephemeral wetlands is disproportionately important when considering naturally rare ecosystems.

Wetlands in Aotearoa have varying levels of legal status, offering differing degrees of protection from damaging processes, and the mechanisms providing the legal status are subject to political change, meaning not every legal status affords absolute and ongoing protection of a wetland. At the highest level of legal protection, land can be protected under the Conservation Act 1987, the Reserves Act 1977, the National Parks Act 1980, or the Queen Elizabeth the Second National Trust Act 1977 (QEII Trust). The Resource Management Act 1991 also provides a further legal mechanism. However, ephemeral wetlands can easily be overlooked as wetlands, because they do not always contain standing water, meaning their protection could be less assured than that of other more prominent and permanently wet sites. Moreover, a legal status may not afford protection if not accompanied by appropriate management. Thus, it is important to know the locations of ephemeral wetlands to alert their custodians.

We focus on a particular subset of ephemeral wetlands in the South Island called kettle holes (hereafter referred to as kettles). Other forms of ephemeral wetland also occur

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in Aotearoa, for example in depressions of coastal dunes, in volcanic substrates, or as bedrock depressions in schist and other hard rock (Johnson & Rogers 2003). Kettles are glacially derived depressions often containing tarns, making them relatively easy to define and map because they occur on recent and old moraines. Kettles are distributed across a large latitudinal range in the South Island due to the extensive periods of glaciation during the Pleistocene (e.g. Gage 1958; Soons 1963; Speight 1963; Borsellino et al. 2017). Being widely distributed across the South Island (Appendix S1), kettles also vary in land tenure and legal status as well as being botanically diverse.

Kettles form as glaciers retreat, stranding blocks of stagnant ice. The stagnant ice melts to leave a depression in the glacial sediments that fills ephemerally or permanently with water (Johnson & Rogers 2003). Not all kettles form ephemeral wetlands, but those in drier areas, like the eastern South Island, usually lack inlet and outlet water courses and undergo substantial fluctuations in water levels leading to the formation of ephemeral wetlands (Johnson & Rogers 2003; Greig & Galatowitsch 2016; Purcell et al. 2019). In very dry places some depressions that originally formed as kettles no longer pond at all and thus never form ephemeral wetlands. In contrast, those in places with high annual and regular precipitation, like the western South Island, or places with iron pans or peaty soils, undergo fewer substantial fluctuations in water level thereby forming permanent, rather than ephemeral wetlands (Johnson & Rogers 2003). The fluctuation in water level varies substantially from kettle to kettle (James et al. 2019). Some dry every summer, whereas others only do so in very dry years. Large kettles and kettle lakes are typically permanently water-filled with an ephemeral margin. The drying of the kettles progressively over a summer season exposes concentric rings of vegetation with the more dry-adapted species around the kettle margin and aquatic species towards the kettle centre (Johnson & Rogers, 2003). Both sources of variation (within a year to form the rings of vegetation, and year-to-year differences in water volume) in the complete drying (or not) of the kettle are significant drivers in the botanical diversity found within kettles (Johnson & Rogers, 2003; Tanentzap et al. 2013).

Kettle-like ecosystems can also be found in the central North Island. However, we know of none that formed following glaciation. Therefore, we focus solely on kettles of the South Island as they form discrete habitat patches in the landscape that are relatively easy to map. Furthermore, kettles are small and easy to miss in classifications of non-forested vegetation. For example, Wiser et al. (2016) classified non-forested ecosystems but did not have sufficient data to classify more than two wetland types. Since many kettles are smaller than 0.5 ha, they have not been included in other projects mapping wetlands such as Ausseil et al. (2011) and Dymond et al. (2021).

We mapped the distribution of kettles that contain ephemeral wetlands and undertook flora surveys across their extent. We described the occurrence of kettles across geographic regions, evaluated land tenure and legal status, and assessed how both land tenure and legal status affected the distribution of threatened plants, all to assist future conservation management and planning for kettles.

Methods

Kettle mapping and environmental data

Literature on Aotearoa kettles was used to identify areas for mapping kettles (Johnson & Rogers 2003; Purcell et al. 2019; Appendix S1). To find additional kettles outside of the existing literature we overlaid a glacial deposition layer (Appendix S2) in a Geographic Information System (GIS) and searched for kettles within these deposits. Using aerial imagery (Appendix S2), kettles were identified from the upper water level, which creates a visually distinctive change in vegetation (even when dry). The upper water level was used to define the edge of hand drawn polygons to map kettles in the programme QGIS, version 3.34.5-Prizren (QGIS.org 2026). Kettle area was calculated from these polygons using the field calculator tool in QGIS. Centroids were made for individual kettle polygons and used to extract the latitude, elevation, and precipitation variables from the New Zealand Environmental V.1.0 data stack (Leathwick et al. 2002; McCarthy et al. 2021; Appendix S2). The distance from each kettle to its closest neighbouring kettle was calculated from these centroids using the "join attributes by nearest" function in QGIS.

We used the Land Cover Data Base (LCDB) version 5.0 (Manaaki Whenua Landcare Research 2024a) and the Threatened Environments Classification (Walker et al. 2015) to examine patterns in land cover and threatened environment classification of kettles (Appendix S2). Both data sets classed some larger kettles as "Lake or Pond". For these, we replaced the classification of "Lake or Pond" with the dominant surrounding LCDB or threatened environment classification. A comparison of LCDB land cover classes in 1996 and 2018 was used to identify broad-scale land-use change at mapped kettles.

Kettles were visited across 27 land parcels for botanical data collection, allowing for some ground-truthing of desktop mapping. After experience on the ground, we re-examined aerial imagery of all mapped kettle areas and searched for further kettles to create the final list. A comparison of kettles mapped prior to the field surveys with the final map of kettles found a 17% difference, mainly from small kettles missed in the initial mapping (n = 104) rather than from initial locations counted as a kettle which field inspection found did not have one (n = 26) (Appendix S3).

Understanding land tenure and legal status of kettles

Kettles are found on a variety of land tenures including public conservation land. To assess patterns in kettle distribution we assigned seven high-level land tenures to kettles (Table 1). All seven land tenures were mapped using publicly available GIS layers and other supporting information (Appendix S2). To assess the legal status of kettles, we considered four pieces of legislation listed in the introduction: the Conservation Act, the Reserves Act, the National Parks Act, and the Queen Elizabeth the Second National Trust Act. Publicly available GIS layers and other supporting information were used to determine which kettles fell into the following legal status categories: public conservation land, QEII covenant, conservation covenant, or none (Appendix S2).

Many Crown pastoral lease properties in the South Island went through a process called tenure review over the last three decades resulting in land either being returned to the Crown or becoming freehold (Brower et al. 2020). To investigate a major change in land tenure of kettles over time, we looked at 14 former Crown pastoral leases that had undergone tenure

Table 1. Seven land tenure types and their definitions, as assigned by us, that we used to examine land tenure patterns for kettles.

Land tenure	Definition
Crown pastoral lease	Crown land administered by Land Information New Zealand (LINZ) but leased for pastoral farming. Public access is at the discretion of the lease holder. Crown pastoral leases can have Queen Elizabeth II Trust (QEII) or conservation covenants.
Defence Force	Crown land administered and managed by the New Zealand Defence Force, used for military training. Public generally have no access for safety reasons.
Freehold land	Privately owned land, managed by the landowner. Public access is at the discretion of the landowner. Freehold land can have QEII or conservation covenants.
Public conservation land (PCL)	Crown land administered and managed by the Department of Conservation (DOC) for the purposes of conservation, heritage preservation, and recreation. Public generally have access. There are different types of PCL with varying levels of protection, including National Park (best protected), Conservation Park, Scenic Reserve, and Stewardship Area (least protected).
Unalienated Crown land	Crown land administered and managed by LINZ without a specific purpose. Land in this category often includes large lakes and riverbeds. Public generally have access.
University of Canterbury (UC) pastoral lease	University of Canterbury (UC) pastoral lease. Crown land granted as an endowment to the University of Canterbury, mostly leased for pastoral farming or forestry. Public access is at the discretion of the lease holder or UC. University of Canterbury pastoral leases can have QEII or conservation covenants.
Road reserve	Crown land, usually adjacent to existing roads, managed by Waka Kotahi/New Zealand Transport Authority. Public generally have access.

review between 2003 and 2022 (Appendix S2). We highlight this land tenure change because Crown pastoral lease properties covered many of the glacial landscapes of the South Island where kettles are found. We used the substantive proposal reports from the tenure review process (Appendix S2) to determine how properties were split, with kettles categorised as having moved from Crown pastoral lease to either freehold land or public conservation land. For kettles that moved to freehold land we also counted how many were included in conservation covenants. We calculated the total numbers of kettles from freehold land within and outside of conservation covenants, the total from freehold land, public conservation land, and the cumulative decline of kettles on the Crown pastoral lease over the same period to understand changes in land tenure of kettles over time.

Plant and lichen diversity and conservation status

We sampled a representative set of kettles across their geographic extent. This included 269 individual kettles from Nelson Lakes National Park in the north to the Oreti-Von catchment in the south (Fig. 1), all surveyed between November 2023 and June 2024. Sites with kettles were selected for survey from land parcels where we had been granted access. We then prioritised kettles throughout the geographic range to give a broad latitudinal spread. Kettles were bundled into land parcels and the 269 kettles we surveyed came from 27 land parcels across public conservation land (n = 142 kettles), Crown pastoral lease (n = 65), University of Canterbury pastoral lease (n =38), freehold land (n = 23), and unalienated Crown land (n = 1). Numbers of kettles within the 27 sites we visited ranged from one to more than 100. For land parcels with more than ten kettles we used a stratified random sampling system to select either ten kettles or one-third of those present (whichever was higher) that we aimed to survey, whereas at land parcels with ten or fewer we surveyed them all. Our stratified random sampling system ensured a range of kettle sizes and inter-kettle distances within each land parcel were sampled.

From within the high-water line (perimeter) of each kettle (Fig. 2) we conducted walk-through surveys producing a vascular plant species list and sampling every observable bryophyte and lichen morphospecies for later identification (Dickie & Gosden 2025). The high-water line was often marked by a substantial increase in the grasses browntop (*Agrostis capillaris*) and sweet vernal (*Anthoxanthum odoratum*) on the terrestrial side of the line and was generally obvious in the field.

Indigenous vascular plant naming followed de Lange et al. (2024), because this allows for the inclusion of putative species (tag-name plants) and their conservation status. One putative and one recently named *Carex* (Ford 2025) found during our surveys but not assessed by de Lange et al. (2024) were assigned a conservation status following Townsend et al. (2008). Exotic vascular plants, bryophytes, and lichen names follow Biota of NZ (Manaaki Whenua Landcare Research 2024b).

The overall kettle species list was used to determine the number of Threatened, At Risk, and Data Deficient vascular plants of kettles as classified by Conservation Status reports (de Lange et al. 2009, 2013, 2018a, 2024). Analysis of vascular plants by their conservation status over time allowed us to compare changes in status of kettle species to changes in the national plant list (de Lange et al. 2024).

Analysis of flora conservation status by land tenure and legal status

We used generalised linear mixed models with a Poisson error distribution, using the "lme4" package in R (Bates et al. 2015), to test whether land tenure or legal status influenced counts of Threatened and At Risk plants and lichens. The most recent Conservation Status report for each taxonomic group was used for this analysis (de Lange et al. 2018b, 2020, 2024; Michel et al. 2026). We removed Data Deficient plants and lichens from analyses, because these were typically found in

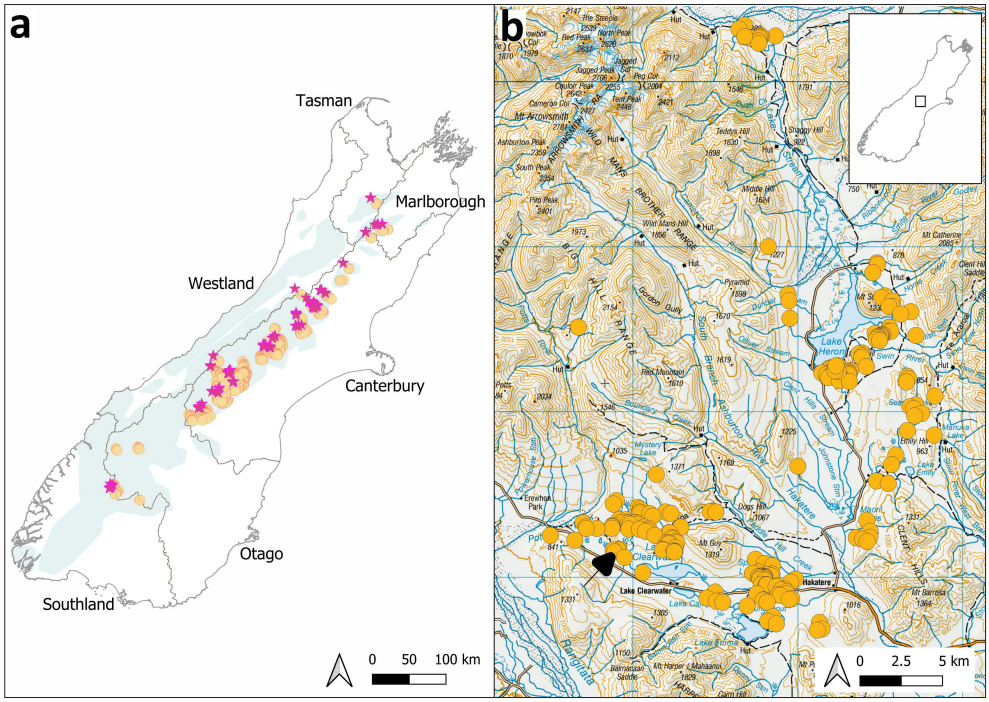

Figure 1. Overview of kettles. (a) Distribution of the mapped kettles (orange dots) throughout the South Island. Areas of glacial deposition are coloured in blue, and the lines show Regional Council boundaries as named on the map. Pink stars are the 269 kettles we surveyed. (b) An example of local kettle distribution: the location of over 200 kettles in Ōtūwharekai (Ashburton Lakes). The arrow points to the location of the kettle pictured in Fig. 2. This figure contains underlying data obtained from Land Information New Zealand (LINZ) under a CC BY 4.0 license.

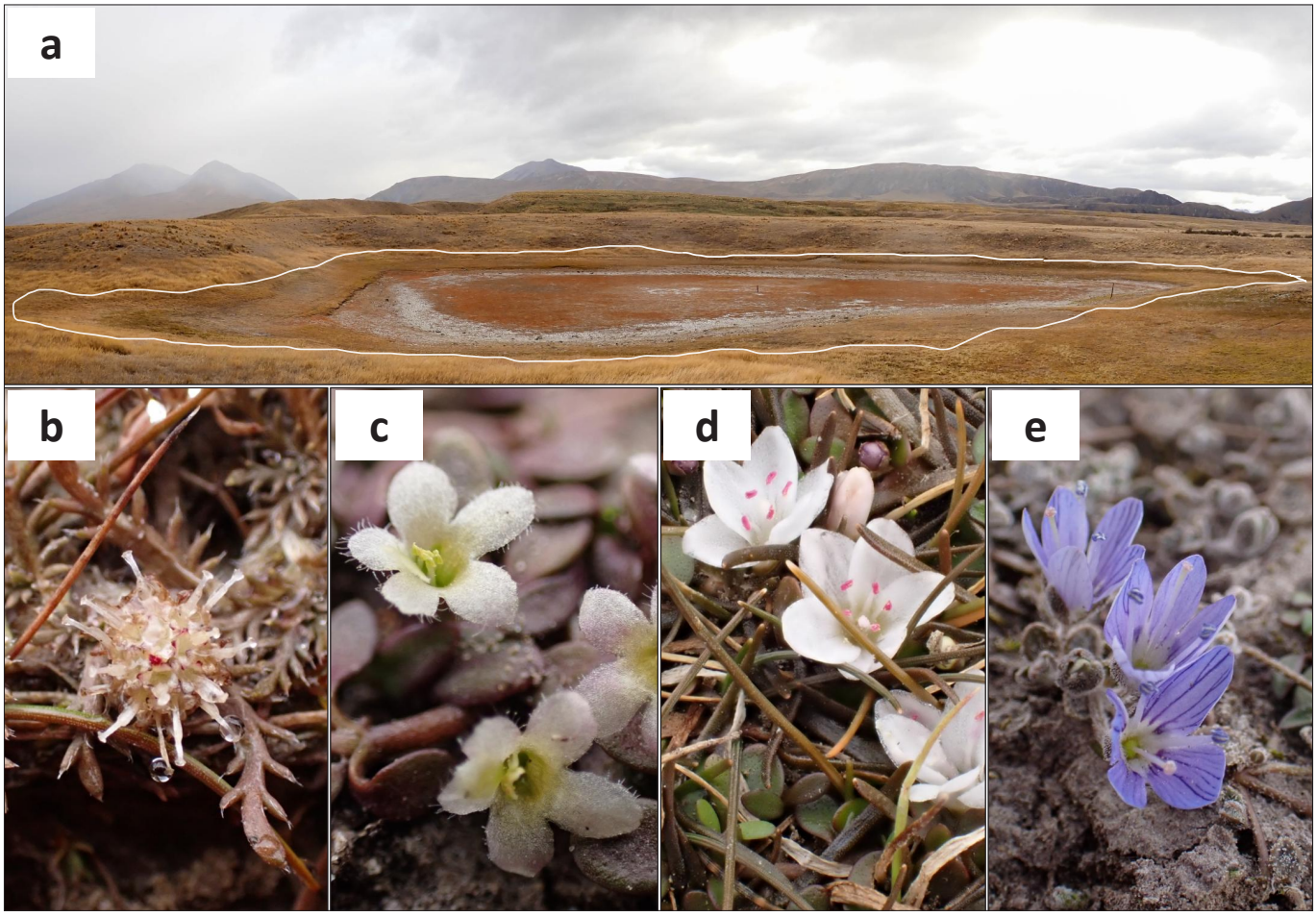

Figure 2. A kettle and some kettle plants. (a) An example of a kettle in a dry phase from Ō Tū Wharekai (Ashburton Lakes). The location of this kettle is indicated by an arrow in Fig.1. The white line demarks the boundary between the wet kettle ecosystem and the dryland grassland ecosystem. (b) *Leptinella maniototo*. (c) *Glossostigma elatinoides*. (d) *Montia angustifolia*. and (e) *Veronica lilliputiana*. All flowers pictured have a diameter less than 10 mm. Photos: Jane Gosden.

low numbers and were not found in all land tenures. For the analysis of land tenure, we merged the only kettle we surveyed from unalienated Crown land into University of Canterbury pastoral lease, because the kettle was unfenced and surrounded by University of Canterbury pastoral lease land. For the analysis of legal status, we excluded conservation covenants as we only surveyed one kettle that fell into this category. We included land parcel (clusters of kettles in one area) as a random effect for both the land type and legal status models to identify appropriate replication for tests.

We also ran a third model comparing the best protected public conservation land (National Park) with the least protected public conservation land (Stewardship Area). For this model, we clumped Threatened, At Risk, and Data Deficient plants into one broader category ('Threatened') and compared counts of these to Not Threatened plants.

For all three analyses we included an interaction term between plant and lichen conservation status and land tenure, legal status, or public conservation land type. All statistical analyses were done in R, version 4.3.3 (R Core Team 2024). The "lme4" modelled responses were plotted with the "emmeans" package (version 1.10.5; Lenth 2024) in "ggplot2" (version 3.5.1; Wickham 2016).

Results

Kettle mapping and environmental data

A total of 1802 kettles were mapped from Nelson Lakes National Park in the north (latitude: 41°47′51″ S) to Kingston in the south (45°20′50″ S) (Fig. 1). Almost all kettles (95%) were found in Canterbury, with only 80 outside this region (Regional authority boundary; Appendix S4), or 92 if using the botanical province (Appendix S5). Kettles were predominately found at mid elevations (mean: 738 m a.s.l.), were small (mean: 0.6 ha), and were close to other kettles (mean: 0.25 km from one kettle to its nearest neighbour) (Table 2). There was a large variation in annual precipitation from the wettest kettles (Arthur's Pass) to the driest (near Mt John in the Mackenzie Basin) (Table 2). The total area of all kettles identified was 1012.95 ha or 0.004% of Aotearoa's land area. Almost three quarters (74%) of kettles were found within areas classed as a Threatened Land Environment under Land Environments of New Zealand IV (Walker et al. 2015). Using LCDB5 2018, most kettles were found in low producing grasslands (n = 976), but 58 kettles were in exotic forest, 229 in high producing exotic grassland, and six in mixed exotic shrubland. Changes in kettle associated land cover were small between LCDB 1996 and 2018 (Table 3). However, the increase in exotic forest cover surrounding kettles is noteworthy; exotic forest surrounded 34 kettles in 1996 and 58 in 2018, despite 20 kettles also shifting to forest harvested by 2018. There has also been an increase in kettles found within high producing exotic grassland from 167 in 1996 to 229 in 2018. Kettles changing from surrounding native cover into either exotic forest or high producing exotic grassland were probably formerly low producing grassland or tall tussock grassland.

Table 2. Averages and range for geographic and environmental features of all 1802 mapped kettles. All data are from the centroid of each kettle.

Kettle variable	Mean	Median	Min	Max
Latitude	43°55′60″ S	43°55′36″ S	45°20′50″ S	41°47′51″ S
Area (ha)	0.56	0.09	0.001	187.42
Elevation (m a.s.l.)	738	745	344	1209
Distance to nearest neighbour (km)	0.25	0.12	0.014	10.08
Annual precipitation (mm yr^{-1})	1079	930	475	5085

Table 3. Counts of kettles according to predominant land covers from the land cover data base (LCDB5) for all identified kettles in 1996 and 2018 and the net change over that time.

Land cover	Kettle count 1996	Kettle count 2018	Net change
Depleted grassland	122	120	−2
Exotic forest	34	58	+24
Fernland	1	1	0
Forest – harvested	0	20	+20
Herbaceous freshwater vegetation	35	35	0
Herbaceous saline vegetation	1	1	0
High producing exotic grassland	167	229	+62
Indigenous forest	1	1	0
Low producing grassland	1053	976	−77
Mānuka and/or kānuka	13	13	0
Matagouri or grey scrub	10	11	+1
Mixed exotic shrubland	6	6	0
Sub alpine shrubland	1	1	0
Tall tussock grassland	358	330	−28

Understanding land tenure and legal status of kettles

Freehold land held the most kettles (44%), followed by public conservation land (29%) (Table 4, Fig. 3). Two kinds of pastoral lease (Crown and University of Canterbury) made up almost a quarter (24%) of the kettles, so together freehold and pastoral lease accounted for 68% of all kettles. Interestingly, kettles on public conservation land tended to be smaller (mean = 0.27 ha) than those on freehold (mean = 0.62 ha), or pastoral lease (mean = 0.70 ha for Crown pastoral lease and 0.53 for University of Canterbury pastoral lease) (Table 4). The different land tenures were not evenly spread geographically. All kettles in Nelson and Marlborough were on public conservation land, most kettles in the Castle Hill and Coleridge Basins were University of Canterbury pastoral lease, and most kettles in Otago and Southland were Crown pastoral lease (Fig. 3; Appendix S4). Land tenure change from Crown pastoral lease to freehold land or public conservation land has not consistently protected kettles by placing them in public conservation land (Fig. 4). In the 14 former Crown pastoral leases we examined, 66% of kettles moved from Crown pastoral lease into freehold land,

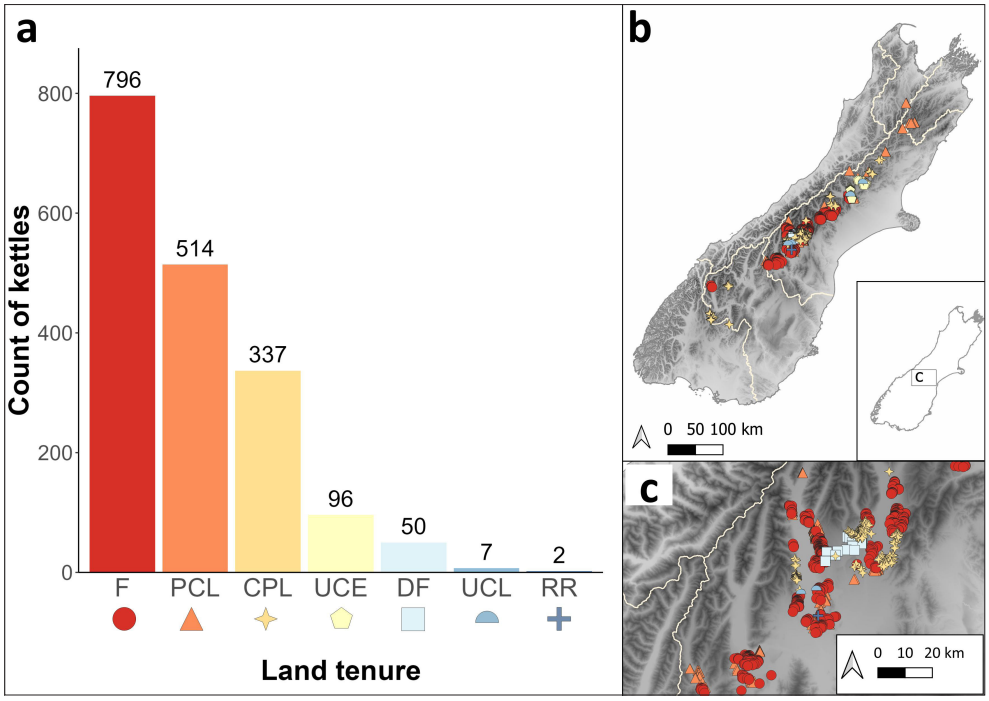

Figure 3. Distribution of mapped kettles. (a) By count across seven land tenures (F, freehold; PCL, public conservation land; CPL, Crown pastoral lease; UCE, University of Canterbury pastoral lease; DF, New Zealand Defence Force; UCL, unalienated Crown land; RR, road reserve). (b) Distribution across the South Island, and (c) distribution in the Mackenzie Basin where 62% of kettles are found. Colours and symbols on (b) and (c) match (a), and pale lines on the maps in (b) and (c) indicate Regional Council boundaries as given in Fig. 1. This figure contains underlying data obtained from Land Information New Zealand (LINZ) under a CC BY 4.0 license.

Table 4. Comparison of total kettle area, mean kettle area, and kettle count across the three analyses of kettle categories used in this study: land type, legal protection status, and public conservation land type.

Kettle category	Kettle count	Total kettle area (ha)	Mean kettle area (ha)
Land type			
Crown pastoral lease	337	235.19	0.70
Defence Force	50	46.88	0.94
Freehold land	796	495.29	0.62
Public conservation land	514	138.08	0.27
Unalienated crown land	7	46.30	6.61
University of Canterbury pastoral lease	96	50.89	0.53
Road reserve	2	0.28	0.14
Legal protection			
Conservation covenant	72	23.17	0.32
None	1098	442.92	0.40
Public conservation land	514	138.18	0.27
Queen Elizabeth II covenant	118	408.75	3.46
Public conservation land type			
Recreation Reserve	14	4.85	0.35
Scenic Reserve	34	2.96	0.09
Conservation Park	69	21.01	0.30
Scientific Reserve	64	9.55	0.15
Government Purposes Reserve	1	0.07	0.07
Fixed Marginal Strip	3	1.03	0.34
Stewardship Area	308	95.59	0.31
National Park	16	2.53	0.16
Conservation Purposes	5	0.50	0.56

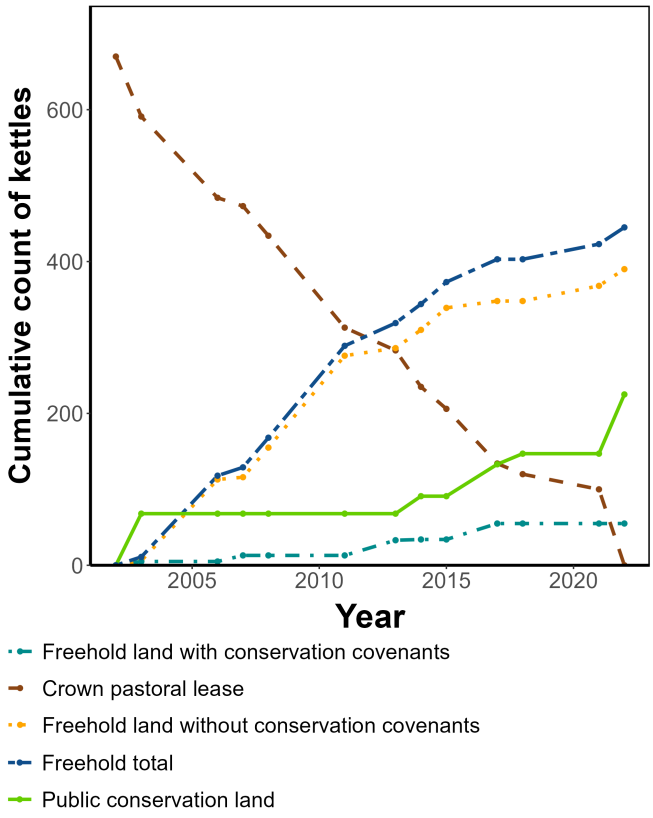

Figure 4. The cumulative count of kettles over time for three land tenures based on kettles from 14 former Crown pastoral lease properties that have undergone Tenure Review from 2002 to 2022.

with the remainder going into public conservation land. Of those that moved into freehold land, 12% were included in a conservation covenant. Therefore, the trend has predominantly been for kettles to pass out of Crown ownership and into the care of freehold land managers.

Most kettles (61%) did not have a legal status that afford them legal protection (Fig. 5), and those without legal protection also tended to be bigger (Table 4). All kettles in Tasman, Marlborough, and Westland were on public conservation land, but none in Otago or Southland were. Within Canterbury, kettles with high-level legal protection were found in all local authorities except for the Timaru District (Appendix S6). Te Manahuna | Mackenzie Basin contained the most kettles under both QEII and conservation covenants (Fig. 5; Appendix S6).

Twenty-nine percent of all kettles were found on public conservation land. Kettles on public conservation land fell into nine classifications (Fig. 6). Over half (60%) of public conservation land kettles were on land classified as Stewardship Land (Fig. 6). Very few kettles (3% of those on public conservation land or 0.9% overall) were in National Parks. Kettles can be found in three National Parks: Nelson Lakes National Park (n =7), Arthur's Pass National Park (n = 4), and Aoraki | Mt Cook National Park (n = 5). Furthermore, kettles in National Parks are around half the size of those found in Stewardship Areas (Table 4).

Plant and lichen diversity and conservation status

A total of 443 plant and lichen taxa were found in the 269 kettles we surveyed (Appendix S7; Dickie & Gosden 2025). The surveyed kettles were 15% of the mapped total. We found 81 bryophyte and lichen species and 362 vascular plants. This included 128 exotic species (five mosses and 123 vascular plants), 314 indigenous species (75 bryophytes and lichens, and 239 vascular plants), and one moss with uncertain biostatus (Dickie & Gosden 2025; Manaaki Whenua Landcare Research 2024b). Endemism (to Aotearoa) was much higher in vascular plants (159 taxa, 44% of species found) than bryophytes and

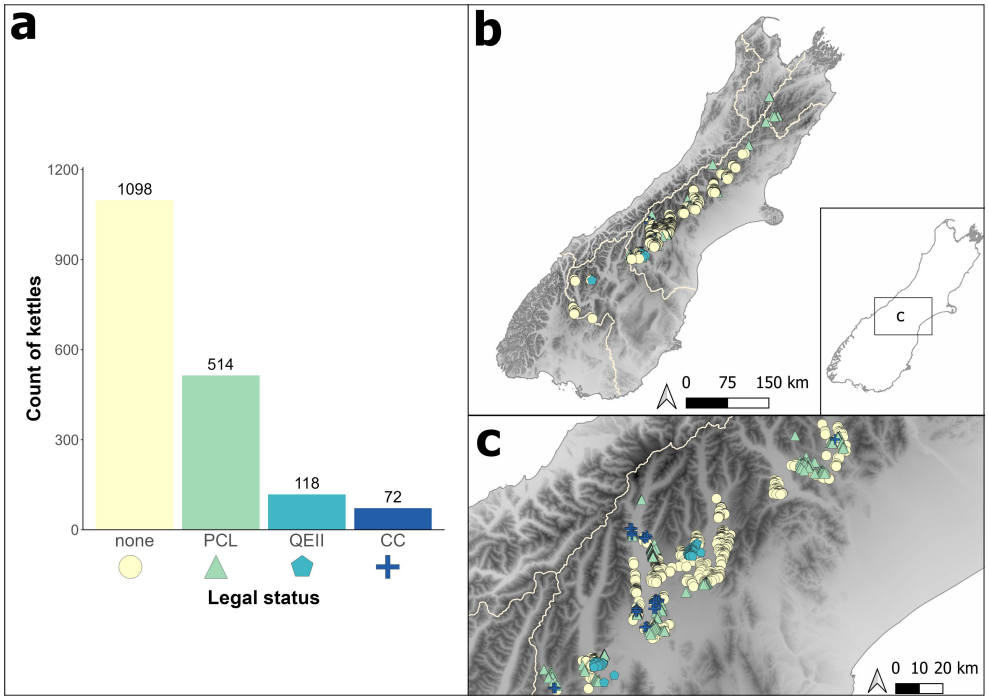

Figure 5. Legal protection status of kettles under the National Parks Act 1980, Reserves Act 1977, Conservation Act 1987, and the Queen Elizabeth the Second National Trust Act 1977. (a) Number of kettles by legal status (None, no legal status under the four Acts above; PCL, public conservation land; QEII, Queen Elizabeth II Trust covenant; CC, conservation covenant). Distribution (b) in the South Island, and (c) through Ō Tū Wharekai | Ashburton Lakes to Te Manahuna | Mackenzie Basin and the Ahuriri Valley. Colours and symbols in (b) and (c) match (a), and pale lines indicate Regional Council boundaries as shown in Fig 1. This figure contains underlying data obtained from Land Information New Zealand (LINZ) under a CC BY 4.0 license.

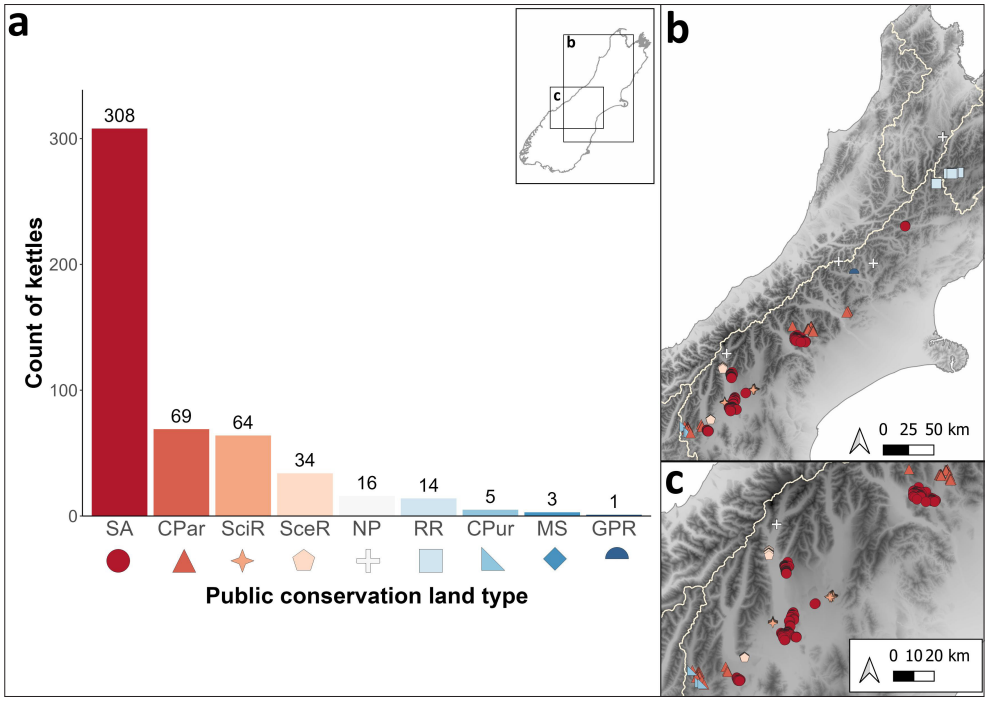

Figure 6. Distribution of kettles on public conservation land classified by conservation land type. (a) Number across each type of public conservation land (SA, Stewardship Area; CPar, Conservation Park; SciR, Scientific Reserve; SceR, Scenic Reserve; NP, National Park; RR, Recreation Reserve; MS, Marginal Strip; CPur, Conservation Purposes Reserve; GPR, Government Purpose Reserve). Distribution (b) across the South Island, and (c) through Ō Tū Wharekai | Ashburton Lakes to Te Manahuna | Mackenzie Basin and the Ahuriri Valley. Symbols and colours in (b) and (c) match the bars in (a), and pale lines indicate Regional Council boundaries as shown in Fig 1. This figure contains underlying data obtained from Land Information New Zealand (LINZ) under a CC BY 4.0 license.

lichens (seven species, 9%). The indigenous vascular plants found in these 269 kettles represented 8% of the entire flora of 2844 native vascular plants currently recognised in Aotearoa (de Lange et al. 2024).

Threatened, At Risk, or Data Deficient plants accounted for 22% of the indigenous vascular plants found in the kettles. By contrast, 15% of the indigenous bryophytes and lichens were Threatened, At Risk, or Data Deficient (de Lange et al. 2018b, 2020; Michel et al. 2026). The number of vascular plant species of kettles classed as Threatened, At Risk, or Data Deficient has increased over time (Table 5). There was a large rise in numbers of At Risk plants of kettles over both 2012–2017 and 2017–2023. However, some of the increase in At Risk species over 2017–2023 can be attributed to some species previously classed as Threatened moving to At Risk in the 2023 classification (de Lange et al. 2024).

Table 5. Counts of conservation status for kettle hole plants that are Data Deficient, At Risk, or Threatened found during surveys for this paper over four assessment years from 2009 to 2023.

	2009	2012	2017	2023
Data Deficient	**4**	**4**	**2**	**1**
At Risk	**16**	**16**	**23**	**30**
Naturally Uncommon	10	7	6	6
Relict	0	0	1	0
Declining	6	9	16	24
Threatened	**12**	**14**	**17**	**15**
Nationally Vulnerable	5	5	5	6
Nationally Endangered	5	5	8	5
Nationally Critical	2	4	4	4
Total	**32**	**34**	**42**	**46**

Flora of kettles by conservation status, land tenure, and legal status

Threatened and At Risk plant and lichen species were widespread across different land tenures (Fig. 7a) and legal status (Fig. 7b). Counts of Threatened and At Risk plants and lichens did not depend on land tenure, legal status, or public conservation land because none of these interaction effects in our models were significant (Appendix S8). For both the land tenure and public conservation analyses, counts of Not Threatened plants did not depend on their land tenure or public conservation land type (Appendix S8). However, in the legal protection analysis there was a slight, but significant, decrease in the counts of Not Threatened plants found on public conservation land when compared to the kettles with no legal protection (Appendix S8). Across all three models we found more Not Threatened species than those with a conservation status, an expected finding (Appendix S8). In both our land tenure and legal status models we found a small but significant decrease in the overall counts of plants and lichens from public conservation land (Appendix S8). We found similar counts of Threatened plants and lichens overall from Stewardship Area kettles as we did from National Parks (Fig. 7C; Appendix S8).

Discussion

Kettles as plant diversity hotspots

Kettles form a distinctive and characteristic part of the South Island high country. Despite only occupying 0.004% of Aotearoa's land area, they contain a disproportionately large subset of Aotearoa's indigenous flora, including many Threatened and At Risk species. By way of comparison, Secretary Island, which is eight times larger than the entire area of kettles, contains 279 vascular plant species (Wardle & Mark 1970), whereas we found 362 in the kettles. Furthermore, as

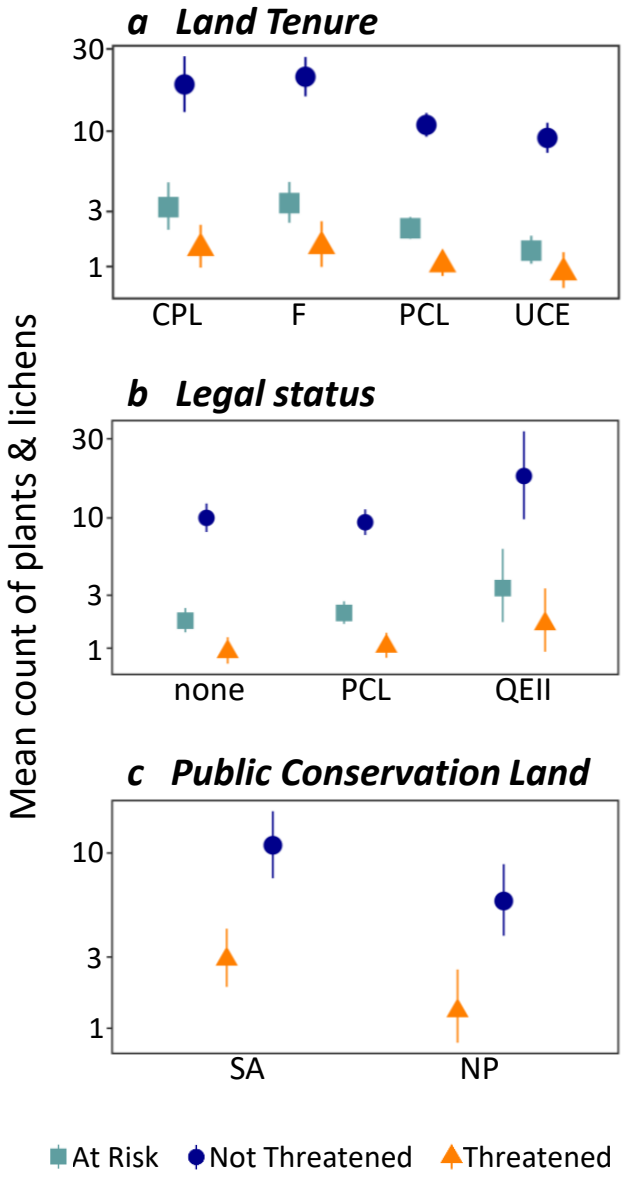

Figure 7. Mean counts (with 95% CIs) of plants and lichens per conservation status across (a) land tenures (CPL, Crown pastoral lease; F, freehold land; PCL, public conservation land; UCE, University of Canterbury pastoral lease), (b) legal status (none, no legal protection; PCL, public conservation land, QEII, Queen Elizabeth II Trust covenant), and (c) classifications of public conservation land (SA, Stewardship Area; NP, National Park).

kettles are so highly variable (Johnson & Rogers 2003; Greig & Galatowitsch 2016; Purcell et al. 2019) and we only surveyed 15% of the total mapped, other species will also be present in kettles. For example, Johnson & Rogers (2003) list species that we did not find and vice versa. Additionally, the At Risk and Threatened (de Lange et al. 2024) spring annuals (Rogers et al. 2002) *Myosurus minimus* subsp. *novae-zelandiae* and *Myosotis brevis*, and the summer green *Crassula peduncularis* (de Lange et al. 2008) are also known from kettles (the latter two having been observed one year prior to our study in one of our survey kettles JLG pers. obs.). Therefore, two decades on from the findings of Johnson & Rogers (2003), ephemeral wetlands remain significant habitats for plant diversity.

The pattern of kettle flora becoming increasingly threatened over time follows the general pattern observed for all vascular plants in Aotearoa (de Lange et al. 2024) and those of dryland ecosystems (Brower et al. 2020). Although we have used counts of Threatened and At Risk plants and lichens as a quick measure of whether kettle biodiversity values are evenly distributed across land tenures and legal status, plant conservation status is not the only factor that contributes value to a kettle. For example, kakī (*Himantopus novaezelandiae*), a Nationally Critical wading bird (Robertson et al. 2021), are known to frequent kettles in Te Manahuna | Mackenzie Basin and kettles are home to threatened aquatic macroinvertebrates (Drinan et al. 2021). Additionally, we used the national lists for the conservation status of plants and lichens, but using national lists can underestimate rarity at a local scale. Species that are common nationally may be rare at a regional or district scale (de Lange et al. 2024; Jarvie et al. 2025). Furthermore, since kettles cover such a small land area, even being found frequently in a kettle may not signify a large population size overall. This means the full value of kettles as biodiversity hotspots for threatened species is probably being underestimated by our analysis of the flora at a national level, and almost certainly at regional scales.

Mapping naturally rare and threatened ecosystems

Our mapping has shown kettles are numerous, small, at mid-elevations and often close together within an area. We have also found hundreds of previously unmapped wetlands through our mapping, simply because previous wetland mapping used a 0.5 ha cut-off and many kettles are smaller than this (Ausseil et al. 2011; Dymond et al. 2021). Since wetlands have undergone substantial losses in the last 200 years (Robertson 2016; Dymond et al. 2021; Burge et al. 2023), mapping the full range of their distribution is vital to understanding patterns in their ongoing decline and our ability to increase their legal protection. Such mapping is particularly important for ephemeral wetlands that contain numerous Threatened and At Risk species and are easily overlooked due to their size and regular drying. We found that most kettles were on freehold and pastoral lease land. Additionally, kettles on public conservation land are much more frequent on Stewardship Area land (lowest protection) than they are in National Parks (highest protection). Kettles are an example of a naturally rare ecosystem (Williams et al. 2007) that has become threatened (Holdaway et al. 2012). By mapping kettles, we have also revealed that they are found across a wide range of land tenures and legal statuses and spread across multiple classifications of public conservation land. It will, therefore, be valuable to map other naturally rare and threatened ecosystems to better understand their current legal protection.

Understanding land tenure and legal protection of kettles

Lack of legal protection has been a strong predictor of habitat loss previously in Aotearoa (Walker et al. 2008a). While slightly over a third of kettles have a legally protected status, the distribution of these legally protected kettles is not evenly spread across their geographic range. Some regions with kettles have 100% under legal protection, but often these are those that contain few individual kettles (e.g. Tasman and Westland). However, just as lack of legal protection does not necessarily mean poor management, having legal protection does not necessarily ensure that kettles are well managed for their biodiversity values. For example, areas of Molesworth Recreation Reserve containing kettles are part of Molesworth

Station and had cattle present at the time of our survey. Covenants of privately owned land with high biodiversity values, like kettles, can be a useful mechanism for providing formal protection (Mark et al. 2009). Currently covenants cover only 3% of native vegetated areas of sheep and beef farms (Norton et al. 2020), meaning there is huge potential for future covenanting to create a network of protected areas on private land. However, these covenants need to be created with the protection of biodiversity as their core purpose. Previously, many covenants were created for reasons other than the explicit protection of biodiversity values, being established instead to prevent soil loss, maintain landscape value, or prevent the widespread planting of conifers. Furthermore, covenant conditions can be weak or still allow activities like cattle farming that are damaging to wetlands (Brower et al. 2020). Therefore, compliance and monitoring are also needed for covenants to be an effective legal protection mechanism (Brower et al. 2020). Very little monitoring of kettles to assess whether native biodiversity is being maintained over time occurs on public conservation land either, and monitoring of small ephemeral wetland plants is inherently difficult. However, problems with legal mechanisms aside, legal protection has been shown to be effective at preventing native vegetation loss in the past (Monks et al. 2019). Clearly, management of kettles with and without legal protection needs to improve otherwise continuing loss of indigenous vegetation is likely (Walker et al. 2008b).

Land tenure and legal status for the land holding kettles has been affected by the now-ended tenure review process, which was a significant driver of change in the land tenure of kettles. The change from Crown pastoral lease to either freehold or public conservation land has predominantly resulted in kettles being on freehold land. Kettles are found on the mid-elevation slopes or valley floor land, the same land that is more valuable for farming, whereas the land that became public conservation land through tenure review was typically steeper areas with mountainous terrain (Parliamentary Commissioner for the Environment 2009, Walker et al. 2008b). Furthermore, kettles are typically found on Threatened Land Environments, and it is these environments that have had the greatest change in the high country to intensified farming (Cieraad et al. 2015; Brower et al. 2020). Given kettles are plant biodiversity hotspots, the overwhelming pattern of kettles becoming privatised to freehold land without legal protection is another example of land reform ignoring the highest conservation value sites (Walker et al. 2008b).

Interestingly, after 2015 there was a notable increase in the number of kettles that became protected by public conservation land during the tenure review process. However, all these kettles are on land currently classed as Stewardship Area, contributing to our finding that 60% of public conservation land kettles are found on this classification. For protected area wetlands overall, Stewardship Area classification accounted for 40% (Robertson 2016). Kettles, therefore, appear to be disproportionately found on Stewardship Area land, even when compared to other wetlands. Contrastingly, very few kettles are found within National Parks, and they tend to be smaller. Importantly, kettles in Stewardship Land had high biodiversity values similar to those in National Parks (they had similar numbers of threatened species and similar flora diversity overall). Stewardship Land is more important for kettles than National Parks because not only are plant biodiversity values across these two categories of conservation comparable, Stewardship Land also contains many more, often larger, kettles across a greater diversity of geographic extent and landscape types. Stewardship Land accounts for one third of all public conservation land (Parliamentary Commissioner for the Environment 2013), and it has the lowest legal status of any public conservation land (Brown et al. 2015). Therefore, as for other wetlands (Robertson 2016), there is a need to review the status of conservation land where kettles are found to ensure that the reserve classification better reflects the biodiversity (and other values) they hold.

We surveyed kettles across a variety of land types and legal statuses, but neither of these classifications provide detailed information on how the land is being used and managed. We also looked at the land cover classes using LCDB5. However, LCDB cover classes are broad and qualitative, and non-forested ecosystems are the least accurate of these classes (Walker et al. 2006). Therefore, while we provided a comparison of changes in LCDB cover from 1996 and 2018 it likely underestimates the change that kettles and their surrounding ecosystems have gone through, although it does provide a high-level overview for the kind of places that kettles are found in (Cieraad et al. 2015). At Risk and Threatened plants of kettles were just as likely to be found on any of the land tenures and legal statuses we surveyed, meaning Threatened and At Risk plants and lichens of kettles are not concentrated in public conservation land or QEII covenants. Because neither land tenure nor legal status classifications offer information on the land use and management, we cannot draw conclusions from this analysis alone over whether kettle plant and lichen communities are better off with or without grazing of domestic stock. Additionally, nearly all kettles we surveyed had some form of wild grazing animals (ungulates, lagomorphs, or Canada geese) present. We also did not survey any kettles that were found on highly intensified farmland; had we done so we expect there would have been lower counts of At Risk and Threatened plants on the intensively farmed land given that the intensification of farming in inland montane basins has led to biodiversity loss for other ecosystems (Walker et al. 2006; Walker et al. 2008b; Weeks et al. 2013; Monks et al. 2019). Furthermore, there is some evidence in both the peer-reviewed and grey literature of direct agricultural intensification of kettles (Brower et al. 2020; Gosden 2020). Therefore, while land tenure types of kettles are expected to remain static (now that tenure review has ended), land use change and subsequent biodiversity loss will probably continue unless there is better recognition and effective management of the important biodiversity values found in high country ecosystems like kettles.

Other threats to kettles

Beyond the loss of kettles to intensified agriculture as discussed above, another major threat to kettles is the continued spread of invasive non-native conifers through all land tenures containing kettles. The advance of these conifers will also likely drive a shift from native to exotic dominance in the surrounding land cover (Etherington et al. 2022). Invasive non-native conifers are known disrupters to hydrological systems, often reducing water availability (Dickie et al. 2022). The natural hydrology of kettles including the filling and emptying of the tarns is a crucial driver of the ephemeral wetland flora they contain (Tanentzap et al. 2013; James et al. 2019). Therefore, increased drying of kettles because of increased non-native exotic conifers could result in a more terrestrial flora for the kettles as drought tolerant species invade. Plantation forestry, therefore, also poses a threat to kettles, particularly because it causes loss of indigenous vegetation elsewhere (Monks et al.

2019). Thus, both plantation conifer farming and weedy spread of non-native conifers could be detrimental to the plant and lichen communities of kettles, requiring careful management to avoid deleterious effects.

Kettles are also vulnerable to invasion by other exotic plants. We found 128 species of exotic vascular plants ($n = 123$) and mosses ($n = 5$). While not directly comparable, Johnson & Rogers (2003) list 82 exotic vascular plants in the kettles of Canterbury and Otago, perhaps suggesting an increase in weediness over time. If this is the case, then kettle floras would be following the trend for Aotearoa with an increase in what DOC consider to be environmental weeds in recent times (McAlpine & Howell 2024). Invasion of kettles by weeds is not an isolated process and is likely linked to other land-use change to kettles. For example, Brownstein & Monks (2024) found land-use intensification on neighbouring land promoted the invasion of remnant native fragments. Walker et al. (2023) also found greater exotic plant dominance in areas where land-use intensification had been higher. Because many kettles now exist in a matrix of higher intensification land-use we also expect greater proportions of them to contain an exotic dominated flora over time. Concerningly, we noted the presence of *Veronica scutellata* in Canterbury, a species that was not previously recorded as a weed of kettles (Johnson & Rogers 2023; references contained in Appendix S1). We consider *V. scutellata* to be an emerging weed of concern, but without directly comparing past and present plant lists from individual kettles we cannot quantify the impacts of weeds on these plant diversity hotspots.

Where to next for conserving kettles?

When better aerial imagery becomes available, more kettles could be mapped. Likewise, it may become easier to map other forms of ephemeral wetland. We mapped 1802 kettles but only surveyed 15% of these on the ground, therefore we recommend further ground surveys when applying our map in consenting or planning processes. Furthermore, kettles can dramatically change in size between dry and wet seasons or even year to year in the same season (Johnson & Rogers 2003; Greig & Galatowitsch 2016; Purcell et al. 2019). With consideration to these caveats, mapping of kettles is still useful, particularly when paired with the distribution of nationally or regionally threatened species, because it could provide better information for prioritising limited conservation resources for the future management of wetland systems in Aotearoa.

Robertson (2016) called for a systematic approach to the protection of wetlands in Aotearoa. Consideration of At Risk and Threatened species is important, but it should not dominate prioritisation processes, otherwise some community types may be missed (Richardson et al. 2015). Prioritisation can take many forms, but for kettles it should at least consider areas that contain numerous individual kettles, those in areas with little or no current legal protection, those with populations of At Risk and Threatened species, and those at the geographic limits of kettle extent. Including a measure of vulnerability to complete loss of a kettle site or substantial land use or management change would also be useful (Ausseil et al. 2011). Another obvious starting point would be to secure the 60% of public conservation land kettles that are currently found on Stewardship Land into another protected area classification that recognises the biodiversity values of the kettles, whilst still allowing for traditional practices like mahinga kai. For example, the Ōtūwharekai area is significant in this respect. Thus, there is a need for the Department of Conservation and other agencies with a role in wetland protection to take a strategic approach that recognises kettles as centres of plant biodiversity, despite their small size individually, when prioritising wetland management.

Recognition of kettles (and other ephemeral wetlands) is important as they are easily overlooked as wetlands, particularly when in a dry state. Like Richardson et al. (2015), we have found further evidence that small wetlands are much more valuable for biodiversity than their size would suggest. Strengthening the protection of kettles would be an easy win for biodiversity conservation given the high numbers of plants and lichens they contain. Protection mechanisms for kettles vary from the high-level legal protection of legislation through to individual management actions on the ground. Some simple changes, like the exclusion of cattle, could go a long way to maintaining the biodiversity of an individual kettle. Other more complex changes, like ensuring covenants are protecting biodiversity values and being monitored to ensure these values are maintained or enhanced, will also be required. Given the distribution of kettles across multiple land types and legal statuses, no one organisation or individual has the sole jurisdiction for maintaining their indigenous flora values; many organisations and individuals would have a role in maintaining a diverse network of kettles in Aotearoa.

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Additional information and declarations

Author contributions: JLG: conception of study, kettle mapping, field surveys, plant identification (vascular plants), data analysis, led manuscript writing. ARM: conception of study, field surveys, manuscript revisions. DK: conception of study, field surveys, manuscript revisions.

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Literature used to identify areas of ephemeral wetland forming kettles in Aotearoa New Zealand.

Appendix S2. GIS layers and other data sources used for mapping of kettles and geographic analysis.

Appendix S3. Comparison of mapped kettle numbers before and after field work from public conservation land sites visited in this study.

Appendix S4. Counts of kettles across regional and local authorities by national count and percent of national total, and by counts across land tenures of kettles.

Appendix S5. Counts of kettles and percent total of national kettle hole count by botanical province, ecological region, and ecological district.

Appendix S6. Kettles by four types of legal status across regional and local authorities.

Appendix S7. Vascular plants found from a survey of 269 ephemeral wetland forming kettles in the South Island.

Appendix S8. Output from the three generalised linear mixed models assessing counts of plants and lichens in three conservation status categories (Not Threatened, Threatened, and At Risk) across land tenure, legal status and type of public conservation land.

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