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REVIEW

Ecology, history, threats, and management of gumland ecosystems in Aotearoa | New Zealand

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Abstract: Gumlands are a critically endangered ecosystem, restricted to Auckland and Te Tai Tokerau (Northland) in Aotearoa | New Zealand. Gumlands usually form in areas once dominated by kauri, where slow decomposition produces poorly drained, infertile soils with a siliceous hardpan. These harsh edaphic conditions result in heathlands dominated by mānuka (*Leptospermum scoparium* agg.), tangle fern (*Gleichenia dicarpa*), and sedges (*Machaerina teretifolia* and *M. brevifolia*). Before human arrival, gumlands were likely to have been small and transient components of the landscape; however, more frequent and widespread fire following Polynesian and European arrival increased their extent. Gumlands now face a suite of threats, including changes to climate, fire regime, and land use, and increased weed invasion. Fire is a critical driver of gumland formation and persistence. However, alterations to the fire regime (intensity and frequency) facilitate invasion by fire-loving (pyrophilic) weeds, potentially resulting in a fire-begets-fire feedback loop that climate change will likely exacerbate. Despite the many and varied ecological and social values that gumlands hold, they remain poorly understood and, thus, there is a limited evidence base to inform management of contemporary threats. Importantly, gumlands are a product of coupled social and ecological processes, so future research must explore social-ecological feedbacks to identify pathways for increasing their resilience. Gumlands share threats (climate shifts, plant invasions, fire) with many other Aotearoa | New Zealand ecosystems; therefore, they may serve as a valuable model system for identifying more widely applicable approaches to reduce the impacts of such threats.

Keywords: cultural landscapes, fire, mātauranga Māori, succession, weeds, wetlands

Introduction

Before human arrival in Aotearoa | New Zealand, forest dominated the landmass (cover of c. 85%) with some non-forested areas covered with scattered grassland and heathland ecosystems (Wardle 1991). Compared to the forested ecosystems of Aotearoa | New Zealand, these non-forested ecosystems are poorly understood. Little is known about the enigmatic gumland ecosystems of northern Aotearoa | New Zealand, which symbolise the region's complex social-ecological history. Gumland ecosystems form under infertile and periodically waterlogged conditions on areas once covered in kauri (*Agathis australis*) forest (nomenclature follows the New Zealand Plant Conservation Network). These unusual edaphic conditions result in distinctive vegetation communities characterised by short heathland, with relatively low species richness and endemism compared to forest ecosystems in Aotearoa | New Zealand. The increased fire activity that accompanied Polynesian and European arrival in Aotearoa | New Zealand is likely to have expanded gumland extent through the combined actions of fire-driven forest and soil removal (Enright 1989). Thus, there is an active debate over the origin of many gumland ecosystems (i.e. are they a pre-human ecosystem or the result of anthropogenic fire?).

Gumlands are named after the extensive deposits of kauri gum (hardened kauri resin, kāpia in te reo Māori) found in them and occur exclusively in the Auckland and Te Tai Tokerau (Northland) regions (Fig. 1). In this review, we consider gumlands across Auckland and Te Tai Tokerau; however, our focus is on those of Te Tai Tokerau as these are better understood and exemplify the challenges facing all gumlands and their management. Gumlands result from the unique influence of kauri on pedogenesis, which produces highly leached, acidic (pH < 5.3 in all sites measured by Clarkson et al. 2011), and nutrient-poor soils (Burrows et al. 1979). Gumlands are typically classified as wetlands (Williams et al. 2007),

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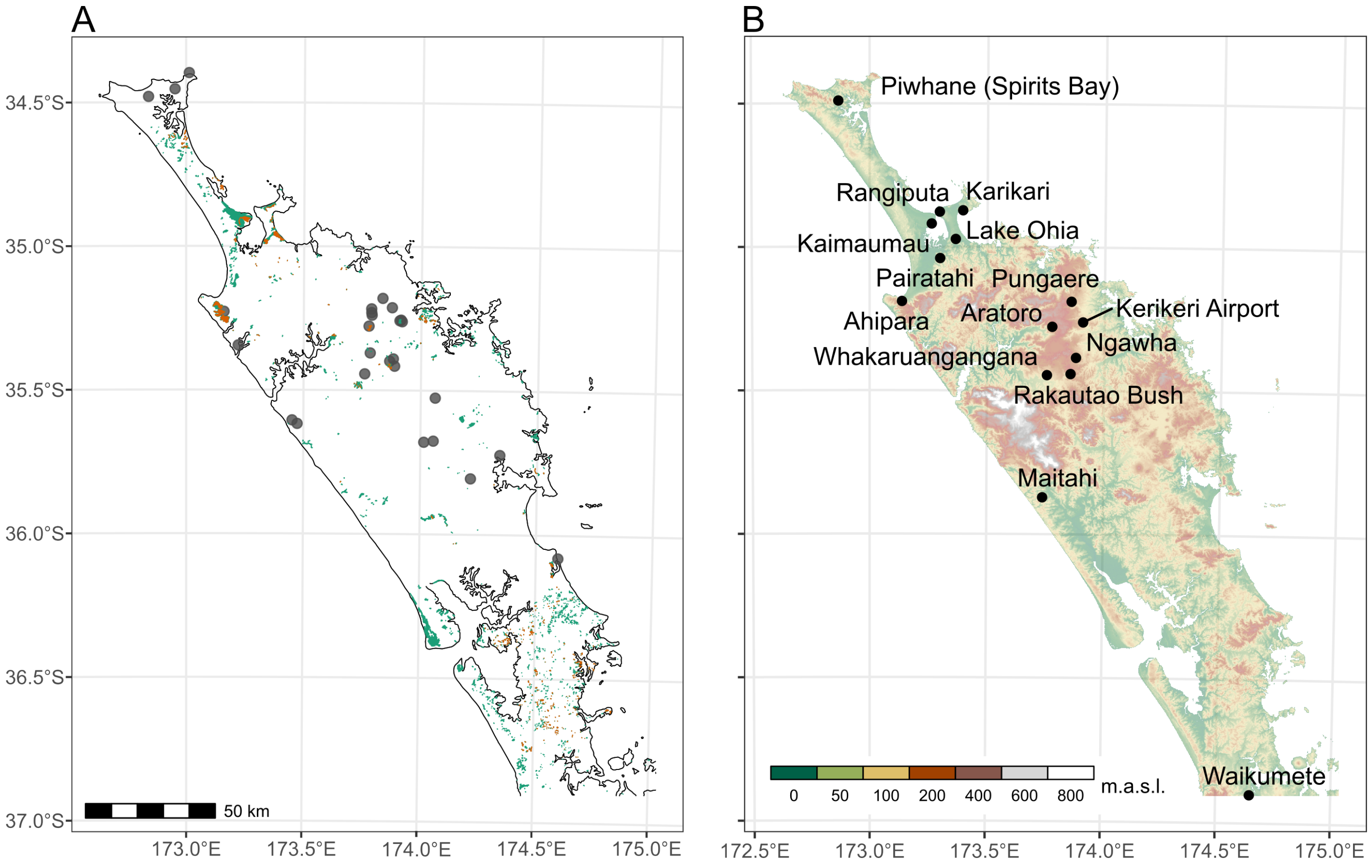

Figure 1. a) Map of wetlands and gumland distribution across northern New Zealand as mapped by the Northland Regional Council (NRC; data from the Ministry for the Environment 2013). Green denotes wetlands and orange denotes those with a 50% probability or higher of being gumlands. Grey dots are gumlands included in the NRC wetland assessment. b) locations of gumlands surveyed by Clarkson et al. (2011).

although Johnson & Gerbeaux (2004, p.34) considered them a "problematical" class of ecosystem. However, their closest global analogues are heathlands, where vegetation is naturally stunted and adapted to poor soils and regular burning (Specht & Moll 1983). Elsewhere in Aotearoa | New Zealand, similar vegetation structures occur on infertile soils, including peats in the Waikato region, volcanic surfaces in the central North Island, and the pākihi wetlands of the South Island (Burrows et al. 1979). Pākihi are an intriguing potential analogue for gumlands in that they too are ecosystems with variable soil-vegetation relationships and uncertainty about their evolution and natural distribution (Mew 1983).

The low nutrient status of gumland soils arises from leaching and the acidic input from kauri litter decomposition. On gumland soils, drainage can vary depending on the local conditions and the extent of the siliceous hardpan that inhibits downward water movement through the soil profile. These harsh conditions result in plant communities tolerant of either chronically dry conditions or seasonal inundation (Clarkson et al. 2011), with mānuka (*Leptospermum scoparium* agg.) and tangle fern (*Gleichenia dicarpa*) dominating each end of a dry-to-wet continuum respectively. Enright (1989) describes different community structures in northern Aotearoa | New Zealand heathlands, again mainly as a function of soil conditions, and speculates that these also represent a gradient from regenerating forest to persistent landscape elements. In short, gumland plant communities are far from homogeneous and are shaped by parent substrate, nutrient availability, drainage, fire regimes, and historical human activities.

Fire is perhaps the most critical of the processes that drive the formation and persistence of heathland ecosystems. Before human arrival in Aotearoa | New Zealand, in the mid-late 13th century (Wilmshurst et al. 2008; Tomlinson et al. 2024), fire in forest ecosystems was infrequent. However, natural fires were frequent throughout the Holocene in many northern wetlands where the dominant plant cover (such as Restionaceae and Myrtaceae) was both flammable and relatively well-adapted to more frequent burning (McGlone 2009; Perry et al. 2014). Thus, gumlands were probably scattered through the landscape before human arrival, but subsequent anthropogenic fire activity has played an essential role in their formation and persistence (Burrows et al. 1979; Enright 1989). Māori and Europeans widely used fire to clear land for settlement and agriculture, among other reasons (Ogden et al. 2003; Perry et al. 2014). Abandoned agricultural areas often transitioned into gumland ecosystems, a change also facilitated by changes in soil drainage (Thode 1983). The expansion of the kauri gum market in the early 20th century led to widespread digging and removal of much of the topsoil, reducing the already low fertility (McConnell 1980) and facilitating the spread of gumlands across the landscape.

Remnant gumlands have a wide range of values for diverse groups of people. To Māori, gumlands are home to taonga (treasured) species and, as with all land, connect people back through its development to its creation through whakapapa (genealogy). Settlers from around the world also made the gumlands home when economic value was found in kauri gum (mainly for linoleum and varnish), bringing diverse peoples together and tying their culture to the land in complex ways (Božić-Vrbančić 2019). Gumlands provide habitat for many threatened species and ancient swamp kauri offers a valuable record for palaeo-science (Lorrey & Boswijk 2017). The connection to land, history, and whakapapa that gumlands embody for Māori are priceless taonga (McIntyre-Tamwoy et al. 2017). However, the ongoing direct (e.g. habitat transformation) and indirect (e.g. via altered drainage) effects of human activity seriously threaten gumlands. The degree of disturbance that gumlands have experienced has left them vulnerable to further plant invasion, particularly species adapted to infertile conditions or fire (e.g. *Hakea* spp.). Paradoxically, fire is now also a threat as shifts in fire frequency can result in exotic species dominating plant communities (McQueen & Forester 2000; Hicks et al. 2001; Perry et al. 2014). Finally, agricultural development is a significant threat, causing habitat fragmentation and disturbance of hydrological regimes (Hicks et al. 2001). Climate change is likely amplifying many of these stressors, which will intensify as the climate changes further (Macinnis-Ng et al. 2021).

Irrespective of their origin, gumlands are threatened with destruction by a broad suite of stressors (e.g. changes to climate, fire activity, land use, and weed invasion) and are considered critically endangered based on a more than 80% decline in their distribution over the last 50 years (Holdaway et al. 2012). This loss parallels wetland loss more generally in Aotearoa | New Zealand, with Dymond et al. (2021) estimating the current national extent of wetlands at just 10.8% of that in pre-European times. However, despite their national and global uniqueness, the range of ecological and social values they hold, and their high-threat status, surprisingly little is known about gumlands. Here, we review the ecology of gumland ecosystems by exploring the social-ecological processes that create and maintain them and the threats to their persistence in the landscape. We also discuss the social and ecological values that gumland ecosystems hold and the ecosystem services that they provide. We conclude by considering some of the critical knowledge gaps in our understanding of gumlands that hinder their management for long-term persistence in the landscape. In particular, we explore the unique value that gumlands have for Māori and the importance of mātauranga Māori in ensuring the persistence of gumlands in the face of rapid environmental change. Our aim is to synthesise current knowledge on the ecology, history, and threats to gumlands, including the first integration of social and cultural values of these ecosystems in an effort to help better understand how to manage and sustainably use them in the face of future environmental change.

Drivers of gumland formation and ecological structure

Globally, heathlands are a diverse and widely distributed biome, recognised for their high biodiversity value (Fagúndez 2013). Heathlands typically occur on infertile soils in climates with high seasonal climate variation and are dominated by sclerophyllous shrubs or trees (Specht & Moll 1983). Human activity is central to maintaining many, but certainly not all, heathlands, often through regular burning, which can further reduce nutrient levels and plant growth rates (Borghesio 2008). Consequently, these ecosystems are dominated by shrubs, with trees existing in stunted or mallee (multi-stemmed) growth forms, varying in height from 1–5 m, and ground cover from 10 to > 90% (Specht & Moll 1983; Keith et al. 2013). In this setting, highly specialised and diverse plant communities have developed in many regions worldwide.

Origins of heathland ecosystems in Aotearoa | New Zealand

In Aotearoa | New Zealand, heathlands are widely distributed, occurring on infertile soils from the north of the North Island to Rakiura | Stewart Island in the far south (Wardle 1991). Interactions between diverse soils, climates, landforms, histories, and vegetation communities have produced a range of heathland types spread over Aotearoa | New Zealand's landmass (Burrows et al. 1979). Aotearoa | New Zealand's heathlands include the pākihi of the West Coast of the South Island, which occur on infertile water-logged soils in high rainfall areas (Mew 1983; Williams et al. 1990), and areas around Tongariro National Park where naturalised heather (*Calluna vulgaris*) dominates large areas under low nutrient conditions (Chapman & Bannister 1990). However, north of approximately 38° latitude, the natural range of kauri begins. Kauri drives the formation of Te Tai Tokerau's unique gumlands (Fig. 2), which are unusual among heathlands in that they are so strongly influenced by a single dominant plant species. But aside from this distinction, Aotearoa | New Zealand's gumlands have similar origins and drivers of vegetation composition to the rest of the world's heathlands, specifically soil fertility, drainage, and fire frequency (Clarkson et al. 2011).

Gumland soil and drainage characteristics

Te Tai Tokerau is a geologically old and weathered landscape, relatively less affected by the volcanic, glacial, and tectonic influences that have shaped much of the Aotearoa | New Zealand landmass (Burns & Leathwick 1996; Molloy 1998). Tertiary claystone and sandstone and Quaternary coastal sands are the parent materials most associated with gumlands, and sedimentary base layers are widespread (Enright 1989; Molloy 1998). During warm and moist interglacial climates, leaching produced poor soils by removing water-soluble nutrients from upper layers and, in some cases, impermeable hardpans formed atop the subsoil (Dodson et al. 1988; Clarkson et al. 2011). Further, under kauri forest, where the depth of acid bark and leaf litter can exceed 2 m at the base of a tree (Silvester & Orchard 1999), slow decomposition raises acidity and enhances leaching, producing the podsols that underlie most gumlands (Bloomfield 1953; Enright 1989; Clarkson et al. 2011; Fig. 3). Thus, identifying the ecological origins of gumlands requires an understanding of the long-term history and ecological dynamics of kauri in the landscape; e.g. as described by Ogden et al. 1992. Ultic soils are widespread and similarly leached but have a very dense clay layer rather than a hardpan (Clarkson et al. 2011). Broadly, these processes result in two types of gumlands; dry gumlands where soils contain a greater proportion of sand or are more elevated, and wet gumlands in depressions where drainage is impeded and the soils remain inundated through the wetter seasons. Fine-scale variations in the depth of the siliceous hardpan can result in strong species-sorting within sites (Esler & Rumball 1975). Wiser et al. (2016) place the northern gumlands in the *Leptospermum scoparium*/ *Schoenus brevifolius*– [*Gleichenia* spp.] shrubland alliance, recognising the two groups described by Clarkson et al. (2011) of *Leptospermum-Gleichenia* shrubland (poorly drained, low fertility) and *Leptospermum* shrubland (moderately drained, higher fertility).

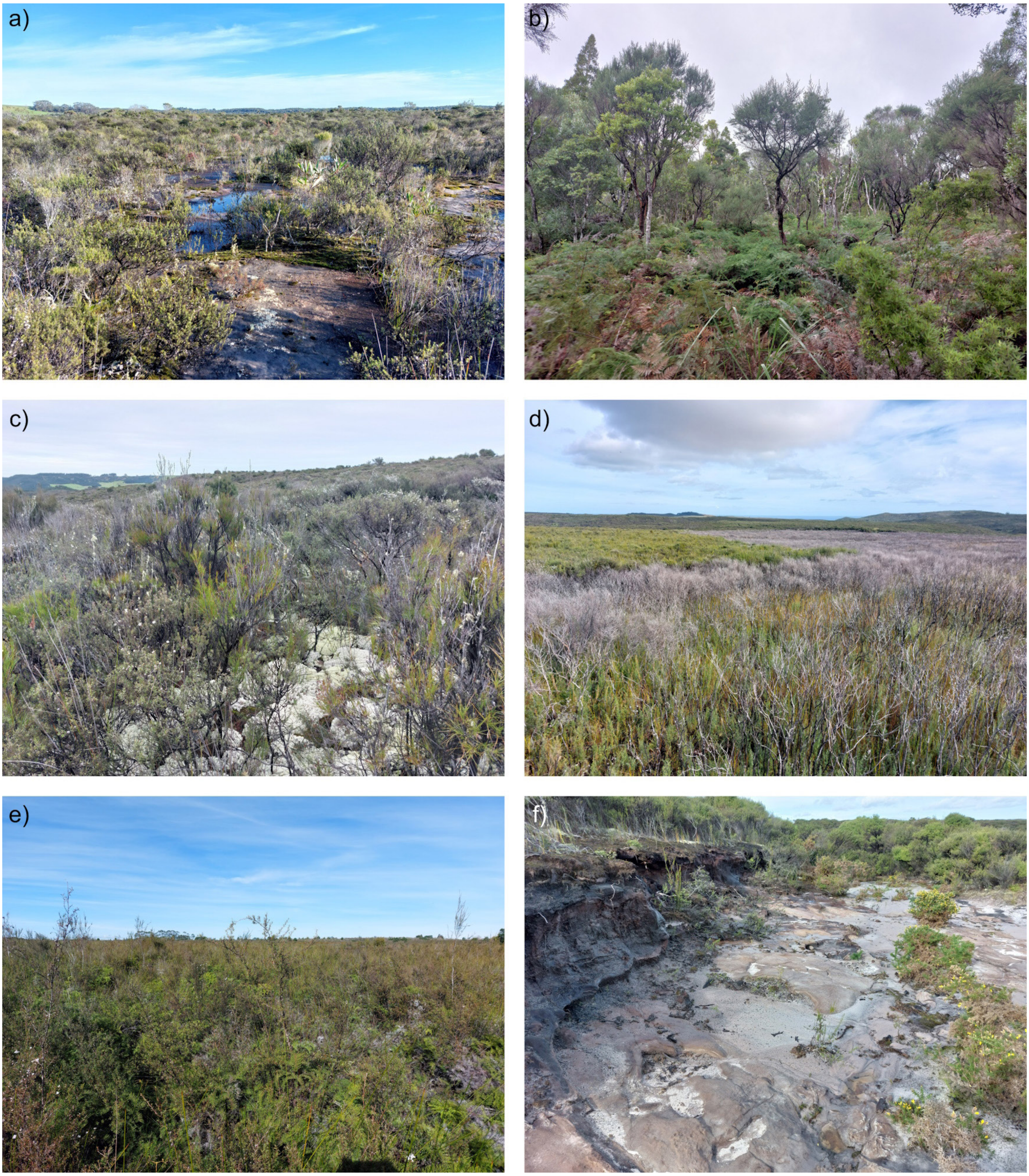

Figure 2. Examples of gumland ecosystems from (a) Lake Ohia, (b) slow succession on heavily podsolised soils at Waipoua Forest, (c) Maitahi, (d) young vegetation and recent burn on the Ahipara Plateau, (e) Kerikeri, and (f) exposed hardpan with *Ulex europaeus* (gorse) at Ahipara. See Fig. 1 for the locations of each gumland site.

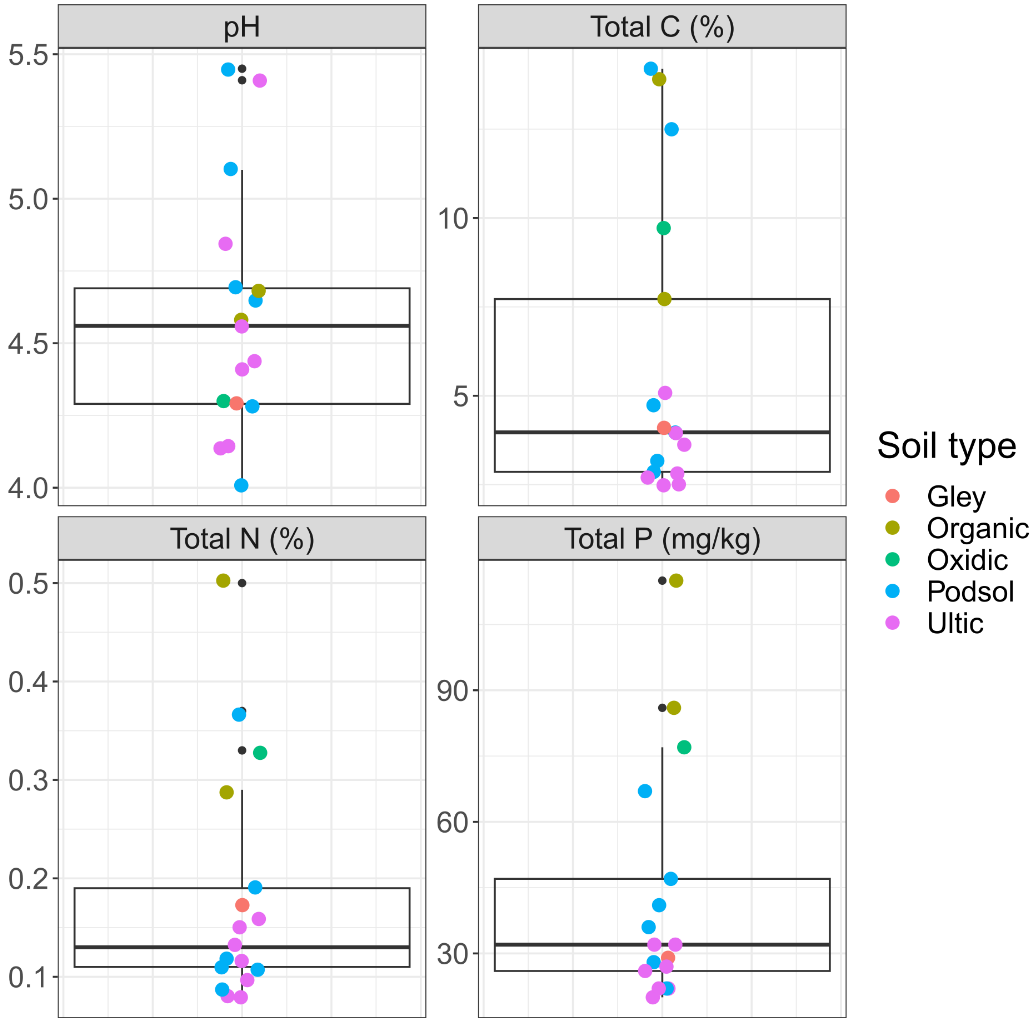

Figure 3. Soil conditions in the 15 gumland sites surveyed by Clarkson et al. (2011). Gumland soils are typically highly acidic with low available N and P, especially in podsols.

Gumland flora and fauna

Gumland vegetation is dominated by just a few plant species that are strongly limited by soil properties and hydrology. This homogeneity contrasts with heathlands globally, which are hotspots for biodiversity and endemism (Fagúndez 2013). Based on field surveys, Enright (1989) and Clarkson et al. (2011) estimated that 40% and 47%, respectively, of vascular plant species in gumlands were endemic, compared to the national average of 82% for native ecosystems (Millar et al. 2017). Much of the gumland flora is shared with Australia, suggesting a recent biogeographic origin and helping to explain the fire-adapted nature of many native gumland species. For example, of the 72 native species listed by Clarkson et al. (2011), 38 (53%) are also native to Australia; of the 41 native species listed by Enright (1989), 19 (46.3%) are also native to Australia.

Mānuka (*Leptospermum scoparium* agg.) is widespread across gumlands, and is well-adapted to frequent disturbance, particularly fire (Stephens et al. 2005; Battersby et al. 2017a). These are Aotearoa | New Zealand's only serotinous native plant species, with serotiny increasing from south to north (Battersby et al. 2017a, b). The persistence of serotiny, which also occurs in *L. scoparium* in south-eastern Australia, suggests a relationship with fire that is likely to have persisted since it arrived in Aotearoa | New Zealand under an infrequent and patchy fire regime, at least in the north. Other indigenous woody species that occur in gumlands include shrubs such as tall mingimingi (*Leucopogon fasciculatus*), tamingi (*Epacris pauciflora*), gumland grass tree (*Dracophyllum lessonianum*), and kūmarahou (*Pomaderris kumeraho*). In systems where gum digging has removed the topsoil and exposed the hardpan, mānuka and larger shrubs are often the only species to persist as their tap roots can penetrate fissures in the pan and access the soil and water below (Esler & Rumball 1975).

Beneath the low canopy, the plant community is more diverse, with the sedges *Machaerina teretifolia* in wetter areas and *Schoenus brevifolius* in drier areas, and tanglefern (*Gleichenia dicarpa*) often dominant. The relative abundance of these species depends mainly on drainage, with mānuka dominant on well-drained sites, the sedges becoming prevalent as drainage decreases, and tanglefern dominating the wettest places (Clarkson et al. 2011). Acidic and poorly drained soils are favoured by terrestrial orchids (McCrae 1990) and, consequently, gumlands are an important habitat for many of Aotearoa | New Zealand's orchids, offering refugia in regions dominated by agriculture and forestry. Habitat degradation has almost outpaced orchid species identification and description. For example, *Thelymitra* "Ahipara" is still undescribed, despite being saved from its then only known habitat in 1990, less than three years after it was identified, and only three months before the habitat was cleared, drained, and converted to pasture (de Lange et al. 1991). Although the species has since been found at several sites, its taxonomy and relationship with Australian species remains unclear.

As with the flora, Aotearoa | New Zealand's gumlands have a depauperate and poorly understood indigenous fauna, with few species unique to the gumland ecosystem and low overall species richness. Of the birds that occur in gumlands, mātātā (North Island fernbird; *Bowdleria punctata vealeae*, At Risk/Declining) and matuku-hūrepo (Australasian bittern; *Botaurus poiciloptilus*, Threatened/Nationally Critical) are of particular conservation concern (Robertson et al. 2017). Fernbirds prefer wetlands with low, dense ground cover (Anderson & Ogden 2003) as occurs in gumlands, particularly those with *Gleichenia* fernland (Clarkson et al. 2011). Matuku-hūrepo are more widely distributed and move through catchments (O'Donnell & Robertson 2016). However, because of the loss of around 90% of wetland habitat in Aotearoa | New Zealand since human settlement (McGlone 2009), gumlands have become important refugia for both species (Conning & Miller 1999; Hicks et al. 2001). Even North Island brown kiwi (*Apteryx mantelli*), typically a forest-dwelling species, have been recorded in gumlands in Te Tai Tokerau (Conning & Miller 1999). No comprehensive assessment of the avian communities of gumlands has been undertaken, but clearly, these ecosystems lack the diversity of nectar-producing and fleshy-fruited plant species that are an important resource for so many of Aotearoa | New Zealand's avifauna.

Freshwater species are limited by the ephemeral nature of inundation in gumlands. However, this seasonal drainage pattern offers ideal habitat for mudfish (*Neochanna* spp.), of which Te Tai Tokerau is home to at least three genetically unique groups (Conning & Miller 1999; Lux et al. 2009). Areas still pockmarked with holes dug to extract gum provide excellent habitat for these species, some of which (e.g. *Neochanna helios*; Northland/burgundy mudfish) are highly range-restricted.

Little is known about the invertebrate fauna of gumlands. Lepidoptera (the only invertebrate group that has received much attention in gumlands) seem well-adapted to these habitats, with two new endemic species in the genera *Paramorpha* (*Carposinidae*) and *Megacraspedus* (*Gelechiidae*) identified from gumland sites in 2011 (Hoare 2011). Overall, Hoare (2011) recorded 161 Lepidoptera species at 14 gumland sites across Te Tai Tokerau, emphasising the high ecological value of these ecosystems.

Importance of fire and other disturbances for gumland formation

In Aotearoa | New Zealand, fire has a clear role in the creation and persistence of gumlands, helping to create a system that harbours plant species with some level of adaptation to fire. The history of fire in Aotearoa | New Zealand is coupled with the fluctuating climate of the Quaternary period. During the last glacial maximum (from 22 500 to 14 000 BP), the climate of northern Aotearoa | New Zealand was colder and drier, and fires occurred more frequently, as evidenced by increased quantities of charcoal in the sedimentary record (Newnham 1992; Elliot 1998). Accompanying this charcoal is a concurrent increase in *Leptospermum*-type pollen along with other typical heathland plant taxa, and a decrease in kauri pollen suggesting a decline in kauri forest cover (Dodson et al. 1988; Newnham 1992; Elliot et al. 1998). However, using pollen analysis to interpret the historic representation of kauri in the landscape is problematic, given discrepancies between kauri pollen abundance and peaks in kauri establishment as inferred from tree rings (D'Costa et al. 2009). The presence of charcoal in sediment records from northern wetlands and the current expression of serotiny in mānuka (Battersby et al. 2017a) suggests periodic fire during the Holocene, even if modern lightning strike rates are very low (< 0.1 km^{-2}; Etherington & Perry 2017). Thus, the available pollen and charcoal evidence suggests gumlands were present in the landscape before human arrival, although to confirm this hypothesis greater spatial representation of higher resolution pollen and tree ring palaeoecological studies are needed.

The arrival of humans to Aotearoa | New Zealand was accompanied by increased fire activity (Perry et al. 2014). Māori burned forest to clear land for settlement, encourage regeneration of rarauhe (bracken; *Pteridium esculentum*) for its edible rhizome, and maintain seral vegetation as hunting sites for birds such as kiwi (Ogden et al. 2003; Perry et al. 2014). Vegetation clearance continued with the arrival of Europeans who converted land to pasture with regular burning to exclude woody species and maintain grass cover. In addition, numerous other causes, such as accidental ignitions, escaped burns, and arson further increased the frequency and spatial extent of fire in Aotearoa | New Zealand (Anderson et al. 2008; Pearce et al. 2008). Hicks et al. (2001) comment that fire was an annual occurrence in the Kaimaumau gumland during the height of gum digging (c. 1910 to 1940). Therefore, while gumland communities may have been ephemeral components of a naturally dynamic landscape before human arrival, the area covered by gumlands now has drastically increased under a much-increased disturbance regime (Enright 1989). Although fire is seen as the dominant disturbance in gumlands, it is not the only disturbance shaping the landscapes of Te Tai Tokerau. For example, the region often experiences tropical cyclones and summer droughts, both of which have been implicated in changes to forest composition since c. 1600 ybp (Elliot et al. 1998) but may not leave a clear signal in the stratigraphic sedimentary record.

Gumland successional processes

Although many studies have described successional pathways in Aotearoa | New Zealand's forest ecosystems (Wardle 1991; Wyse et al. 2018), long-term successional trajectories in gumlands remain poorly understood (Fig. 4). Nevertheless, it appears that systems considered gumlands include both permanent features in the landscape and patches of (slowly) regenerating forest; it is essential but difficult to differentiate these (Enright 1989). McQueen and Forester (2000) reported that after fire at Kaimaumau, regeneration and recolonisation by *Schoenus brevifolius*, tanglefern, bracken, and weedy species such as Sydney golden wattle (*Acacia longifolia*) occurred within four months via rhizomatous regrowth and aerial and soil seedbanks. These initial stages of post-fire succession (Fig. 4a) are similar to those described in wetlands elsewhere in Aotearoa | New Zealand (Johnson 2005). Once these pioneer species regenerate, the resulting vegetation community is often similar to that before the fire, albeit with a greater proportion of weedy species. Without further disturbance, McQueen and Forester (2000) suggested that succession would be imperceptible on the scale of a human lifetime, and that fire would recurrently halt and reset the successional process. Recruitment limitation

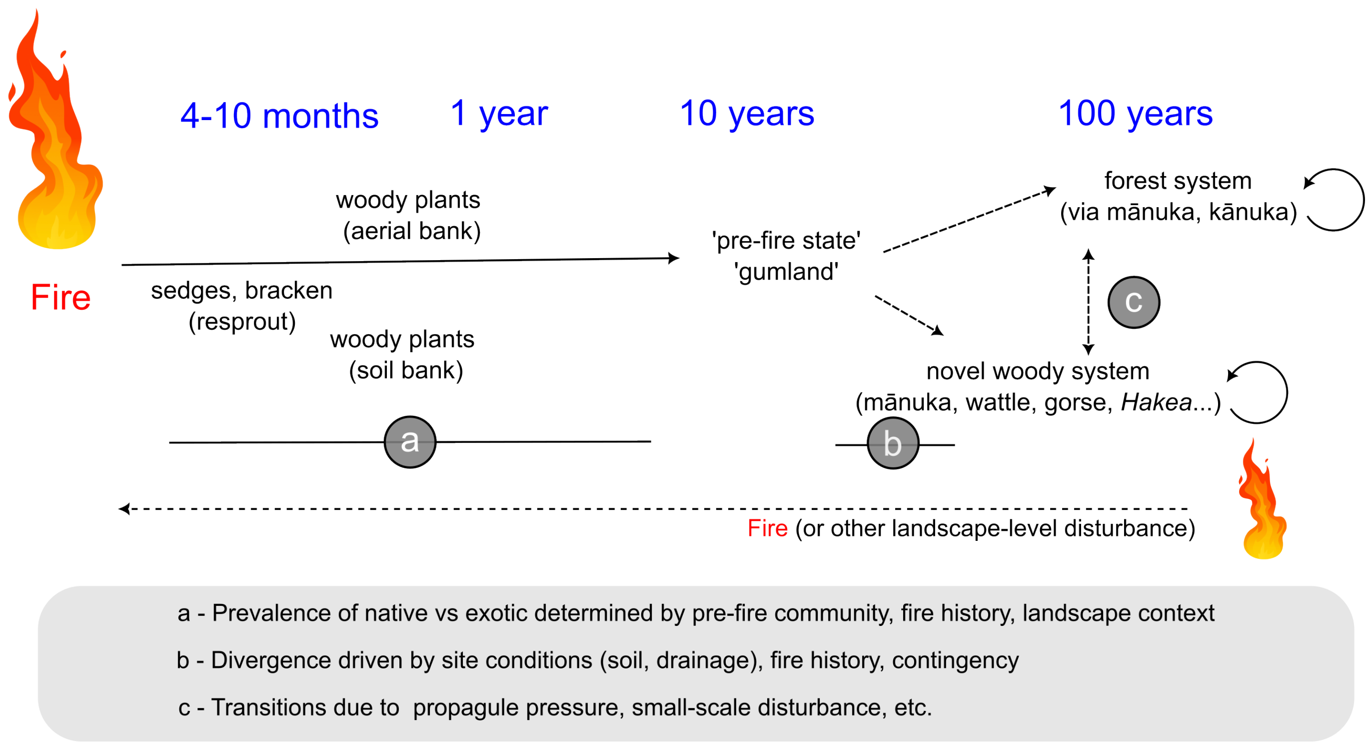

Figure 4. A schematic view of successional change in gumlands after fire, based on descriptions in Enright (1989), McQueen & Forester (2000), and Clarkson et al. (2011). Early succession can be rapid with the composition determined by fire history and seed bank dynamics; the pre-fire state can be returned to within a decade, after which succession to forest (b) will be determined by soil conditions, disturbance history, and landscape context. Once forested, community composition shifts (c) may arise from factors such as local disturbance and propagule pressures. Fire image by FreePik.

through loss of dispersers, seed predation by exotic mammals, or seedling herbivory may further slow succession, as in forest successions elsewhere in Aotearoa | New Zealand (Perry et al. 2010; Richardson et al. 2014). However, Enright (1989) notes that on more fertile soils, succession to native forest is likely, pointing to a key difference between slow post-fire succession and more permanent gumland. Clarkson et al. (2011, p. 105) excluded many of Enright's plots from their survey because the vegetation exceeded 2 m, commenting that they were "evidently reverting, albeit slowly, to forest in the absence of fire". They also recorded successional forest species, such as hangehange (*Geniostoma ligustrifolium*) and towai (*Pterophylla sylvicola*), at the margins of some of the sites they surveyed, especially on steeper locations where there are well-drained soils, suggesting a slow succession to forest. Where propagule pressure is high, these more seral communities might become dominated by exotic woody species and form novel assemblages. In general, though, gumland vegetation dynamics over longer timescales are poorly understood; again, this is an area of research where multi-site, high-resolution palaeoecological studies would be valuable. At some sites, gumland is transitioning to forest, but whether this is simply a function of site conditions is unclear. In other locations, gumland communities appear locked into a state of arrested succession and, while unlikely to become forested, are vulnerable to invasion by woody weeds (e.g. the invasion of the Kaimaumau gumland by golden wattle, gorse (*Ulex europaeus*), and *Hakea sericea* after fire described by McQueen and Forester 2000; Hicks et al. 2001).

Cultural, social, and economic values of gumlands

Gum digging

Kauri gum (copal) is a decay resistant resin exuded by kauri over wounds to protect tissue from the entry of fungi and bacteria and is preserved in acid peat soils. Deposited into the soil over generations of forests since at least the Tertiary, gum has been found many metres deep (Ecroyd 1982). Māori used kauri gum (kāpia) in small quantities for torches, as chewing gum, and as a source of tattoo (tā moko) pigment. From the 1850s, the gumlands of Te Tai Tokerau attracted many European labourers to extract and sell kauri gum, mainly for linoleum and varnish, but also for varied uses such as explosives, fire-starters, a component in glue, candles, and dentures (Reed 1978; Matich et al. 2011).

The changing process of gum digging is described in detail by Reed (1978) and Matich et al. (2011). Gum digging was initially a manual endeavour, primarily undertaken with a long spear (up to 7 m) to probe the soil and a spade to remove the gum, of which only large nuggets could be sold (McConnell 1980). As the process became mechanised, allowing more and deeper gum to be extracted over time, smaller gum chips and gum of lower purity became commercially viable (Ecroyd 1982; Matich et al. 2011). Manually powered hurdy-gurdies (drums in which gum was rinsed from the soil) and then machine-washing were used to separate gum from soil collected *en masse* (McConnell 1980). Finally, sluicing by high-pressure hoses using continuous stream-supplied water completely removed the upper layers of soil in long trenches down to the hardpan below (McConnell 1980). Each step progressively reduced soil fertility and removed any seedbank that may have existed, destroying the soil and leaving a bare hardpan that is often still present today (Fig. 5). The increase in gum-digging capacity coincided with a drop in gum price, so by the 1950s recovering the remaining small fragments of gum was no longer viable and most gumlands were abandoned (Fig. 6).

From the early days of kauri gum extraction, kauri trees were climbed to harvest gum from living trees. Eventually, to speed this process, trees were damaged to force the production of resin, while fire was used to burn forest patches to gain access to the gum below (Reed 1978). These practices were less well-documented due to their illicit nature, with kauri bleeding made illegal after 1905. In total, nearly 500 000 tonnes of kauri gum were exported from 1853 until 1969 (Fig. 6) with a commercial value of around £25 million (around $100 [1983] per ton), which equates to half the economic production of many of Aotearoa | New Zealand's major goldfields (Thode 1983; Matich et al. 2011).

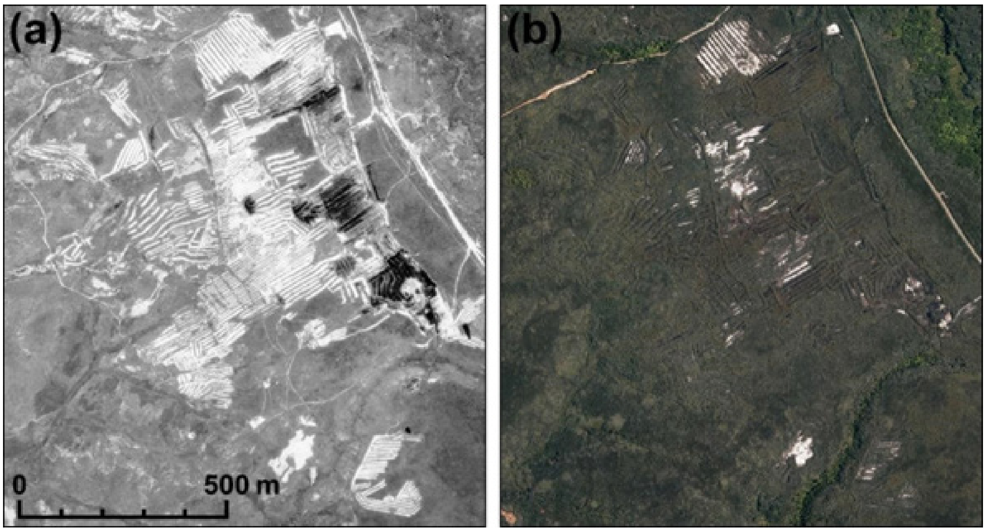

Figure 5. Aerial imagery of the Ahipara gumlands showing the severity of disturbance and regeneration after abandonment: (a) recorded in 1953, two years before the site was abandoned; (b) recorded between 2014 and 2016. Pale bands in (a) are sluiced trenches of exposed hardpan, black areas are inundated trenches and dams. Sources: (a) http://retrolens.nz and licensed by LINZ CC-BY 3.0; (b) https://data.linz.govt.nz and licensed by LINZ CC-BY 4.0.

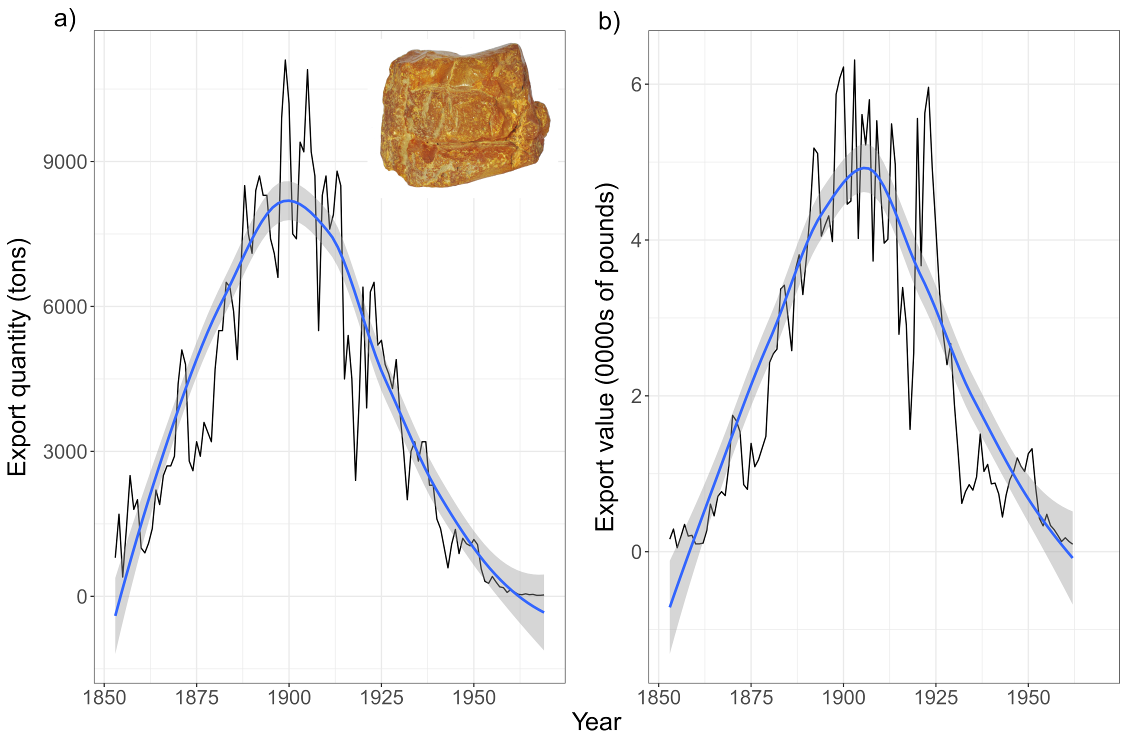

Figure 6. Quantity (left) and economic value (right) of kauri gum exported from Aotearoa | New Zealand; at the peak of the trade in the early 1900s nearly ten thousand tons, worth more than £500 000, were exported annually. Data from Reed (1978). Image shows a fist-size unpolished lump of kauri gum (image: Jarek Tuszyński under CC-BY 4.0)

Socio-ecological values

The array of interacting ecological and social processes that generated gumlands also produced a complex and sometimes contradictory suite of social and ecological values. For Māori, gumlands represent a small and degraded remnant of their former rohe (tribal lands), a connection vital for wellbeing and cultural expression. European purchase or theft of land targeted the most productive areas, resulting in a greater proportion of marginal, unproductive, and degraded land now under Māori ownership compared with that owned privately by non-Māori (Harmsworth et al. 2012). The costs of management and conservation, combined with lost opportunity costs if land is not developed, present challenges to Māori, whose ability to participate in kaitiakitanga (guardianship of the land) is already limited by other social and economic reasons.

Other cultures see significant value in gumlands, especially those descended from Dalmatian (coastal region of present-day Croatia) migrant gum diggers, who comprised a large portion of those working the gumfields (Reed 1978). Gum digging was considered a last resort, indicating desperation or lack of success in more profitable endeavours, such as silver or gold mining, and was looked on poorly by many pākehā (New Zealanders of European descent) (Penrose 1912). Gum diggers themselves were perceived as misfits at "the bottom of the economic and social ladder" (Božić-Vrbančić 2019, p. 67). For Dalmatian migrants, the latter was probably true, with the economic depression of the 1880–1890s being a key factor in their migration; their deftness and efficiency in the gumfields, however, belied the former (Božić-Vrbančić 2019). The British colonial government quickly enacted dehumanising language and racist laws in response to the presence and growing wealth of Dalmatian communities and to protect the interests of British gum diggers. This shared experience of Māori and Dalmatians helped bring these two communities together, generating social bonds and many Māori-Dalmatian marriages (Božić-Vrbančić 2019). As a result, Te Tai Tokerau's gumlands are a cultural nexus of highly valued connections that remain today in communities throughout Aotearoa | New Zealand that trace their lineage back to the gumlands (Božić-Vrbančić 2005).

Swamp kauri, the remains of trees fallen over in past millennia and preserved in anoxic bog conditions, carry strong—yet sometimes conflicting—scientific, cultural, and commercial values. To science, swamp kauri are a "world-class" archive of Quaternary climate and ecology (Lorrey & Boswijk 2017). Culturally, kauri is a taonga species and is deeply ingrained in mātauranga Māori, going back to the creation of the world. Attitudes towards swamp kauri differ among Māori of Te Tai Tokerau (Northland). These include the understanding that swamp kauri is no longer usable timber, having been returned to Papatūānuku (the earth) and become a taonga, which conflicts with the desire by some stakeholders to sell the wood and improve the quality of associated farmland (McIntyre-Tamwoy et al. 2017). Swamp kauri carries high economic value, and its extraction has been described as "Aotearoa | New Zealand's third kauri bonanza" (Evans 2016). Consequently, unscrupulous landowners have been accused of environmental destruction, including that of protected wetlands, and the export of raw timber has only recently been curtailed (Smellie 2018).

In marginal (low productivity) land such as gumlands, economic value is increasingly being found, particularly through the production of mānuka honey. Unique medicinal properties have been identified in mānuka oil and honey (Stephens et al. 2005), and this has contributed to a global boom of honey sales. Landowners and apiarists have worked quickly to take advantage of mānuka-dominated land. Public conservation land (PCL) often provides valuable native nectar resources for the honey industry. Importantly, Beard (2015) notes that in 2006 there were 2036 individual hives on PCL, and that number had risen more than seven-fold by 2015 to 14 850, although demand has recently slowed. However, the potential ecological effects of high hive stocking density (e.g. competition for floral resources with native vertebrate and invertebrate nectar feeders and the facilitation of weed spread through pollination of invasive species) remain unclear.

Threats to gumlands

Many heathland ecosystems are threatened around the world (Fagúndez 2013). Their extreme edaphic setting and position at the beginning of successional trajectories make them vulnerable to diverse types of environmental change. Climate change poses a particularly serious threat to gumlands, through direct effects such as drought as well as indirect effects such as changes in fire regime that favour weed species. These threats are amplified by ongoing land use change causing both the degradation and loss of habitat and the loss or depletion of ecological interactions critical for ecosystem functioning (e.g. pollination and seed dispersal).

Climate change

More research is needed to predict the effects of climate change on gumland composition, structure, and function. Projections for future climate change across Te Tai Tokerau are variable. Pearce et al. (2016) extensively review projected climate change to 2090 for the region. They argue that there is likely to be an increase in mean annual temperature of 0.7–3.1°C by the end of the 21st century, with most warming in summer and autumn. Projections of future rainfall patterns are complex, and many locations show no signal of change. However, in eastern Te Tai Tokerau, precipitation is predicted to decline by up to 20% in spring by 2090, while increasing in summer and autumn; other parts of Te Tai Tokerau are predicted to become wetter (Pearce et al. 2016). Intensification of drought in Te Tai Tokerau appears likely. Te Tai Tokerau's drought history is patchy, with variable rainfall across the region leading to localised droughts, but these have increased in frequency since 1994 (Pham & Donaghy 2019) and are expected to further intensify under future climate (Pearce et al. 2016).

Under projected future climates, Melia et al. (2022) predict that Te Tai Tokerau will experience a slight increase in the number of days per year when weather conditions are conducive to "highly vigorous surface fire" (p. 5). Shifts in climate may be exacerbated by the flammable nature of gumland fuel, which has high loads and volatile contents. Changing climate conditions may facilitate invasion by new and existing weedy species, potentially amplified by increased fire activity (Macinnis-Ng et al. 2021). Some potential impacts, such as changes in plant phenology, are not well understood. In summary, climate change will likely affect gumland ecosystems in many ways, and these effects may be especially pronounced in combination with habitat transformation and weed invasion.

Shifting fire regimes

Fire is a critical process that supports heathland ecosystems globally. However, it is important to emphasise that plant species are adapted to disturbance regimes, not disturbances per se (Keeley et al. 2011). The broader landscape context is also important. Gumland comprises flammable native and exotic species (Wyse et al. 2016); they may, therefore, be foci for fire, which then spreads into the surrounding landscape, but they can also receive fire, especially where land use in neighbouring areas presents high fire risk. As discussed previously, climate change will likely alter fire regimes, potentially altering fire frequency, timing, and intensity. Such changes could have lasting effects on gumland ecosystems, including shifting successional trajectories to alternative stable states such as highly degraded and flammable weed-dominated communities (Bowman et al. 2015; Kitzberger et al. 2016). Hence, while some fire may be essential for the formation and maintenance of gumlands, an increase in its frequency through, for example, accidental ignitions and wildfire due to increasing development and human populations, poses a threat to their ecological integrity. Alternatively, a lack of fire could result in encroachment by tree species and succession to the forest, as is occurring in many European heathlands (Ascoli & Bovio 2010). In Aotearoa | New Zealand, excluding fire for an extended length of time may facilitate the arrival of seral plant communities and subsequent regeneration of forest, and the loss of communities that are characteristic of gumlands (Clarkson et al. 2011). This poses the question: is there a role for prescribed fire in the management of gumland ecosystems (as suggested by Wardle 1991)? Answering this requires an improved understanding of the history and role of fire in the development and maintenance of gumland vegetation and soils. However, in some gumlands the rate of degradation means there is limited time to act. In short, there are risks associated with using fire to maintain early successional conditions (such as exotic serotinous weed invasion where propagule pressure is high), but if we wish to maintain these unique systems, there may be little other choice.

Since the Holocene, people have been key drivers in transforming many of the world's terrestrial ecosystems and landscapes with the intentional use of fire (Ellis et al. 2021). Indeed, in other parts of the world, fire is a widely used tool for altering ecosystems and maintaining or increasing biodiversity (Kelly et al. 2020). Globally, contemporary ecosystem management to reduce the risk of severe fire tends to focus on fuel reduction by prescribed burning. Yet, in Aotearoa | New Zealand, management of fire-prone ecosystems such as gumlands is constrained by cultural attitudes where fire prevention is seen as best practice. While prescribed fire is an accepted practice in many of the world's heathlands due to their fire-adapted indigenous flora, long histories of anthropogenic fires, and the application of indigenous knowledge in management, fire is not used in this way in Aotearoa | New Zealand. Where the history of fire and vegetation change is poorly known and local and indigenous knowledge is largely unrecognised, ecosystem management has often defaulted to fire suppression. Such ill-informed management has resulted in elevated fire risk and degradation of ecosystems that may otherwise benefit from prescribed burning. Fire management in Aotearoa | New Zealand has focused on reducing fire occurrence through prevention measures such as fire breaks, fire bans, and community education around fire risk (Perry et al. 2014). Indeed, nationally, current levels of burning are lower than they were in the early 20th century and most fires now occur in scrub and grass.

Evidence from overseas indicates that fire management programmes are most effective when they involve indigenous peoples in partnership with land management agencies (Snitker et al. 2022). Such programmes are community-centred, place-based, and use systems of traditional knowledge. Human activity has been the primary driver of fire in Aotearoa | New Zealand's recent ecological past and will continue to be influential in the future (Perry et al. 2014). Present-day societal values in Aotearoa | New Zealand do not see customary fire use as an effective ecosystem management practice. Legislation has prevented traditional Māori land use practices that include some form of fire use (Stone & Langer 2015). Nevertheless, a better understanding of traditional fire use is slowly emerging, aiming to better inform fire authorities and enhance Māori kaitiakitanga and cultural connection to the land. For example, wildfire risk awareness and prevention is high among Māori on Te Tai Tokerau's Karikari Peninsula due to their attachment to land and traditional protocols governing the use of fire (Langer & McGee 2017). Accordingly, appropriately managing fire in gumland ecosystems requires acknowledging the complex social-ecological feedbacks between people and ecosystems. Thus, mātauranga of ahi (fire) and its role in shaping ecosystems will be valuable in effectively managing fire in gumlands, given the historical connection and alteration of these systems by local people (Stone & Langer 2015). The maramataka, or lunar calendar, and associated traditional environmental knowledge (Hikuroa 2017) were developed and successfully applied for centuries before the arrival of Europeans (Matamua 2020). In gumlands and other ecosystems, the use of fire to improve management, alongside non-indigenous methods of knowledge production (Warbrick et al. 2023), while uplifting hapū in their role as kaitiaki warrants more exploration.

Weed invasion

There are around 1790 naturalised plant taxa in Aotearoa | New Zealand, of which just over 300 are considered environmental weeds; of this pool of invaders, 936 (54.1%) and 238 (77.3%) of the naturalised plant species and environmental weeds, respectively, occur in Te Tai Tokerau (Brandt et al. 2021). Thus, probably due to the benign climate, Te Tai Tokerau's ecosystems have a rich naturalised flora. Recurrent disturbance is often associated with susceptibility to plant invasion (Hobbs & Huenneke 1992). The altered disturbance regime that gumlands have experienced since human arrival has also increased their vulnerability to weed invasion. Compared to other ecosystems, there is low invasive species richness in gumlands (Esler & Rumball 1975; Burrows et al. 1979). Esler & Rumball (1975) only list *Hakea sericea* and *Ulex europaeus* in their plot data. Enright (1989) lists eight exotic (adventive; 20%) species across eight community types (77 samples), with *Hakea gibbosa*, *H. sericea*, and gorse the most widespread, and the adventive assemblage predictable from soil conditions (Fig. 7a). Clarkson et al (2011) reported almost the same proportion of exotic species (18 exotic species, 20% of the measured species pool) but most of these exotics were restricted to a single site (Fig. 7b), with only *H. sericea* occurring at more than half of the sites (n = 10).

Invasive plant species that occur in gumland habitats have a suite of traits that make them well-adapted to the harsh environmental conditions and frequent fire (Fig. 8). For example, several gumland invaders can fix nitrogen or thriving in low nitrogen conditions (e.g. *Hakea*, Proteaceae; brush wattle, *Paraserianthes lophantha*, Fabaceae; gorse, Fabaceae), whereas few indigenous Aotearoa | New Zealand species can fix nitrogen (McQueen et al. 2006). *Pinus* spp. (Pinaceae), specifically *P. pinaster* and *P. radiata*, are serotinous and occur in gumlands, can grow rapidly on low-nutrient soils and overtop other tree species within a few years to eventually overshade large areas (Bellingham et al. 2023). Elsewhere

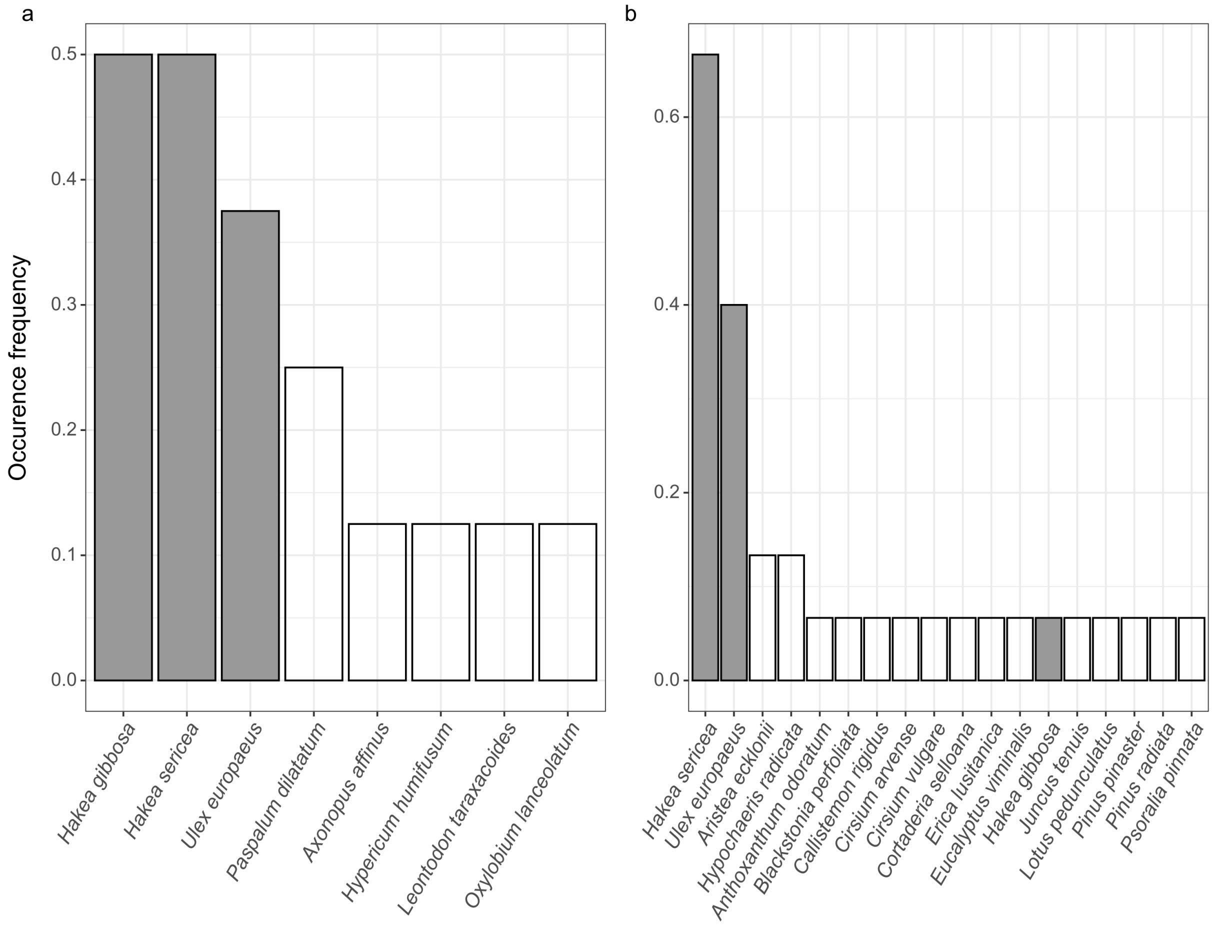

Figure 7. Frequency of occurrence of exotic species in the (a) eight community types considered by Enright (1989) and the (b) 15 gumland sites surveyed by Clarkson et al. (2011). Grey bars are species common to both studies.

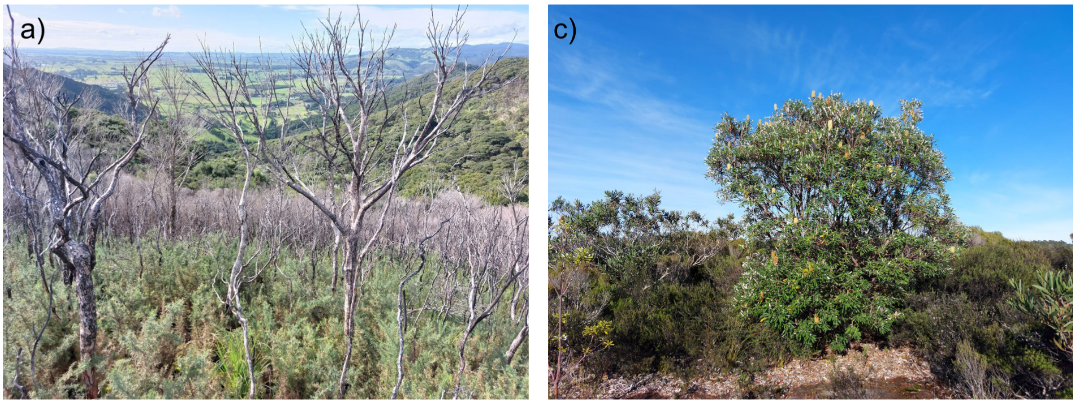

Figure 8. Examples of three exotic woody species that are widespread in gumland communities; (a) dense ground cover of gorse in recently burned gumland on the northern edge of the Ahipara Plateau, (b) *Hakea sericea* (foreground) at Maitahi, and (c) large *Banksia integrifolia* in the Lake Ohia gumland. See Fig. 1 for locations of each gumland site.

in Aotearoa | New Zealand, the large quantities of litter produced by invasive Pinaceae can have flow-on effects for fire regimes, with the speed and quantity of litter production potentially resulting in more frequent and more intense fires (Taylor et al. 2017). Other fire-adapted invasive species that are widespread in gumlands include gorse and Sydney golden wattle (Fabaceae), *Callistemon* spp. (Myrtaceae), *Eucalyptus* spp. (Myrtaceae), and *Banksia* spp. (Proteaceae) (Esler & Rumball 1975; Enright 1989; McQueen & Forester 2000; Hicks et al. 2001). In short, the invasibility of gumlands and the range of gumland-tolerant traits exhibited by invasive plant species (e.g. adaptions to infertile soils and fire) make these species a critical threat to gumland plant communities.

Threats to ecosystem structure and function

Successful plant invaders in gumlands tend to carry traits favouring them under low fertility conditions or repeated fire. However, species with such traits can change more than just community composition; they may also alter abiotic conditions, fundamentally changing ecosystem structure and function with their nitrogen-fixing bacteria symbionts (Gaertner et al. 2014). In Aotearoa | New Zealand's ecosystems, pyrophyllic or fire-tolerant species tend to be flammable, which results in increased fire risk when replacing mature indigenous (and less flammable) species. The positive feedback cycle of increasing fire frequency has been implicated in various ecosystem shifts, with fire having a key stabilising role in some systems, such as grasslands and heathlands outside of Aotearoa | New Zealand (D'Antonio & Vitousek 1992). Using a spatial state-and-transition model, Perry et al. (2015) show how flammable invasive woody weeds can alter the fire frequencies required to tip forests into early successional shrubland systems dominated by mānuka and kānuka (*Kunzea* spp.) on Aotea | Great Barrier Island. While the systems they consider are not gumlands, similar tipping point dynamics between alternate gumland states are likely. While burning does appear to be a historically significant process for Aotearoa | New Zealand gumlands, the invasive feedbacks associated with a fire-begets-fire cycle present a severe new threat in the presence of weed species (Perry et al. 2014). The widespread invasion of N-fixing species into gumlands can potentially increase available nitrogen in gumland systems, especially after successive generations. McQueen et al. (2006) outline two reasons why invasive nitrogen-fixing species might have widespread effects on successional trajectories in Aotearoa | New Zealand. First, they seem capable of occupying a broader range of conditions than the few native nitrogen-fixers. Secondly, they seem more efficient in N-cycling than their native counterparts, which is likely to influence successional dynamics on low-nutrient soils. Adding nutrients may enable further invasion by exotics or the establishment of indigenous seral species, thereby allowing succession towards forest whether native or novel woody ecosystems dominated by exotic species. Although increased fire and nitrogen-fixer dominance yield different outcomes (early successional systems dominated by exotics vs. forest), both threaten the ecological communities that constitute gumlands.

Regional development, habitat fragmentation, and land use change

Before human arrival in Aotearoa | New Zealand, natural gumlands were likely to have been ephemeral in the landscape and confined to small localised disturbed areas. However, changes in the disturbance regime and land use have altered this dynamic so that they are now stable (at least at human timescales). Although fragmentation of gumlands across Te Tai Tokerau may be ostensibly similar to their pre-human distribution, they are now embedded in a matrix of highly modified land uses. Since around the 1930s, gumlands have been converted for sheep or cattle farming, and now 45.2% (584 142 ha) of Te Tai Tokerau is covered by high producing exotic grassland (New Zealand Land Cover Database version 5.0; 2018) and 12.3% under exotic plantation forest. Some species may be favoured by the formation of higher light environments (e.g. road margins), but these are also centres of invasion (Clarkson et al. 2011) and potentially have higher nutrient concentrations from spillover effects. Indeed, Clarkson et al. (2011) reported that weed impact was highest in the smallest gumland sites they surveyed. In short, there is a pressing need to understand how land use change affects gumland ecosystems at multiple scales.

Hydrological processes are key drivers of gumland ecology (Clarkson et al. 2011). Consequently, irrigation required to maintain the amount of pasture in Te Tai Tokerau is a direct threat to gumlands. Water abstraction and clearance for horticulture are also increasingly important threats. This is especially the case for avocado growing, which has more than doubled in spatial extent between 2002 and 2011 (Northland Regional Council 2015). The effects of avocado orchard expansion are already evident at the Kaimaumau wetland, with consents for water extraction from the local aquifer creating tensions between the government conservation and local authorities, with outcomes dependent on the "adaptive management" approach taken by local authorities (Hancock 2018). Like many wetlands nationally, gumlands are negatively affected by nearby drains (Ausseil et al. 2011). Conversely, increased freshwater discharge into gumlands could result in conversion into permanently wet wetlands, such as bogs, and the loss of taxa intolerant of long-term inundation, such as mudfish (Hicks et al. 2001). Increased runoff into gumlands also poses a threat through increased nutrient input, particularly from nitrogen applied to pasture or forestry (two of Te Tai Tokerau's three most extensive land use types).

As honey production continues to grow in Aotearoa | New Zealand, honeybees may threaten the composition and function of gumland communities (including both flora and fauna). Although honeybees exploit a wide range of floral resources, they tend to target the most abundant ones and can outcompete other invertebrates through their exceptionally high foraging efficiency (Magrach et al. 2017). The threat posed by honeybees results from extremely high hive densities and apiarists transporting hives to facilitate foraging over much of the landscape. Honeybees can affect target plant species by disrupting reproduction through excessively high visitation rates, especially where close pollination mutualisms exist between plants and indigenous pollinators. In analysing the risks of honeybees on public conservation land, Beard (2015, p. 15) recommended "excluding managed beehives from areas of high conservation value where there has been no history of commercial use". This dynamic presents a clear and direct conflict of values where honey represents a new potential revenue source for the local economy.

Plant pathogens

Myrtle rust, *Austropuccinia psidii*, is a fungal pathogen (native to South America) that affects Myrtaceae and causes the death of host trees, potentially in widespread, devastating outbreaks (Lambert et al. 2018). Myrtle rust was first detected on the

Aotearoa | New Zealand mainland in Te Tai Tokerau in 2017 and has since spread around the North Island (Biosecurity New Zealand, n.d.); it can infect 17 of the 28 (60.7%) Myrtaceae native to Aotearoa | New Zealand (Jo et al. 2022). The threat that Myrtle rust poses to gumlands is clear, with mānuka (Myrtaceae) being the most widespread gumland species and having the greatest economic value.

Knowledge gaps and future research direction

Gumlands: a priority for research

Despite the ecological uniqueness and broad range of values that gumlands hold, they are understudied, and numerous knowledge gaps hinder effective conservation management. The Department of Conservation recently identified the naturally uncommon ecosystems in Aotearoa | New Zealand that most urgently require research to fill critical knowledge gaps (Department of Conservation 2020). Experts identified high-priority ecosystems and, of the 92 naturally uncommon ecosystems that were scored, gumlands were ranked second equal (alongside ephemeral wetlands, with limestone pavements top) for research priority. In particular, gumlands were ranked exceptionally high for the potential to leverage from previous research, the feasibility of completing the research required, and the likelihood of research having clear application for management.

Underlying many of these knowledge gaps is the lack of a definition for gumlands. Unlike forest ecosystems in Aotearoa | New Zealand, the long-term successional pathways for gumlands are poorly understood. It is possible that in systems currently defined as "gumland" quite different successional trajectories are playing out. Thus, research is required to determine the extent to which gumlands are longer-term features of the landscape or patches of slowly regenerating forest. Answering this question requires a better understanding of contemporary gumland dynamics and a systematic study of the fire and vegetation history from the soils under different types of gumlands through pollen and charcoal analyses. Additionally, it would be valuable to (1) develop a set of criteria to differentiate between ecosystems currently defined as 'gumland' but that follow different successional trajectories and (2) identify how much local site conditions drive these successional trajectories. Predicting how gumland plant communities change over longer time scales would be valuable, especially across sites with different ecological and human disturbance histories. In this vein, there is a clear need for higher resolution palaeoecological data to determine to what degree gumlands were present in the landscape before human arrival and the frequency and nature of key driving factors such as fire.

Ten years ago, Clarkson et al. (2011, p. 105) commented that "Research on the judicious use of fire as a management tool is recommended for long-term conservation of gumland community diversity and their threatened species". The need to better understand the role of fire in Aotearoa | New Zealand's heathlands has also been raised in the context of pākihi (Williams et al. 1990), and is more pressing than ever. Fire is critical to the formation and persistence of gumland ecosystems but an increase in fire frequency and intensity will likely erode the integrity of these systems and resilience to further environmental change. Thus, it is urgent to identify optimal fire regimes and decisions for gumlands that maintain their ecological integrity while mitigating or reducing danger to human communities and infrastructure. Identifying such regimes will require investigating the most effective approaches for reducing risk of severe fires, including the potential use of prescribed burns and mechanical fuel reduction. It is also important to acknowledge that there is unlikely to be a one size fits all fire regime – decisions will need to be made about the values attached to different social and ecological components of the system. Compounding this challenge, climate change will further alter fire regimes and shift conditions in favour of weeds, particularly those adapted to fire. European management of fire-prone ecosystems in Aotearoa | New Zealand has focussed on recovery, but under future climates we will need to develop adaptive and transformative resilience to fire. Indeed, using traditional fire management as embodied in mātauranga Māori offers a pathway toward more effective management of these dynamic ecosystems. At the landscape level, there is a pressing need to understand how land use changes impact gumlands, especially through interactions with direct threats (e.g. fire regime change, weed invasion). Further, other land use activities are likely to have diffuse effects on gumlands. For example, edge effects along roads may increase light, favouring threatened species (e.g. some orchids), but roads may also be an entry point for weeds. In short, we need to identify ways to integrate local site management of gumlands with other landscape-level conservation and land use objectives.

The resilience of gumland ecosystems is closely tied to social processes. We have little understanding of the interactions and feedbacks among societal values, disconnection of people to the land, loss or disconnection with mātauranga Māori, and current ecological threats. Therefore, research into social regime shifts and how these interact with ecological and broader-scale environmental processes would be valuable besides the ecological knowledge gaps outlined above. Wilkinson et al. (2022) describe shared principles from Te Ao Māori (elicited via interviews) that can guide human response to events that reshape landscapes: tūhononga (connection), whakauka (sustainability), tauutuutu (reciprocity), urutaunga (adapatability), and ma te wā (time/natural healing). Together these principles emphasise a worldview in which a landscape does not just revert to some pre-perturbation state but is constantly reshaped, and one where people and nature are deeply intertwined. Applying this perspective to gumlands affords different views about their management and resilience to the threats they face. Gumlands epitomise the difficult trade-offs involved in managing biodiversity in a rapidly changing world. Challenges and tensions exist alongside opportunities for protecting biodiversity, shifting societal values, and differing aspirations among diverse stakeholder groups.

Summary

Gumlands are an enigmatic ecosystem. How much their origins lie in human activity is unclear, and their ongoing management poses difficult challenges involving the place of early-successional ecosystems in the landscape. The complexity of the ecological and social interactions that produced Auckland and Te Tai Tokerau's gumlands offers a complex range of questions and directions for further research. Gumland plant community composition and its determinants have been the primary research focus thus far, underpinning questions about the successional trajectories that may have arisen in the intervening decades. The landscape context of many gumlands offers opportunities for identifying edge effects on community composition and succession, while other landcover types adjacent to gumlands, such as intact forest, may also hold clues to potential successional trajectories. The gumland fauna remains understudied. Gumland fauna offer unique opportunities to explore indigenous pollinator networks, the ecosystem services they provide, and how honeybees might reshape them.

Appropriate gumland management strategies are becoming increasingly important under a changing climate. These include the identification of an appropriate fire regime, especially the optimal frequency, intensity, and severity to protect people and biodiversity. Achieving a desired fire regime will undoubtedly require fire suppression and, potentially, prescription, but how to manipulate the fire regime to achieve a diverse set of aspirations for gumlands is a much larger question. Likewise, ensuring the hydrological regimes of gumlands remain intact over the long term requires determining the current hydrological regime and how it can be maintained as demand for water increases while water availability declines. Finally, as with all contemporary science challenges in Aotearoa | New Zealand, mātauranga Māori must be acknowledged and local hapū and whānau empowered to enact kaitiakitanga and steer conservation efforts.

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Ethics: there are no animal ethics requirements associated with this research.

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