Te Rangahau Aroturuki i ngā Rākau Rangatira o Te Wao Nui ā Tiriwa

2021 Waitākere Ranges Kauri Population Health Monitoring Survey

June 2022, Technical Report 2022/8

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Glossary of Te Reo Māori words
Te rārangi kupu Māori

The list below defines Māori terms and concepts used within the text.

Te Ao Māori	The Māori world view
Hapū	Subtribe, the primary political unit in traditional Māori society
Hui	Meeting
Iwi	Tribe comprising a number of hapū (sub-tribes) related through a common ancestor and associated with a distinct territory
Kaitiaki	Guardians
Kaitiakitanga	Guardianship. The practice of looking after the environment, rooted in tradition
Mahaki	Blight; disease
Mātauranga Māori	The body of Māori knowledge; referring to all things physical, emotional and spiritual in a Māori context
Moana	Sea
Mana whenua	Territorial rights, power over the land / by extension: Māori who have customary authority over land through ancestral links
Ngahere	Forest
Rāhui	A temporary ritual prohibition to restrict access and separate people from things that are tapu; in this context, placed by Te Kawerau ā Maki on Te Wao Nui ā Tiriwa as a measure to protect and restore balance to the forest
Rākau rangatira	Chiefly trees
Rongoā	Traditional Māori medicines; cultural health measures
Tapu	Sacred or prohibited
Tohu	Indicator
Tikanga	Cultural values, customs and practices
Te Wao Nui ā Tiriwa	The Great Forest of Tiriwa, known as the Waitākere Ranges
Whakataukī	Māori proverb
Whānau	Family

Terminology
Ngā kupu whāiti

The definitions below are specified in accordance with standard epidemiological usage. Where the same word is defined differently between different disciplines, the definition used for this study and the alternative definition are provided for context.

Baseline	The first comprehensive measurement of symptomatic tree prevalence, pathogen prevalence and impact variables in a population. A baseline is set so that future measurements can be compared against it to detect a change over time.
Case definition	The consistent criteria by which the health condition of an individual tree is included as a 'case' in a disease outbreak or study.
Confounding	Refers to the distortion of the true association between an exposure and an outcome, because of the influence of a third factor. A key difference of confounding from correlation is that the exposure variable and confounder should have a separate causal relationship or association mechanism from the outcome variable.
Cross-sectional study	Cross-sectional studies are a type of observational study, rather than an experimental study. They provide a snapshot in time. Individuals in the study are examined for the presence of an outcome of interest, such as a pathogen or cases of disease. At the same time data is collected about the presence or absence of factors that may increase or protect from the risk of disease. These are called risk factors.
Delimiting surveillance	Surveys designed to determine the extent and distribution of a new biosecurity risk outbreak or incursion.
Disease	A dynamic development of abnormal life processes due to a pathogen or abiotic disorder, lasting long enough to cause vital disturbances in the life of the host, possibly leading to its death (Tronsmo et al., 2020).
Ill-thrift	Ill-thrift describes plants that fail to thrive. For the purposes of this study, ill-thrift refers to kauri trees that are not healthy, but their poor health is caused either by other biotic or abiotic causes, or very early kauri dieback, where conclusive symptoms are not yet apparent.

Incidence	The number of new cases of disease (i.e. trees that meet the case definition) in a defined population over a defined period of time. *NOTE: This should not be confused with incidence as defined in plant pathology, as the number of diseased/symptomatic individuals within a defined population at a point in time. This is much closer to the epidemiological definition of prevalence (Madden et al., 2007).*
Incubation period	The time between an individual (tree) being infected by a pathogen and when symptoms become visible (also referred to as the asymptomatic period).
Interaction	Interaction is said to be present when the association between an explanatory variable and an outcome variable differs between, or depends in some way on, the level of a third variable.
Latency / Latent period	The time period between an individual (tree) being infected by a pathogen and when the pathogen has completed its lifecycle and becomes infectious, in that it releases reproductive structures (e.g. zoospores) and can infect other trees. Note that the pathogen can spread prior to the host tree becoming symptomatic (during the incubation period).
Misclassification bias	A type of measurement error where a study unit (e.g., kauri tree) is classified into the wrong group e.g., being classified as diseased when healthy. Or when an imperfect test is used to detect a pathogen and the pathogen is classified as absent when it is present. Misclassification can bias estimates of disease or pathogen prevalence or measures of association between variables (Haine et al., 2018).
Monitoring	Repeated surveys to determine changes in the frequency and distribution of a disease over time.
Pathogen	An infectious agent that causes disease in a host. In plants, this includes oomycetes, fungi, viruses, virus-like organisms, bacteria, and nematodes.
Positive predictive value	The probability that an individual (tree) with a positive test is actually positive; e.g., the proportion of trees identified as kauri through remote sensing that are actually kauri.
Precision	A description of random error, a measure of statistical variability.

<table>
<tr><td>Prevalence</td><td>The number of individuals in a defined population having a specified outcome at a given point in time. Where the outcome may be presence of a pathogen (pathogen prevalence) or meeting the case definition for diseased (disease prevalence).

NOTE: This should not be confused with prevalence as defined in plant pathology, as the count of geographical sampling units where disease is present (e.g., fields, plots, regions, countries) divided by the number assessed.</td></tr>
<tr><td>Prevalence ratio (PR)</td><td>The ratio of the proportion of trees with the outcome (e.g., disease or pathogen detection) to the proportion of trees exposed to the risk factor.
Using a 2 x 2 table and disease as an example:

<table>
<tr><td></td><td>Disease +ve</td><td>Disease -ve</td></tr>
<tr><td>Risk factor -Yes (exposed)</td><td>a</td><td>b</td></tr>
<tr><td>Risk factor -No (unexposed)</td><td>c</td><td>d</td></tr>
</table>
Prevalence ratio: PR = $\frac{a/(a+b)}{c/(c+d)}$
Where:
a/(a+b) is the prevalence of disease among those exposed to the risk factor
c/(c+d) is the prevalence of disease among those that are not exposed to the risk factor
Where the prevalence is the same between the exposed and the unexposed PR equals 1.0</td></tr>
<tr><td>Risk factors</td><td>Any factor or variable that is associated with either an increase or decrease in disease prevalence or pathogen prevalence.</td></tr>
<tr><td>Sensitivity (Se)</td><td>This is the diagnostic sensitivity of a test.

Proportion of trees with the disease that will test positive.

$$\frac{True\ positives}{True\ positives + false\ negatives}$$

Where false negatives are trees that test negative but do have disease. Highly sensitive tests can be used to rule out disease because they will have few or no false negatives. Less sensitive tests such as the soil bioassay may fail to detect P. agathidicida even when it is present. Typically, if a test has high sensitivity, it</td></tr>
</table>

	will have lower specificity (i.e., you will find almost all cases of disease (high Se), but you will also call lots of things diseased that are not (low Sp). *NOTE: Diagnostic sensitivity should not be confused with analytical sensitivity which is the lowest level of target agent that can be measured accurately by the test (Cardwell et al., 2018).*
Specificity (Sp)	This is the diagnostic specificity of a test. Proportion of healthy trees that will test negative $\frac{True\ negatives}{True\ negatives + false\ positives}$ Where false positives are trees that test positive but do not have disease. Highly specific tests will have very few or no false positives e.g., if we detect *P. agathidicida* in a soil sample using culture and sequencing it is almost certain that *P. agathidicida* is present. Typically, if a test has high specificity, it will have lower sensitivity (i.e., the cases you find are truly diseased, but you will miss quite a few cases of disease). *NOTE: Diagnostic specificity should not be confused with analytical specificity, which is similar, but is concerned with performance around excluding non-target species and cross-reactions (false positives) in laboratory testing (Cardwell et al., 2018).*
Surveillance	Surveillance is the systematic ongoing collection, collation and analysis of information related to health (plant health in this case) and the timely dissemination of that information to those who need to know so that action can be taken.
Symptoms/ symptomatic	Physiological or structural changes in a plant that indicate the presence of disease by reaction of the host, e.g., canker, leaf spot, wilt, lesion, dieback.

Chapter 1

Long-term kauri health monitoring framework and objectives of the 2021 Waitākere Ranges Monitoring Survey

Te anga karioi e aroturuki ana
ki te hauora o te kauri
Ngā whainga o te rangahau aroturuki i ngā rākau
rangatira o Te Wao Nui ā Tiriwa

1.1 Introduction

Te whakataki

The iconic and endemic kauri (*Agathis australis*) is a dominant keystone conifer species in northern Aotearoa / New Zealand forests (Ecroyd, 1982). Kauri is also a culturally significant taonga species to Māori and highly valued by New Zealanders across its natural range from the Far North to the southern ‘kauri limit’ in the Waikato (Waipara et al., 2013, Lambert et al., 2018). Mature kauri typically reach around 30 m in height with a trunk diameter of up to 3 m and are known to live longer than 1000 years; however, very large trees of up to 60 m tall and a trunk diameter of up to 7 m are known (Ahmed and Ogden, 1987).

Historically, much of the Auckland region was covered in kauri forest, particularly in areas such as the Waitākere Ranges, the Hunua Ranges, northern Auckland, Awhitu Peninsula as well as Hauturu/Little Barrier Island and Aotea/Great Barrier Island. These highly biodiverse ecosystems are unique and distinct, with some species found only in association with kauri, such as the kauri greenhood orchid (*Pterostylis agathicola*).

The discovery of kauri timber being a valuable wood by settlers in the early 1800s meant that New Zealand kauri forests became the backbone of a major industry. Much of the original range of kauri was reduced in the late 19th and early 20th centuries due to timber harvesting, clearance of land for other use and fire (Steward and Beveridge, 2010). In 2010 it was estimated that only 7,500 ha of virgin kauri forest (less than 1%) and 60,000 ha of regenerating kauri forest remained of the 1,000,000 ha estimated at the time of European settlement of New Zealand (Steward and Beveridge, 2010).

1.2 The Waitākere Ranges

Te Wao Nui ā Tiriwa

Te Wao Nui ā Tiriwa / the Waitākere Ranges is highly significant as one of the largest remaining tracts of native forest in the Auckland Region. Substantial modification of the native vegetation has occurred over time. Extensive logging of native timber, particularly of kauri, occurred across the Ranges with the first logging operations beginning in the late 1830s. Land clearance for farming and horticulture also occurred with increasing settlement, mostly around coastal areas. The rugged land and poor soils made agriculture difficult, and many farms were subsequently abandoned, reverting to native scrub and subsequently were succeeded by regenerating kauri forest. Settlers also undertook flax milling, gum digging and bled kauri for gum.

The intensive deforestation of the ranges in the 1800s led to public concern and advocacy for the protection of the remaining bush. In 1895, a tract of native bush in the Nihotupu area was vested in the Auckland City Council for conservation of native flora and fauna in perpetuity. The eventual decline in logging led to many properties being abandoned or purchased by Auckland City Council for water supply in the early 1900s. In 1940, the Centennial Memorial Park was created in the Waitākere Ranges to commemorate the Auckland City centennial, covering 6400 hectares of parkland.

Today, the Waitākere Ranges Regional Park consists of more than 17,000ha of parkland. Despite the significant disturbance that occurred, it is still one of the largest areas of remaining kauri forests in Auckland and New Zealand. Kauri forests have been substantially fragmented in the rest of the Auckland region. Kauri occur in the Waitākere Ranges as mature old-growth forest, intermittently with other podocarps and broadleaf species, and dense young ricker stands in regenerating forest. The long-term survival of these remaining kauri and associated ecosystems are now under threat by kauri dieback (Beever et al., 2009).

1.3 Kauri dieback and *Phytophthora agathidicida*

Te puruheka patu kauri

Kauri dieback, a soil-borne root rot disease caused by *Phytophthora agathidicida* (Weir et al., 2015), was first reported, under the mis-identified name of *Phytophthora heveae*, causing kauri stand decline on Aotea / Great Barrier Island, in Tīkapa Moana / the Hauraki Gulf in 1974 (Gadgil, 1974) and again in Te Wao Nui ā Tiriwa / the Waitākere Ranges in 2006 (Beever et al., 2009). Since then, the disease and pathogen have been detected in most kauri forests in New Zealand (Froud, 2020, Bradshaw et al., 2020), yet both disease and the pathogen remain undetected in some areas.

Kauri dieback has been described as a lethal root rot disease for which there is no known cure (Bradshaw et al., 2020). Kauri dieback is not evident until the onset of visible above-ground symptoms which form following infection of the roots, leading to dysfunction in the outer vascular tissues of the host (Bradshaw et al., 2020). Dieback is considered to be the chronic phase of the disease, observed to progress for 1 to 10 years before tree death (Bradshaw et al., 2020).

Kauri dieback affects all size classes of kauri (Bradshaw et al., 2020). Field trials have shown that phosphite injections can halt and reverse disease progression with healing of lesions and regained canopy health (Horner and Arnet, 2020, Horner et al., 2017). However, this treatment does not eliminate the pathogen from the site and at present, neither natural nor treated recovery to a healthy state from kauri dieback is known to be present in the kauri population.

Phytophthora agathidicida, the causal agent of kauri dieback, has been classified as an Unwanted Organism under the Biosecurity Act 1993. *Phytophthora agathidicida* is believed to be an introduced pathogen, rather than native, and sits within Clade 5 of the genus *Phytophthora*, which has host and geographic associations that suggests a centre of diversity in the East Asia-Pacific region (Weir et al., 2015), and overlaps with the postulated centre of diversity of *Agathis* (Bellgard et al., 2013). Recent research into the mitogenome of *P. agathidicida* has suggested that *P. agathidicida* has potentially been present in New Zealand for several hundred years (Winkworth et al, 2021). However, kauri dieback is a relatively recently reported disease. While the primary role of *P. agathidicida* as the causal agent has been confirmed (Gadgil 1974, Beever et al. 2009, Bellgard et al. 2013), the epidemiology and the other contributing factors are still under investigation. It is thought that environmental conditions and possibly human and animal interactions affect the pathogen-host relationship and may contribute to the risk of a tree becoming symptomatic (Froud 2020). At present, there is no field evidence of *P. agathidicida* infecting other alternative host species, however infection of some native species has been observed under ideal laboratory conditions (Bellgard et al., 2013, Ryder et al., 2016).

Kauri dieback has been the subject of a joint agency biosecurity response since 2009, currently under Tiakina Kauri, a partnership programme with Māori, led by Biosecurity New Zealand (as part of the Ministry for Primary Industries) involving iwi and hapū with an interest in kauri lands, the Department of Conservation, Auckland Council, and the Northland, Bay of Plenty and Waikato Regional Councils (previously called the National Kauri Dieback Programme). Tiakina Kauri invests in kauri protection activities and aims to implement a National Pest Management Plan (NPMP) to help protect kauri from the disease caused by *P. agathidicida*.

1.4 Auckland Council kauri dieback surveillance

Te tūtei i te korenga o te puruheka patu kauri

There has been significant investment by Auckland Council on kauri protection and *P. agathidicida* delimiting surveillance over the past 12 years. To date, the objectives of kauri dieback surveillance have been to delimit the extent of kauri dieback and the presence of *P. agathidicida* in the Auckland Region (Hill et al., 2017, Hill et al., 2014, Jamieson, 2014c, Jamieson, 2014a, Jamieson, 2012b, Jamieson, 2012a, Jamieson, 2014b, Jamieson et al., 2014, Jamieson et al., 2012). The delimiting surveillance used a risk-based approach, focused on sampling trees close to the track network as well as aerial identification of kauri with canopy ill-thrift (signs of canopy decline and yellowing), followed by ground survey to confirm disease symptoms and maximise *P. agathidicida* detection. The risk-based approach was particularly useful to identify areas where symptomatic trees were highly prevalent and narrow down sites with the pathogen present.

Due to this surveillance effort, we know symptomatic kauri and *P. agathidicida* were spread across the wider Auckland region, including within Te Wao Nui ā Tiriwa / Waitākere Ranges, Āwhitu

Peninsula, and northern Auckland. Severe symptoms consistent with kauri dieback have not yet been detected in areas such as Kohukohunui / Hunua Ranges and Waiheke Island and there have been no detections of the pathogen in these areas to date either.

However, this approach resulted in one of the identified constraints of the existing kauri dieback surveillance data, in that, information on non-symptomatic trees was severely limited, particularly away from the track network to form a comparison group for epidemiological analysis (Cogger et al., 2016). Another constraint of a risk-based approach to surveillance is that prevalence of disease or pathogen detection cannot be calculated to measure change over time (Lázaro et al., 2020, Cogger et al., 2016). To measure change or risk after a pathogen has established, the baseline prevalence of disease symptoms and pathogen presence must be understood (Stevenson and Froud, 2020, Lázaro et al., 2020).

1.5 Epidemiological approach to kauri dieback

Te huarahi matai tahumaero ki te puruheka patu kauri

The delivery of a long-term disease management programme is a complex and difficult task, particularly when the disease is widespread (Hill et al., 2017), cryptic (Beever et al., 2010), has extended latency and incubation periods (Bradshaw et al., 2020, Lázaro et al., 2020) and is within a heterogeneous natural ecosystem (Froud, 2020). To manage this complexity, Auckland Council adopted an epidemiological approach to plan operational management and understand the impacts of management interventions for kauri dieback (Stevenson and Froud, 2020).

This epidemiological approach follows 8 steps as illustrated in Figure 1-1. It has been clear since 2006 that a problem exists, and the initial steps to establish a consistent case definition for kauri dieback has been completed based on existing observation and knowledge of disease expression from a range of experts (Stevenson and Froud, 2020), which will allow disease and symptoms to be recorded consistently over time. Designing a baseline survey and ongoing monitoring plan will enable us to progress through steps 2 to 6 in the short term with evidence-based and mātauranga-informed management strategies. The baseline survey will then provide a framework for steps 7 and 8 to adaptively manage kauri health over the decades and generations to come.

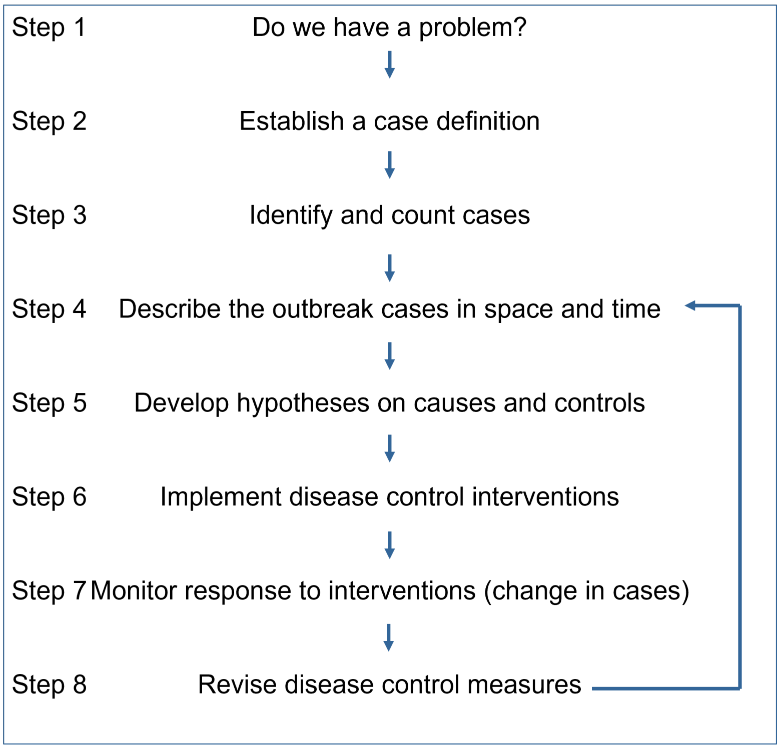

Figure 1-1. The epidemiological approach adopted for this study, showing the steps taken to investigate and manage a disease outbreak, adapted from Stevenson and Froud (2020).

The strong relationship between kauri dieback and *P. agathidicida* and pathogenicity has been demonstrated (Bellgard et al., 2016, Gadgil, 1974). A key principle of the epidemiological approach to disease management is to focus on expression of disease in the population to understand impacts on the health of the population, rather than having a pathogen-centric view. Quantifying the prevalence (the number of individuals in a defined population having a disease or a pathogen at a given point in time) of kauri dieback and *P. agathidicida,* along with other potential component causes (risk factors), can help clarify their relationship and generate hypotheses for control. Kauri dieback has an extended incubation period (the time between initial infection by *P. agathidicida* until symptoms become visible). Therefore, there will be a lag period between detection of *P. agathidicida* in soil and the detection of kauri dieback symptoms on trees if disease develops. Measuring disease symptom prevalence separately to pathogen prevalence allows a comparison of disease development over time.

The presence of *P. agathidicida* is necessary to cause kauri dieback but it is rare in nature for a single pathogen to be sufficient to cause disease in the absence of other factors. Other component causes such as a vulnerable host and environmental conditions favouring the pathogen and increasing host susceptibility (e.g., drought, rainfall, disturbances) are generally required for disease to develop (Rothman and Greenland, 2005, Martin, 2008). This is illustrated in Figure 1-2, the disease triangle, where you can see that disease (in the centre) only occurs when host, pathogen and environmental factors suitable for infection align. For a cryptic disease like kauri dieback, where many of the symptoms could have other biotic or abiotic causes, it is also useful to determine what else could be contributing to poor health in kauri where *P. agathidicida* may not be the cause.

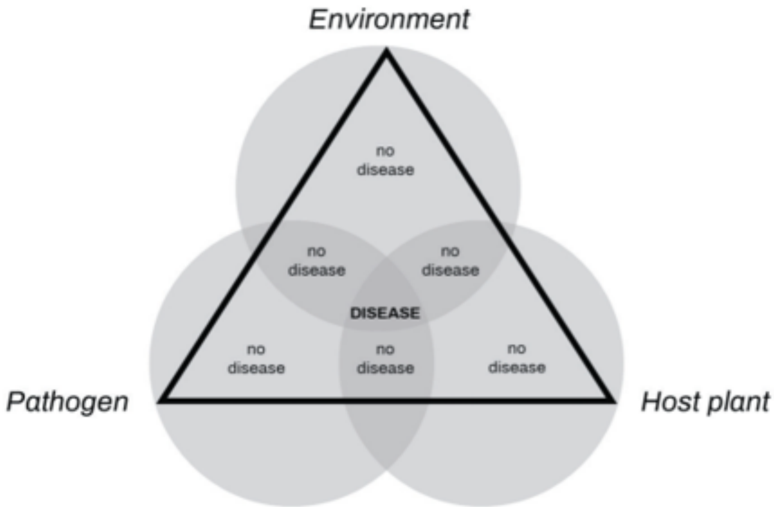

Figure 1-2. Disease triangle showing that disease only occurs when sufficient factors relating to a host, pathogen and environment (including management) intersect (Bhopal, 2016, p 136).

With the benefit of the Natural Environment Targeted Rate, Auckland Council is rescoping its kauri dieback surveillance and monitoring approach to better understand and manage kauri health.

1.6 Design of the long-term kauri health monitoring framework

Te hoahoa i te anga karioi e aroturuki ana ki te hauora o te kauri

Using the described epidemiological approach, a multi-level cascading and modular design for monitoring kauri health was developed to address four objectives:

1. To understand kauri health, pathogen prevalence, disease prevalence and other impacts in order to monitor changes over the long term.

2. To identify risk factors which are associated with disease or pathogen prevalence to inform potential management intervention options.

3. To identify ecological impact variables to provide better information on the long-term impacts of kauri dieback within the forest.

4. To understand the long-term impacts of management interventions and then focus intervention efforts on those identified as effective.

The long-term kauri dieback monitoring framework was developed through co-design hui with mana whenua o Tāmaki Makaurau, which included further discussions with mana whenua representatives of Te Kawerau Iwi Tiaki Trust, Pou Tāngata Ngāi Tai ki Tāmaki Community Development Trust, Ngāti Paoa Iwi Trust Board, Ngāti Whanaunga Incorporated Society, Ngā Maunga Whakahii o Kaipara Trust, Te Ākitai Waiohua Waka Taua Inc, Ngāti Maru Rūnanga Trust and Environs Te Uri o Hau. The framework acknowledges that mātauranga Māori will also contribute to measuring forest health and intervention efficacy outside/alongside this monitoring framework.

The design of this monitoring framework was based on core epidemiology surveillance approaches; in particular the application of an observational study design using a repeated cross-sectional study (Dohoo et al., 2009, Cogger et al., 2016), the baseline monitoring recommendations of Stevenson and Froud (2020) and significant progress in applicability of remote sensing from Meiforth (2020), Meiforth et al. (2020). It was also informed by reviewing the last 10 years of kauri dieback surveillance, particularly contributions from Tiakina Kauri Partners, Planning and Intelligence team members and the Technical Advisory Group and research from Ross Beever, Stan Bellgard, Ian Horner, Margaret Dick, Nick Waipara, Nari Williams, Tony Beauchamp, Lee Hill, Alastair Jamieson, Andrew Macdonald, NRT integrated surveillance workstream members and many others (Froud, 2020, Black and Dickie, 2016, Bradshaw et al., 2020).

The use of an observational study design, such as a cross-sectional study is most appropriate when an experimental design is not feasible (Froud and Cogger, 2015, Dohoo et al., 2009a) for reasons including:

(i) Risk factors are not easily manipulated in the field for practical (difficult to implement), ethical (kauri is a slow-growing and threatened endemic species) or economic reasons.

(ii) The disease cannot be practically manipulated in field trials, such as controlled pathogens during a biosecurity incursion (*P. agathidicida* is an Unwanted Organism under the Biosecurity Act 1993).

(iii) Interactions between multiple factors are of interest but are too complex to manipulate experimentally, such as complex native ecosystems.

(iv) Some factors of interest cannot practically be manipulated experimentally, e.g. soil type, temperature, distance to waterways and elevation.

(v) Where disease is multi-factorial and not all potential causative factors of a disease outbreak are known, and the aim is hypothesis generation.

(vi) When large-scale management interventions have been applied and their efficacy needs to be quantified.

In the case of kauri dieback in natural indigenous forest, all these reasons are relevant.

Three key components form the basis of the monitoring framework as illustrated in Figure 1-3.

Kauri dieback long-term monitoring framework

A] Kauri forest-level health monitoring
Remote sensing detection of stress in the kauri tree population. Aim: set baseline kauri tree health prevalence and monitor change over time.

B] Tree level symptomatic kauri trees and *Phytophthora agathidicida* monitoring
Ground monitoring of symptomatic kauri trees consistent with kauri dieback and risk factors on randomly selected trees across the forest, to set baseline prevalence, monitor pathogen and disease incidence, severity, disease determinants and mitigation impacts over time. Includes a sub-sample of soil sampling for *Phytophthora* spp. B] is carried out on a subset of trees from A].

C] Tree level *Phytophthora agathidicida* freedom surveillance
Aerial/Ground surveillance aimed at early detection of *P. agathidicida* in soil or on trees. Survey sites and soil sampling for pathogen detection are selected based on risk within high value disease free sites. C] is carried out on a subset of trees from B].

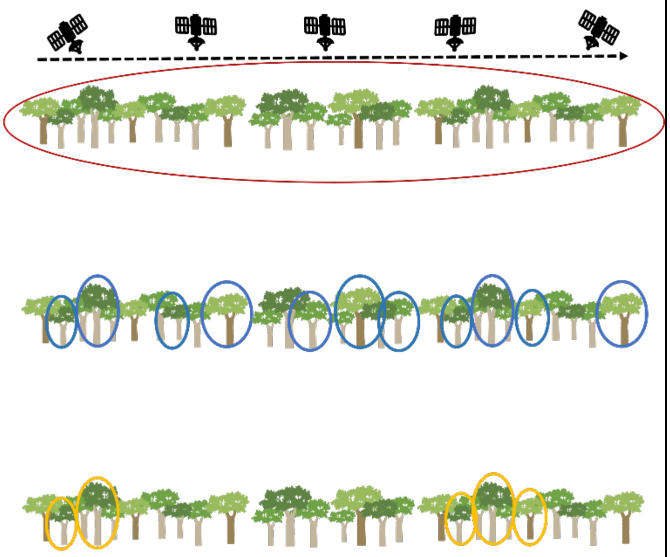

Figure 1-3. Proposed long-term kauri health monitoring framework.

The modular design of the framework means that the same methodologies and three-level system may be applied at different scales, whether at a regional or national level, if deemed appropriate. This could be within a single kauri forest, or across multiple kauri forests and kauri forest remnant areas. It may also be adapted to include possible alternative hosts if host detection methods are developed for them and could be adapted to other canopy tree species such as *Myrtaceae* or for assessing full forest ecosystem health.

The proposed monitoring framework will be rolled out over time as the methods required to deliver it are refined. In particular, the A and C levels require additional knowledge before they can be implemented.

1.1.1 (A) Kauri forest-level health monitoring

Kauri forest-level health monitoring is aimed at early change detection of canopy stress symptoms in kauri. It may help to reduce the reliance of future monitoring on intensive ground surveys. This is underpinned by new remote sensing host detection methods which were applied in the 2021 Waitākere Ranges survey and are described in Chapters 2-5 of this report. Validation of stress detection and the setting of a consistent stress index is required before a baseline can be set and the steps to deliver this are detailed in the future steps section of this report (Chapter 6).

1.1.2 (B) Tree-level symptomatic kauri and *P. agathidicida* monitoring

The roll out of tree-level symptomatic kauri trees and *P. agathidicida* monitoring was applied in the 2021 Waitākere Ranges Regional Park survey and uses a repeated cross-sectional study design

(Diehr et al., 1995). This is a type of observational study that measures disease prevalence (or another outcome) in a population at a point in time and is often referred to as a prevalence study. A cross-sectional study can also measure potential disease determinants (risk factors) and ecological impacts. A repeated cross-sectional study is a study in which the same group of trees is examined at different time points with the prevalence of disease estimated on each occasion (Diehr et al., 1995). The results of the study are described in Chapter 2 of this report and the steps to deliver ongoing tree level monitoring across Tāmaki Makaurau are detailed in the future steps section (Chapter 6).

1.1.3 (C) Tree-level *P. agathidicida* freedom surveillance

Tree-level *P. agathidicida* freedom surveillance is carried out to quantify confidence that kauri dieback is absent from areas thought to be free of disease. The most efficient way to conduct a proof of freedom study is to use a risk-based approach where search effort is (logically) concentrated on individuals where the probability of disease is thought to be high. An initial investigation to identify risk factors for kauri dieback was undertaken in the 2021 Waitākere Ranges survey and the results are described in Chapter 2. In addition, the diagnostic test performance parameters of any tests used to detect the pathogen need to be quantified to calculate the number of trees to be tested and found to test negative to quantify confidence in disease freedom. A study to evaluate the Auckland Council visual assessment of disease and soil bioassay tests to detect *P. agathidicida* was also conducted as part of the 2021 Waitākere Ranges survey. The results of this study are described in Chapter 4 of this report.

1.7 2021 Waitākere Ranges monitoring survey

Te rangahau aroturuki i ngā rākau rangatira o Te Wao Nui ā Tiriwa 2021

The year 2021 marks the third time Auckland Council has surveyed the Waitākere Ranges Regional Park for kauri dieback disease. However, this is the first time that an epidemiological approach has been used. Baseline monitoring provides a reference point to which future estimates of kauri dieback prevalence and *P. agathidicida* prevalence can be compared.

For the 2021 Waitākere Ranges survey, the detailed design, delivery and analyses of data occurred in partnership with Te Kawerau ā Maki, mana whenua and kaitiaki of Te Wao Nui ā Tiriwa / the Waitākere Ranges. This research supports the 2012 Auckland Council Indigenous Biodiversity Strategy's vision of He taonga, ka whaihua ngā rerenga ke o te Ao Tūroa i Tāmaki Makaurau (Auckland’s indigenous biodiversity is flourishing and treasured).

The next steps of this epidemiological approach are to implement steps 2 through 5 (Figure 1-1) using a single cross-sectional prevalence study. The 2021 Waitākere Ranges survey was designed as one survey with three inter-related studies. The objectives for these three studies were:

1. Prevalence study – to identify and count the number of symptomatic trees (Step 3) and describe the prevalence and spatial distribution of symptomatic kauri and of *P. agathidicida* at a point in time (Step 4). This is described in Chapter 2.
2. Risk factors study – to generate and test hypotheses of why some trees are at greater risk of disease compared to others and whether any additional control interventions could be applied (Step 5). This is described in Chapter 3.
3. Test performance study – to quantify the diagnostic test performance of visual assessment of symptomatic kauri trees consistent with kauri dieback and our soil sampling bioassay to detect *P. agathidicida.* This is described in Chapter 4.

The test performance study supports the epidemiological approach. A knowledge of diagnostic test performance allows 'apparent pathogen prevalence' estimates to be converted to 'true pathogen prevalence' estimates. This allows prevalence estimations to be compared for different populations and over different time frames using different diagnostic tests (if they are available). This is important because it is likely that new (improved) diagnostic tests for kauri dieback will become available in the coming years and there will be a need to ensure that the pathogen prevalence estimates derived using older test procedures are comparable with those derived from newer test procedures.

These three studies will provide evidence to inform management strategies and interventions (Step 6) and provide baseline data to measure change in disease and efficacy of control measures in the future (Step 7) alongside mātauranga Māori measurements of forest health and intervention efficacy.

These three studies are reported as separate chapters within this technical report, with different co-authors, based on specific expertise. The three studies are written in the format of scientific manuscripts which supports the Auckland Council commitment to a robust study design and peer review of methodological approaches and study inference.

The methods for the three studies within the 2021 Waitākere Ranges survey were co-designed with mana whenua, subject matter experts and then peer reviewed by international experts prior to field work. Each study has a specific introduction which goes into more detail of the study and specific discussions of the results and builds on the methods and knowledge of each other.

On completion of writing, the three studies were sent for final expert review to international experts. This full report concludes with a section that weaves together the new knowledge gained from these three studies and provides a strategy for implementation of the long-term monitoring framework for kauri dieback in the Tāmaki Makaurau region.

Chapter 2

Baseline prevalence study of *Phytophthora agathidicida* and kauri dieback in the Waitākere Ranges and frequency of potential risk factors using a cross-sectional study

Te whakarāpopoto e whakaahua ana i te puruheka patu kauri i Te Wao Nui ā Tiriwa me te auau o ngā take tūraru tērā pea ka puta

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2.1 Abstract

Te whakatūporotanga

A cross-sectional study was co-designed with mana whenua to set a baseline for monitoring kauri (*Agathis australis*) health and the prevalence of both kauri dieback (disease) and *Phytophthora agathidicida*, the pathogen that causes kauri dieback, in space and over time. This study had 5 objectives: i) operationalise new remote sensing methods to develop a kauri sample frame; ii) spatially describe the baseline prevalence of *P. agathidicida*; iii) spatially describe the baseline prevalence and severity of symptomatic kauri; iv) identify and collect data on key factors that could affect disease risk for hypothesis generation; and v) collect baseline data on ecological factors as indicators of ecosystem impacts from kauri dieback.

A sample frame was constructed using remote sensing to detect kauri trees >15 m tall within the forest canopy of Te Wao Nui ā Tiriwa / the Waitākere Ranges parkland identifying 68,420 trees. A total of 2140 randomly selected trees were surveyed from this sample frame and the soils beneath a subset of 761 of these trees were tested for *P. agathidicida* presence.

The spatial distribution of *P. agathidicida* showed the pathogen was distributed in a localised pattern around the periphery of the study area. In contrast, symptomatic kauri trees were more widespread and present in the centre of the Park. There was an elevated relative risk of symptomatic kauri in the north of the Park, which matched an elevated relative risk for *P. agathidicida,* and in the south-east area of the Park. The relative risk of symptomatic kauri was also elevated, but to a lesser degree, in the mid-west area of the Park where there was also a higher risk for *P. agathidicida*. Baseline disease severity was recorded so repeated surveys can inform disease progression over time. The prevalence of *P. agathidicida* detected in soil from soil-sampled trees was 10%. The baseline prevalence of symptomatic kauri trees was 16.5% (95% CI =14.1 to 18.9%).

Baseline data collected during the survey were focused on potential risk factors affecting kauri tree health, which were identified through two hui / meetings involving kauri ecosystem health experts from mana whenua and research organisations for data collection and analysis. Baseline measures of ecological impact factors were collected on a subset of trees for future comparisons. An interesting finding was that kauri seedlings and saplings were surviving in soils where *P. agathidicida* was confirmed. This study provides a consistent cohort of monitored trees that can be remeasured to understand change in disease and pathogen prevalence over time.

Results will be used to help inform the ongoing and adaptive management of kauri dieback in Te Wao Nui ā Tiriwa / the Waitākere Ranges and across New Zealand.

2.2 Introduction

Te whakataki

Kauri dieback, caused by *Phytophthora agathidicida* (Weir et al., 2015), was reported causing kauri (*Agathis australis*) stand decline in Te Wao Nui ā Tiriwa / the Waitākere Ranges in 2006 (Beever et al., 2009). Subsequent delimiting surveys detected *P. agathidicida* in several, but not all areas where symptomatic trees were observed within the Waitākere Ranges (Hill, 2016, Hill et al., 2017). However, the overall symptomatic tree prevalence and *P. agathidicida* prevalence in the Waitākere Ranges remains unknown.

Auckland Council therefore carried out a large cross-sectional survey of tree-level kauri dieback monitoring across the Waitākere Ranges during the summer and autumn of 2021. The monitoring design and methodology was co-developed with consultation and discussion between Auckland Council staff, mana whenua (the indigenous people that hold authority and guardianship over the land) representatives of the wider Tāmaki Makaurau (Auckland) region, a multi-disciplinary group of researchers, and partners of Tiakina Kauri. Further detailed and ongoing discussion was undertaken with Te Kawerau ā Maki first and foremost as mana whenua and kaitiaki (guardians) of Te Wao Nui ā Tiriwa, the forested area of the Waitākere Ranges.

As well as detailing distribution and prevalence, this study measures the health status of individual kauri trees so that an increase or reduction in the number of symptomatic trees in the population over time can be assessed. In addition, the study measures the presence of *P. agathidicida* in soils of both healthy and unhealthy trees, so a change in distribution of the pathogen can be assessed over time with repeated surveys.

A kauri dieback case definition was developed to record disease in the forest consistently over time (Stevenson and Froud, 2020). The symptomatic criteria of this case definition for kauri dieback include 'bleeding' (release of copious resin) lesions on the basal trunk, lesions on lateral roots, yellowing of the foliage, the presence of canopy thinning, and ultimately tree death (Stevenson and Froud, 2020). These disease symptoms alone or in combination may also occur in the absence of *P. agathidicida* because the physiological disorders can be caused by other biotic (different pathogens) or abiotic (physical, environmental or climate) factors. However, bleeding lesions in conjunction with one or more other symptoms is typical for infection with *P. agathidicida* (Beever et al., 2009).

Cross-sectional studies (also called prevalence studies) are a common epidemiological study design, that are especially useful in disease outbreak investigations. This type of study is suited to document the prevalence of disease (or pathogen) at a given point in time and to identify characteristics associated with relatively high or low prevalence of disease (Diehr et al., 1995, Dohoo et al., 2009).

This study had five key objectives:

1. Operationalise new remote-sensing methods to randomly select kauri for ground survey.
2. Spatially describe the baseline prevalence of *P. agathidicida.*
3. Spatially describe the baseline prevalence and severity of symptomatic kauri with suspected kauri dieback.
4. Identify and collect data on key factors that could affect disease risk for hypothesis generation.
5. Collect baseline data on ecological factors as indicators of ecosystem impacts from kauri dieback.

The study design used for this survey broadly followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (O'Connor et al., 2016). The results from this study will be used to inform the ongoing and adaptive management of kauri dieback in the Waitākere Ranges and across New Zealand. The collection of baseline data will provide a comparison dataset for repeated cross-sectional monitoring of the same cohort of trees.

2.3 Methods

Ngā tikanga

2.3.1 Study design

2.3.1.1 Unit of interest

The units of interest were individual kauri trees. This is consistent with the recommended unit of interest for the National Kauri Dieback Programme (NKDP) baseline surveillance (Stevenson and Froud, 2020). The classification of individual trees was further refined by size with a minimum diameter at breast height (DBH) of 10 cm. This is consistent with historical tree assessments in native New Zealand forests of mature trees (Ahmed and Ogden, 1987).

2.3.1.2 Population of interest and sampling frame

The population of interest for this study was kauri within the Waitākere Ranges that could be detected by an analysis of remote sensing data. From the population of interest, a sample frame was derived for Auckland Council-managed land that included the Waitākere Ranges Regional Park and a small number of local parks that were contiguous to the Regional Park and these made up the study area (Figure 2-1).

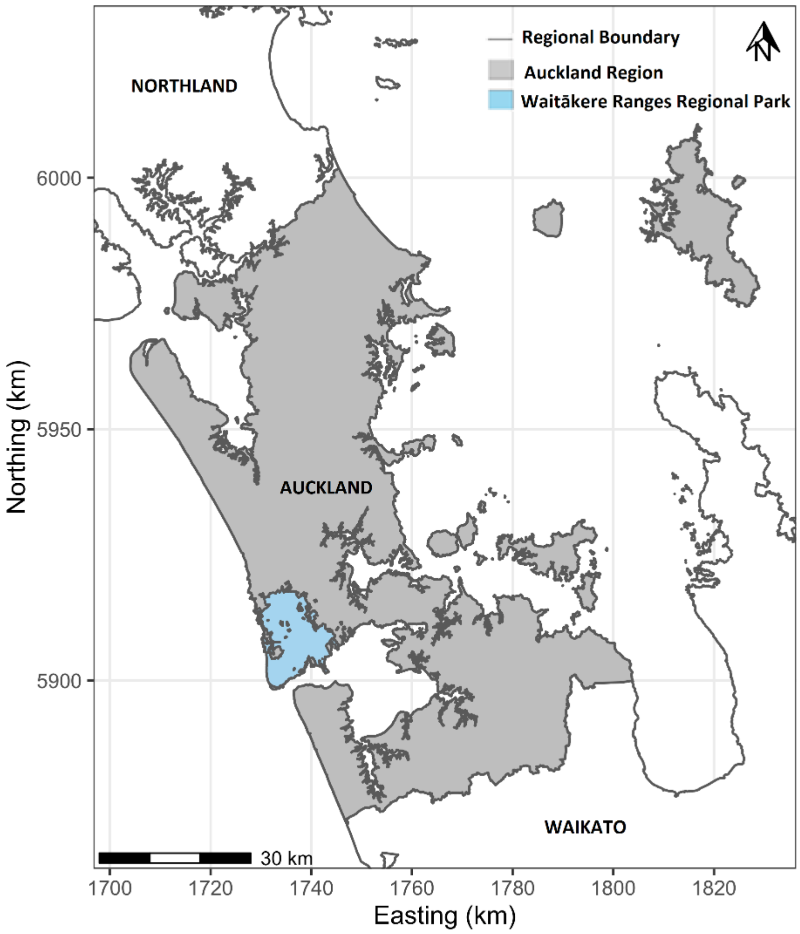


Figure 2-1. Geographical boundary for the study area (coloured in light blue) of the Waitākere Ranges Regional Park and adjacent local parks where this survey was undertaken.

The sample frame included all trees taller than 15 m that could be identified from LiDAR data and classified as kauri. It also included dead and dying trees from both kauri and other species that were indistinguishable from kauri.

Initially tree crowns in the entire Waitākere Ranges >15 m were identified from a canopy height model with 1 m pixel size following Zörner et al. (2018). This method identified 272,295 trees >15 m in the study area. Trees >15 m in the Waitākere Ranges were classified into either "kauri", "dead/dying", or "other" from HiRAMS aerial imagery and LiDAR data (Meiforth, 2020). Training reference data came from photo-interpretation of stereo HiRAMS imagery (systematic cluster sampling) (Meiforth et al., 2019). The method detected 62,998 kauri trees > 15 m and 2,765 dead/dying trees > 15 m in the Waitākere Ranges Regional and local parks where HiRAMS aerial imagery coverage was available. From those classified as "kauri", 1,300 kauri trees > 15 m were sampled randomly for manual validation and confirmed as "kauri" by photointerpretation of HiRAMS imagery (Figure 2-2).

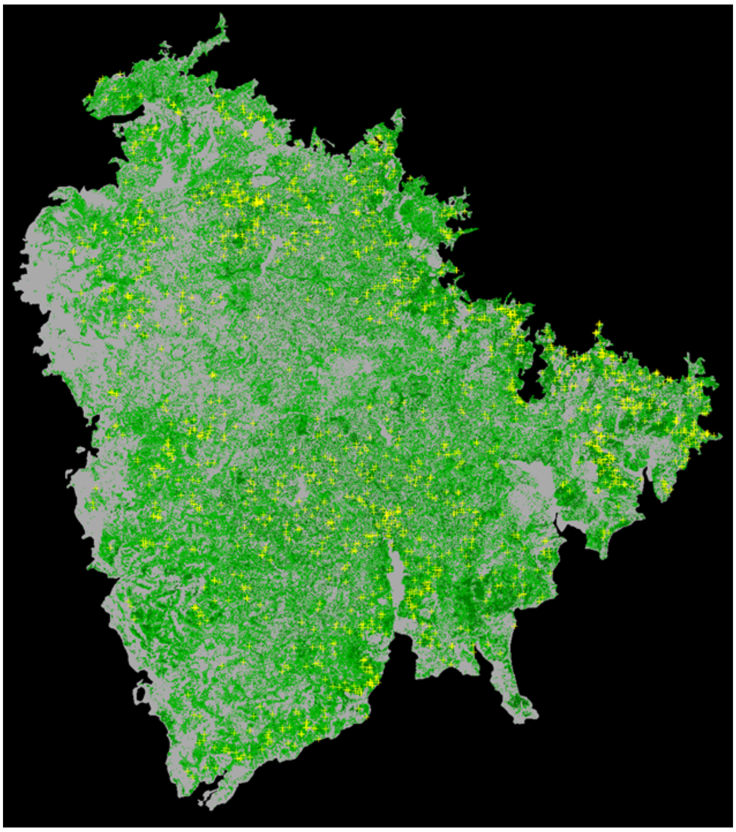


Figure 2-2. Random sample (yellow crosses) of 1300 kauri trees > 15 m tall in the Waitākere Ranges. Dark green is forest >15 m tall. Light green is forest 8-15 m in height. Grey is shrubland less than 8 m in height.

The sample frame GPS coordinates were extracted from a map, based on the central point of large trees (avg. height >20 m) that had been automatically canopy segmented and for the central point of smaller emergent canopy trees >15 m (or small ricker stands where canopy overlap prevents the automatic segmentation of individual crowns) (Figure 2-3).

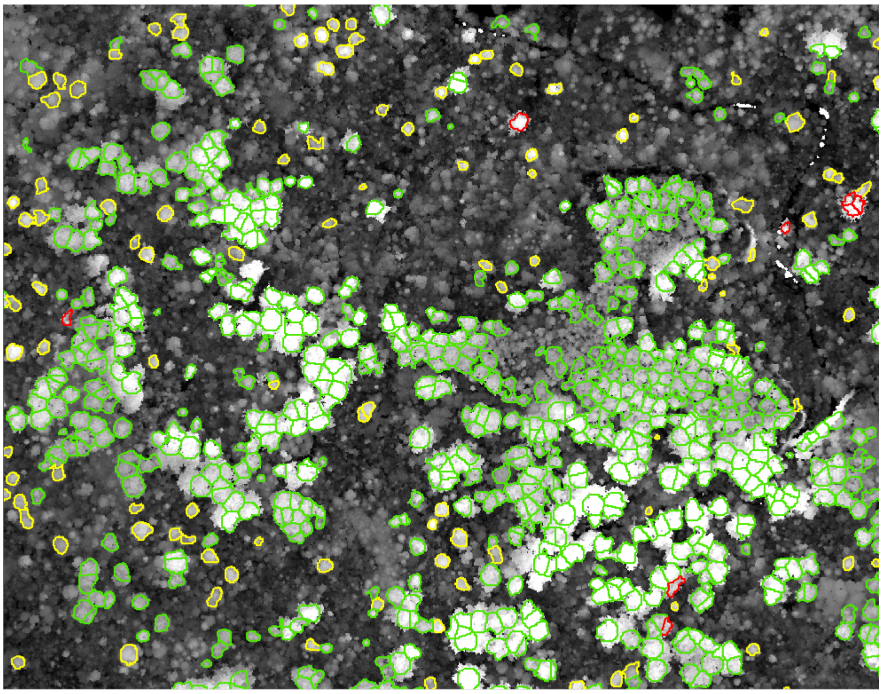


Figure 2-3. Example of large trees >20 m tall, identified by remote sensing in a map of the Cascades area of the Waitākere Ranges. The map has 3 classes: GREEN = kauri with healthy crowns or thinning canopy or thinning with some branch dieback (canopy score 1-3), RED = trees with severe dieback or dead trees (canopy score 4 & 5) and YELLOW = other tree species (canopy score 1-3).

Using aerial image interpretation on reference data of 807 trees >15 m across the Waitākere Ranges, the mapping accuracy (a measure commonly used in remote sensing, meaning the proportion of units correctly classified) was estimated to be 90.2%.

A predicted kauri extent layer for the whole of the Waitākere Ranges combining 68,420 GPS coordinates of predicted kauri trees formed the sampling frame within the study area (Figure 2-5).

The GPS coordinate sites for the sample trees were drawn at random from the sample frame and then confirmed as likely kauri by manual interpretation of imagery. Two separate classifications were performed using stereo image interpretation for training, an object-based LiDAR/HIRAMS combination and an object-based LiDAR/WorldView2 2019 (WV2) combination (where HiRAMS coverage was not complete). Both results had cross-validation scores around 91%. Where the random forests probability result from either classification process showed a strong likelihood of kauri, they were considered for potential sampling. Trees were chosen randomly from that population and checked on screen using a combination of three imagery sources side-by-side on screen, HiRAMS (25 cm) where available, HIRES (8 cm) and pan-sharpened WV2019 (50 cm). The trees in the Worldview2-only area (i.e., where HiRAMS was not available) were more difficult to confirm but were informed by what had been learned in the areas where all three image types were present. In addition, two distinct areas of the western coastal area had cloud obscuring both the HiRAMS and WV2 imagery. Kauri trees were manually identified from high resolution (7.5 cm)

RGB aerial imagery in these areas. There were 5228 trees above 15 m (identified via LiDAR) reviewed in these cloud areas, of which 1899 were classified as kauri. Some of the cloud covered areas did, however, overlap with AISA spectral imagery and therefore AISA methodology described above was used to identify 1244 kauri and 26 dead and dying trees in the overlap areas. The 1899 kauri from manual RGB classification plus the 1244 kauri and 26 dead and dying were combined and randomly sampled at the same rate as the LiDAR/HIRAMS detected trees (detailed numbers are provided in Figure 2-5).

While <15 m tall and non-canopy kauri rickers, saplings and seedlings were excluded from the sample frame due to the limitations of remote sensing, the field monitoring included a brief assessment of kauri in smaller size classes growing near sample trees.

Samples were drawn in a fully randomised process to ensure that all eligible trees had an equal chance of selection. As the remote sensing methodology does not differentiate groups of trees that fit within the kauri dieback canopy classes of dead (but still standing) and dying (canopy classes 5 and 4 respectively), both classes were included in the sample frame and were eligible for sample selection as they are an important component of the baseline prevalence. Canopy classes are defined in Figure 2-7. Dead trees were reported separately from the baseline prevalence estimate. However, as these dying trees may be lost to follow-up for repeat monitoring in the future, a sample size buffer was included to achieve robust sample numbers even in their absence.

Eligibility for inclusion of trees in the sample selection was considered with mana whenua to ensure appropriate cultural consideration was given to trees or areas of cultural significance. Mana whenua were offered the opportunity to review the location of selected trees to exclude any on cultural grounds, if necessary. No selected trees were excluded by mana whenua. Trees inaccessible due to health and safety risks were identified by field survey teams and these were replaced wherever possible with the kauri tree of > 10 cm DBH closest to the original selected tree, regardless of disease status.

The sample size calculation was adjusted to account for potential future loss of trees from the monitoring population. Loss of trees could occur through misclassification as kauri by remote sensing, incomplete field data, tree death, failure to locate tree from the ground survey, landslips, felling for works, accessibility issues or other reasons that may occur over time.

2.3.1.3 Sample size calculations

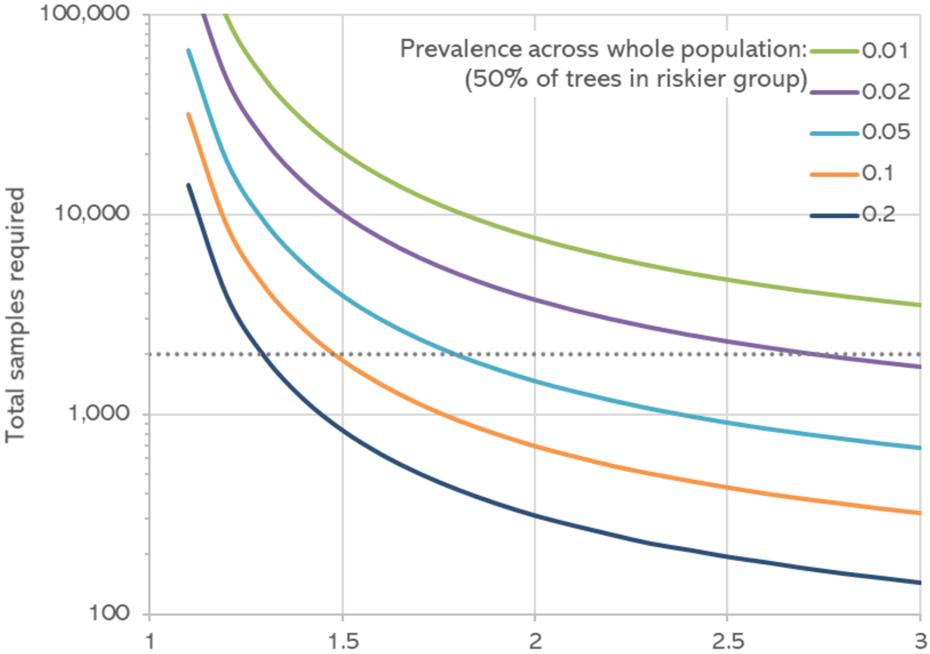
The number of mature kauri over 15 m tall in the study area was estimated by remote sensing to exceed 68,000 trees. Another aim of the study was to collect enough data to estimate the frequency of potential factors associated with the development of kauri dieback to guide future research on understanding such risk factors. A prior conservative estimate of kauri dieback disease prevalence of at least 5-10% (A. Jamieson, Auckland Council, pers. comm.) was used to inform sample size calculations to obtain sufficient risk factor data to measure effects (Lázaro et al., 2020, Thrusfield, 2007). In addition, sufficient random samples needed to be taken to ensure that enough were sampled across the main risk categories of interest, such as: proximity to walking tracks; forest age (mature or regenerating); and tree size (emergent or ricker). Ideally, comparison would occur between equal numbers of trees from high and low risk groups, but this is rarely possible from a completely random sample of trees, so it is important that sufficient samples are taken to have enough statistical power to analyse potential risk factors where the probability of exposure was low (i.e., the risk factor is uncommon in the population).

A suitable sample size minimises Type 1 and Type 2 error rates. A type 1 error occurs when a study declares a factor which is not truly a risk factor as significant. This is primarily guarded against during the statistical analyses by setting the probability that a non-important factor will be identified as a risk factor by chance alone at a suitably low level (usually 5% – which means the results have 95% "confidence") (Kasiulevičius et al., 2006). A type 2 error occurs when a study fails to detect a risk factor which is real, and large enough to be relevant. This is guarded against by setting the "power" of the study to a relatively high level (usually 80%) and this determines the minimum sample size (Dohoo et al., 2009, Kasiulevičius et al., 2006). This means that if a risk factor is sufficiently important to warrant detection, the study has an 80% chance of detecting it.

The final element needed to determine minimum sample size is the magnitude of the risk effect that we wish to detect. This can be characterised by the prevalence ratio, being the prevalence of kauri dieback in the presence of the risk factor relative to that in its absence. Factors that elevate the risk of disease by only a little will be much more difficult to detect (i.e., require a greater number of observations) compared with those where the strength of association is much stronger. A disease prevalence ratio of 2 (i.e., the risk of disease in trees exposed to a specific risk factor is 2 times higher than those that are not exposed to the risk factor) was considered a reasonable magnitude of risk effect for the study to detect.

Given the overall estimated prevalence of kauri dieback, the proportion exposed to a risk factor, the prevalence ratio and the desired Type 1 and Type 2 error levels, the minimum random sample size required was calculated (Fleiss et al., 1980) (Figure 2-4).

(a)



(b)

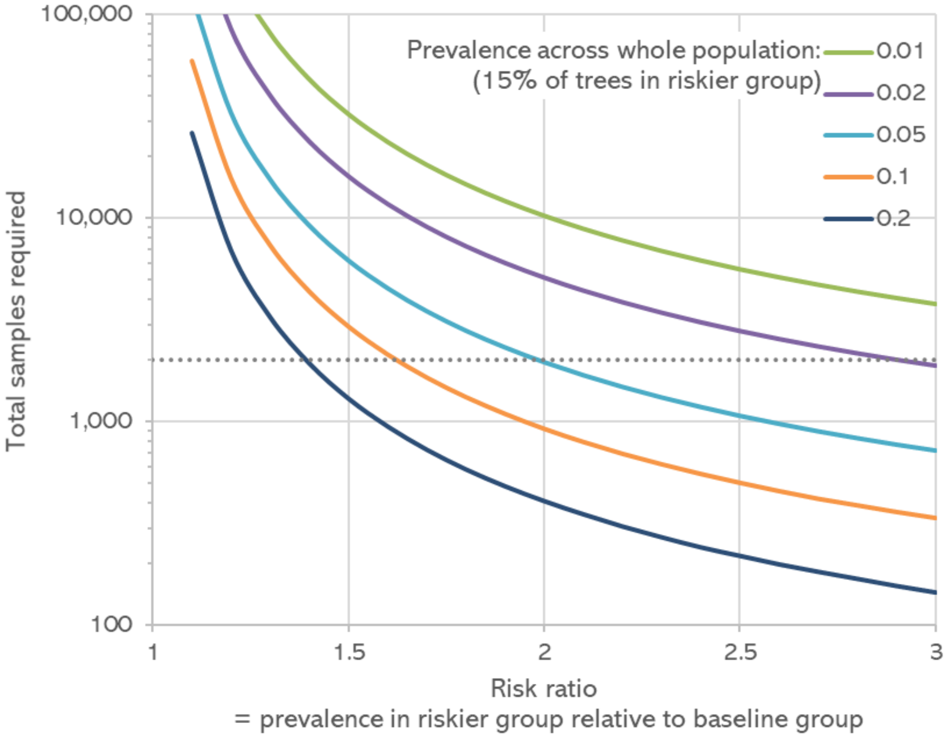


Figure 2-4. Total random samples required to detect a risk factor for kauri dieback disease with 80% power and 95% confidence, depending on the prevalence ratio (strength of the risk effect) and disease prevalence (different lines). In (a) half of all samples are exposed to the risk; in (b) only 15% of samples are exposed. The dotted line shows a proposed sample size of 2000 trees.

Given prior estimates ranging from 5-20% disease prevalence, provided by experts familiar with kauri dieback expression across the study area, a sample of 2000 trees provides a suitable minimum sample size according to the sample size calculations. However, consideration was given to ensuring the proposed sample size accounted for the possibility of misclassification bias arising from imperfect testing (visual assessment of kauri dieback). Misclassification of the disease status of trees means that targeting a prevalence ratio of 2 would require sampling for a prevalence ratio of 1.5 (I. Dohoo, University of Prince Edward Island, Canada, pers. comm.). Based on prior minimum estimates of 5% overall disease prevalence and 15% of trees exposed to risk, this would increase the number of samples needed from around 2000 to around 6000 but reduces to 3000 if the overall disease prevalence is closer to 10%, which is estimated to be more likely by our field experts. Given more sampling provides greater statistical support to assess factors contributing to development of disease in kauri consistent with kauri dieback and accounting for potential missing data, an initial target of 3500 trees was set and protocols to minimise misclassification by having standardised field observations performed by experienced and trained observers were established. As this was at the high end of sample size estimates, a review of sample sizes was undertaken 6 weeks into the survey to determine if it could be reduced. The sample size was subsequently adjusted to a target of 2500, based on our estimated disease prevalence being closer to 10% and predictions of how many samples could be completed before winter to avoid wet and muddy conditions that may risk further pathogen spread (Figure 2-5).

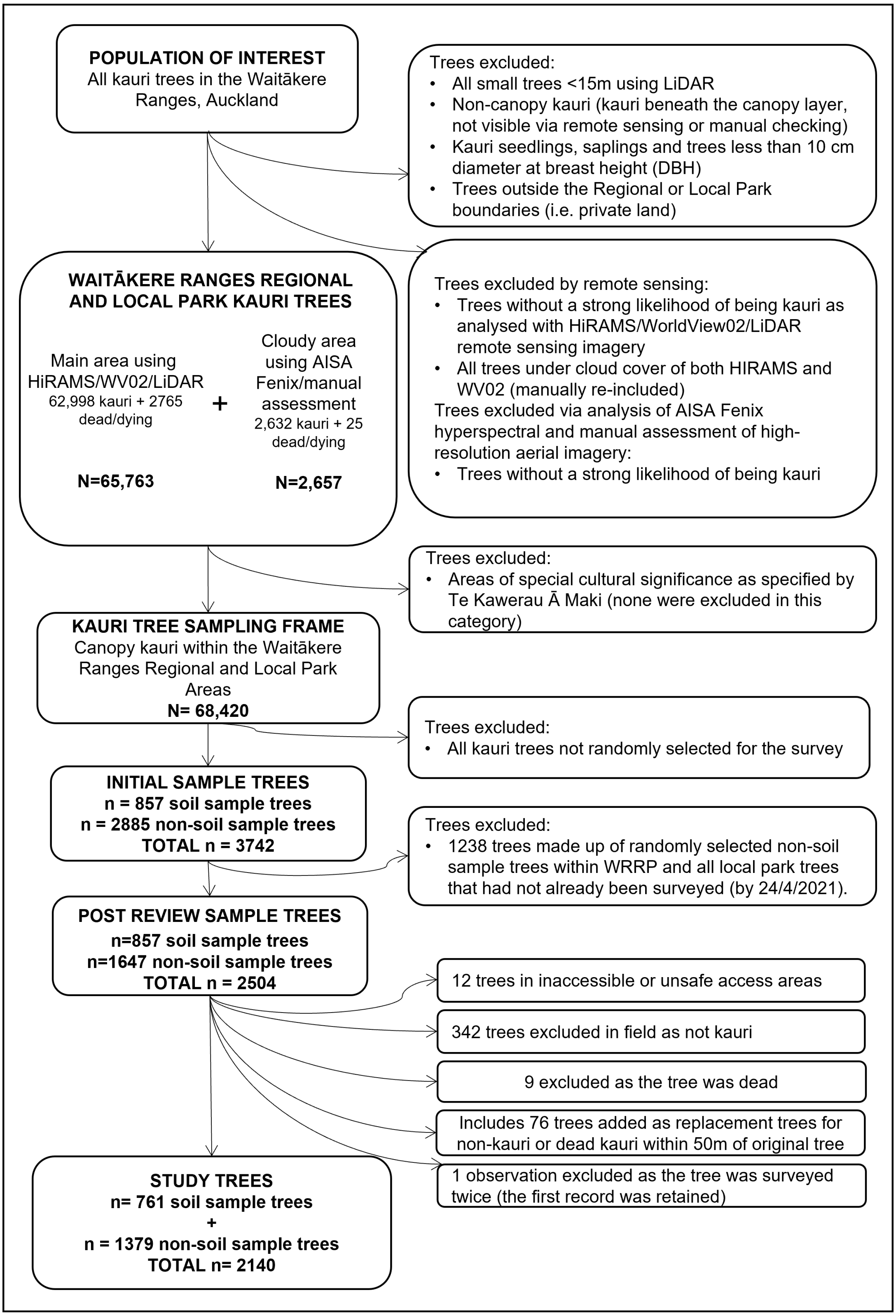


Figure 2-5. Sampling frame diagram showing how trees from the full population of interest were reduced to a sample frame for random selection of trees. It also shows the steps to reduce the sample size halfway through the survey and the final group of trees in the study. WRRP refers to the Waitākere Ranges Regional Park.

2.3.1.4 Identification of risk and impact factors

Variables of interest for ground monitoring were identified through a desktop review of existing ground surveillance variables and special hui (culturally informed workshops), with mana whenua, Auckland Council subject matter experts and a range of external experts in plant pathology and kauri ecosystem health.

The desktop review considered variables from the 2014/15 Auckland Council kauri dieback monitoring form, the National Kauri Dieback Programme (NKDP) monitoring form (unpublished report), Auckland Council kauri dieback objectives, recommended variables for the NKDP phosphite standard operating protocol for field monitoring (unpublished SOP), the Myrtle Rust monitoring form (Sutherland et al., 2019) and a draft kauri dieback causal diagram from Cogger et al. (2016).

Consideration was given to all ecosystem variables that were considered possible for ground monitoring and then a set of representative variables were developed for testing in the monitoring form. These measurements were refined during co-development, pre-testing and peer review by kauri dieback and plant pathology experts.

The final variables are in Appendix A.

2.3.1.5 Pre-testing the monitoring form

The data capture and in-field methodology were further refined during pre-testing prior to the commencement of the survey by a representative from Te Kawerau ā Maki, experienced field team members and ecologists. During pre-testing, each variable was measured, discussed and adjusted if required. The field monitoring form was estimated to take between 15-30 minutes per tree, depending on whether a soil sample was required. Through this process, some variables were identified as being more suitable for detailed plot-based ecological studies than routine surveillance and were not included on the monitoring form.

Adjustments included changes to the standard units of measurement, distance from tree for impact measurements, and changes to levels or options in categorical variables were made to ensure that they covered the range of each variable being observed. The detailed measurement instructions for each variable were updated to ensure clear language and consistency of interpretation of how to undertake the measurement by field survey teams (Appendix A). Hygiene requirements for each measurement were developed (e.g., cleaning of rods used to measure the organic soil layer depth after each tree) and the tikanga (culturally correct way) of undertaking the survey was shared by Te Kawerau ā Maki.

2.3.2 Data collection

Surveys were undertaken by a 16-person team of trained surveyors working in small teams for consistency of assessments and health and safety reasons. Areas estimated to have higher disease prevalence were initially prioritised to increase the exposure to a range of kauri dieback symptoms to allow the methodologies, data capture and consistency across the surveillance team to be tested. Thereafter target areas were scheduled to target different geographical sectors (NW, NE, SW, SE) of the Park each week to minimise the spatial and temporal bias in field assessment and soil collection over the duration of the surveillance programme. Field work was suspended during periods of rainy weather as part of the hygiene precautions.

The survey measurements were collected using a monitoring form loaded into ArcGIS Survey123 on waterproof hand-held tablets. Minor adjustments continued to be made to the electronic survey form to improve functionality during field team training at the start of the survey. Final adjustments were made 6 weeks after the start of the ground monitoring.

The survey was carried out between 8 March 2021 and 8 July 2021. An assessment of progress 6 weeks into the surveillance programme identified the need to rationalise the sample size based on field navigation, observational inputs and logistical challenges. At this point in the programme, 771 trees had been surveyed based on the original design. The revised design retained all previously selected soil sampling trees (857 trees), excluded all local park trees not already sampled and then sub-sampled a further 1647 trees from the originally pre-selected trees for required visual assessment only within the Waitākere Ranges Regional Park (Figure 2-5). Collection of ecological impact variables was reduced to soil-sampled trees only. Because of early site prioritisation for training, statistical advice was sought from expert reviewers and an adjustment to the weighting of samples contributing to the calculation of overall symptomatic kauri prevalence was advised. This was to avoid a bias towards an over-estimate of disease.

Teams were provided with the GPS coordinates of selected trees and used accurate hand-held field GPS units to locate trees. Where multiple kauri trees were present at GPS points, the closest kauri of >10 cm DBH to the GPS coordinate was selected by the ground survey team. Selection of the kauri was based purely on proximity and not on health status.

All monitored trees were tagged with robust aluminium tree tag identifiers to enable future identification and monitoring of the same tree. Tree tags were attached using nails at the uphill point of the tree, or north facing on non-sloping land 1.4 m above the ground as shown in Figure 2-6.

Figure 2-6. Tree tags used for permanent marking of monitored trees.

Measurement guidelines and additional details of all variables collected during the ground survey are detailed in Appendix A.

2.3.2.1 *P. agathidicida* sites

A ***P. agathidicida* site** was defined as a point location where the presence of *P. agathidicida* has been confirmed (from a tree, soil or other substrate), using an approved test at an approved laboratory. This includes historical *P. agathidicida* detections.

A ***P. agathidicida* not detected <u>site</u>** was defined as a point location where the presence of *P. agathidicida* was not detected (from a tree, soil or other substrate), using an approved test at an approved laboratory.

For samples tested in this study, the approved test was soil sampling and bioassay, and the approved laboratory was Plant and Food Research Ltd, Havelock North.

2.3.2.1.1 Soil sampling

Soil samples were collected from all trees that had been randomly pre-selected for soil sampling. The surveyors collected a composite sample comprising four c. 180 g sub-samples from within the root zone of the selected kauri. Soil sub-samples were taken at 90° intervals at 1-2 m from the trunk starting either below the tree tag, or if the tree had a basal or lateral root bleed, below the most active bleed. Soil was taken to a depth of 10-15 cm after scraping away the loose litter layer and contained a mixture of organic material, mineral soil and kauri feeder roots (wherever possible). Surveyors were instructed to optimise the recovery of *P. agathidicida* from the soil, by ensuring that kauri root material, distinguished by its characteristic colour and root nodules, was included in the soil sample. If surface-level roots were absent, surveyors retrieved samples from slightly further than 90°, based on topography of the site and knowledge of where roots are most likely to be located (e.g., away from rocky outcrops or wet depressions) and if there were still no roots at a second point, to collect the root-free sample so as not to disturb the soil any more than necessary. The total volume of the composite sample per tree was required to fill at least ¾ of a medium (220 mm by 250 mm) zip-lock bag and weigh approximately 650-750 g. Trowels were cleared of organic material and soil, washed with methylated spirits and left to dry for a few seconds after each sample before being stored to minimise cross-contamination among trees and meet hygiene requirements.

Samples were stored in backpacks during field collection and taken into storage at the end of each day. The soil samples were stored in a cool (10-25°C), dark place until dispatch. The samples were double-bagged and couriered in boxes overnight to the Plant and Food Research Pathology Laboratory in Havelock North for processing. To ensure they were not left in courier depots over the weekend, they were only sent Monday-Wednesday. Samples were stored at room temperature.

2.3.2.1.2 Soil bioassay

Samples were tested using the standard operating protocol for soil-baiting bioassay which has been optimised to preferentially obtain *P. agathidicida* (Beever et al., 2010). This was followed by morphological identification of resulting cultures following standard laboratory hygiene, isolation and surface sterilisation techniques and specific methods detailed by Beever et al. (2010, Section 7.3, Pg 42.) with a few minor alterations. Approximately 200 mL of soil was dried and then baited in 680 mL circular plastic pottles. Any clods of soil were crumbled with sterile spoons. The soils were moist incubated by spraying with a fine mist of Reverse Osmosis (RO) water until no dry areas were observed, sealed, and incubated for 3 days before being slowly flooded with RO water and baited. Lupin baits were germinated by soaking lupin seed in RO water for 1 h, sowing on moist paper towels sealed in a zip-lock bag and incubated at room temperature for 2 days before use. Himalayan cedar (*Cedrus deodara)* needles were harvested directly from nearby trees targeting dark green mature needles. Four lupin baits were suspended through parafilm on the water surface of the flooded soil samples, while six whole cedar needles were floated directly on the water surface. Samples were further incubated in the light at 20 °C for 2 days at which point bait tissues were removed, rinsed in sterile RO water, soaked in 70% ethanol for 30 s, rinsed again in sterile RO water, blotted dry on paper towels and placed onto P_5ARPH agar plates, sealed and incubated in the dark at 18-20 °C. Plates were inspected at 2-day intervals for *Phytophthora*-like cultures and sub-cultured onto V8 juice agar for 4-10 days and observed periodically for characteristic morphological features under a compound microscope for primary identification of expected species or to genus-level for more cryptic species. Species identities based on morphological features (Scott et al., 2009, Weir et al., 2015) were provided for *P. agathidicida, P.*

cinnamomi and P. multivora, otherwise *Phytophthora* cultures were recorded as *Phytophthora* spp. Where no *Phytophthora* cultures were obtained, samples were given a not-detected result.

Trees with positive *P. agathidicida* soil samples were classified as *P. agathidicida* detected vs *P. agathidicida* not detected and were also classified as *P. agathidicida* sites in accordance with the case definition of Stevenson and Froud (2020) for the calculation of GIS variables.

2.3.2.2 Disease severity variables

Basal or lateral root bleeds consistent with kauri dieback were measured as present, not sure, or absent. Bleed activity was measured following the Horner methodology of whether the gum is sticky (active), soft but not sticky (semi-active) or hard (not active) and relates to whether the tree is still exuding gum.

Basal bleed height was measured to indicate disease severity, in that it indicates how long a tree may have been infected as the pathogen infects via the roots and then travels up the trunk over time, remaining at the leading edge (outer/upper edge) of the lesion. This enables future monitoring to determine how fast lesions develop over time. Where more than one bleed was present on the trunk, then the highest one was assessed.

Percentage of trunk with basal bleeds was measured as an estimate (in deciles) of the base of the trunk that was affected by the basal bleed. This gives a crude indication of the diameter of girdling that has occurred through pathogen infection.

Canopy dieback was quantified based on the Dick and Bellgard (2012) 5-scale canopy health score, with an adjustment to include half-points. This was to provide more differentiation particularly between 2-3 and 3-4 canopy scores which is consistent with more recent disease scoring by Horner et al. (2019b) (Figure 2-7).

Figure 2-7. Canopy symptom class and severity rating: 1) healthy crown with no visible signs of dieback; 2) canopy thinning; 3) thinning and some branch dieback; 4) severe dieback; 5) dead. (Dick & Bellgard 2012) versus the modified half-point scale.

Kauri canopy and bleed symptoms could be caused by other biotic or abiotic factors and therefore the opinion of a trained observer/surveyor is required to determine if the recorded symptoms are consistent with kauri dieback. The kauri dieback field status was assessed by trained surveyors observing all symptoms, the surroundings of the tree and any other potential causes of symptoms. Field status considers whether the observed symptoms were consistent with kauri dieback (to meet the final symptomatic criteria of the case definition). Options were non-symptomatic kauri; kauri with ill-thrift (probably not kauri dieback); kauri with possible kauri dieback symptoms; and kauri with severe kauri dieback symptoms. The field status variable was updated during the sample size review and details of changes are provided in Appendix A.

Canopy colour was assessed from the ground based on all visible canopy and selection was based on what colour the majority of leaves were, rounding down to the healthiest colour if the result was uncertain to enable a change to be detected over time.

Detailed descriptions of disease severity variable measurement are in Appendix A.

2.3.2.3 Symptomatic kauri

The symptomatic kauri prevalence was reported against the Stevenson and Froud (2020) recommended case definition for kauri dieback disease which is updated and summarised in Appendix A. In brief, the case definition for symptomatic vs non-symptomatic trees was met if the symptomatic criteria for kauri dieback (bleeding lesions on the basal trunk, lesions on roots, the presence of canopy thinning, yellowing of the foliage, tree death) were recorded on a kauri tree AND the trained surveyor recorded that these were consistent with possible/probable or severe kauri dieback using the field status assessment variable in the monitoring form (Appendix A).

The surveyors were trained in the variety of basal and lateral root lesion presentations that have been associated with kauri dieback caused by *P. agathidicida.* Trained surveyors only wrote 'Yes' if the bleed was typical of kauri dieback bleeds. Further, they were instructed to select 'Unsure' when they could not determine whether a basal or lateral root bleed was due to kauri dieback or due to other causes (e.g., physical damage). Both 'Yes' and 'Unsure'; were included in the symptomatic criteria component of the algorithm to classify symptomatic kauri. If the field observer stated that symptoms were not consistent with kauri dieback, they were classified as non-symptomatic kauri trees - ill-thrift.

As canopy dieback and colour of foliage were categorical variables, a cut point was selected for each. The level of canopy health score required to be included in the symptomatic criteria was set to a canopy score of 3 or higher after discussion with the field team and I. Horner. This is consistent with being considered symptomatic by Bellgard et al. (2013). Scores from 1-2.5 relate to healthy canopy or some foliage or canopy thinning, whereas scores from 3-5 show signs of branch dieback through to canopy loss and death of the tree. To calculate symptomatic kauri prevalence, trees that scored 5 and were considered dead were excluded. The small number of dead trees are reported separately from the baseline prevalence estimate, as these trees cannot change their disease state in future monitoring, and it is difficult to estimate how long the tree has been dead. The canopy colour score required to be included in the symptomatic kauri group was set to a canopy colour that is more yellow than green and includes yellow-green, copper brown and dead leaves. Trees with a canopy score below 3 or with a canopy colour score below yellow-green were classified as non-symptomatic – healthy or non-symptomatic ill-thrift depending on score and field status. A binary symptomatic kauri and non-symptomatic kauri variable was calculated based on meeting the symptomatic criteria of the case definition, with both symptoms and field status assessed as described in the algorithm in Table 2-1.

In addition, classes within symptomatic kauri were defined by an epidemiological criteria that incorporated soil sample results, where kauri dieback was 'confirmed' for trees at a *P. agathidicida* site (defined in 2.3.2.3), 'probable' for trees within 50 m of a *P. agathidicida* site, and 'suspect' for trees > 50 m away from a *P. agathidicida* site (Stevenson and Froud, 2020).

Table 2-1. Decision algorithm for calculating if the symptomatic criteria were met for the symptomatic kauri trees kauri dieback case definition.

The symptomatic criteria were met if: Basal bleed = 'Yes' or 'Unsure' OR Lateral root bleed = ' Yes' or 'Unsure' OR Canopy score ≥3 OR Canopy colour = 'Yellow-Green' or 'Copper Brown' **AND** Kauri dieback field status (approved observer considers symptoms are consistent with kauri dieback) = 'Kauri with possible kauri dieback symptoms' or 'Kauri with severe kauri dieback symptoms'

2.3.2.4 Risk factors

Risk factors (both causative and protective) that could be measured at the individual tree level, either during ground survey or from existing data sources, were considered for inclusion. They covered host-related variables (e.g., diameter at breast height (DBH)), environmental variables (e.g., aspect, elevation, pig damage) and anthropogenic (human modified) variables (e.g., phosphite treatment, track proximity). The full list of variables and the instructions for data collection are included in Appendix A. Risk maps of GIS collected data are in Appendix G.

2.3.2.5 Ecological impact variables

Several long-term ecosystem outcomes were considered for baseline monitoring and future analysis. Due to the large sample size and relatively short monitoring time available for each sample, plot-based sampling was not considered feasible. However, several ecosystem function variables were included. These variables were measured for all trees selected for soil sampling and were also measured for all trees assessed during the first 6 weeks of the survey. Full details of measurement are provided in Appendix A.

Host-based impact variables included a count of kauri seedlings, saplings, and observations of reproductive structures. Kauri seedling and sapling counts within 5 m radius of monitored trees were assessed and size classes were based on standard plot measures in New Zealand indigenous forests (Hurst and Allen, 2007) of small seedlings (<15 cm); established seedlings (15 cm – 1.35 m) and saplings (>1.35 m tall and <10 cm DBH).

A closest neighbour measure (distance to and DBH) to inform density dependence and succession variables was measured by comparing the DBH of each monitored kauri tree to the nearest neighbouring tree species that had a DBH greater than 10 cm. If the monitored kauri was larger, it was classified as the dominant tree and if it was smaller, it was classified as subdominant.

Forest floor depth (the depth of the soil organic layer) was measured to indicate soil quality and provide a baseline for future potential ecosystem function changes (e.g., forest productivity, nutrient cycle) as described in Appendix A, following the methods of Silvester and Orchard (1999).

A common kauri tree community species checklist (based mostly on tree species) was developed using the University of Auckland Waitākere kauri plot data (unpublished data) and tree species that had the highest mean association with kauri from Wyse et al. (2014) (Table 2-2). These were used to come up with a list of 15 most common tree species within Auckland kauri forests. Presence of trees from this checklist were recorded within 10 m of the monitored tree to provide an indication of species diversity.

Table 2-2. Common kauri forest-associated plant species (scientific and common names) selected for observation during the 2021 Waitākere Ranges survey

Scientific name	Common name
Astelia trinervia	kauri grass
Brachyglottis kirkii	Kirk's tree daisy
Coprosma arborea	māmāngi
Coprosma lucida	shining karamū
Dacrydium cupressinum	rimu
Knightia excelsa	rewarewa
Kunzea robusta	kānuka
Leucopogon fasciculatus	mingimingi
Pseudopanax crassifolius	lancewood
Melicytus macrophyllus	large-leaved māhoe
Myrsine australis	māpou
Nestegis lanceolata	white maire
Olearia rani	heketara
Pectinopitys ferruginea	miro
Phyllocladus trichomanoides	tanekaha
Toronia toru	toru

2.3.3 Data analysis

All data analysis was carried out using R Statistical Software (R Core Team, 2020).

2.3.3.1 Descriptive statistics

A descriptive summary of each variable for the monitored trees was calculated to set a baseline for future monitoring. For variables that were similar, such as disturbance categories of fallen tree and windthrow, these data were combined into new variables for reporting.

Histograms and boxplots were used to visualise data distributions and frequencies. Univariable analyses using two by two tables and the Fisher exact test in the epiR package or separate, unmatched, logistic regression procedures were used to determine associations between ecological impact variables and disease. The level of statistical significance was set at $P \leq 0.05$ and was assessed using the log-likelihood ratio test statistic. Linear regression was used to determine associations between continuous variables and correlations were tested with the Pearson correlation coefficient.

2.3.3.2 Survey design adjustment

A weighted survey design adjustment procedure was used to calculate an adjusted symptomatic tree prevalence following the methodology of Kneipp et al. (2021) based on (Lumley, 2011). The weighting adjustment calculated the estimated symptomatic tree prevalence within stream sub-catchments where monitoring of one or more trees had occurred (n=162, with 59 stream sub-catchments excluded as they did not contain any surveyed trees). The total estimated number of kauri in each stream sub-catchment area was divided by the number of kauri sampled in each stream sub-catchment to return a sampling weight for each sub-catchment. The number of diseased kauri consistent with kauri dieback in each sub-catchment was then multiplied by the sub-catchment weight to return the estimated number of diseased kauri in the sub-catchment. The estimated number of diseased kauri in each sub-catchment area were then summed and divided by the total estimated number of kauri across all sub-catchment areas to return a survey adjusted prevalence estimate.

The adjusted prevalence and confidence intervals of diseased trees were calculated using the contributed epiR (Stevenson et al., 2012) and survey (Lumley, 2012) packages in R. This only applied to the symptomatic kauri prevalence calculation as the *P. agathidicida* prevalence was based on the soil sample trees where no sample size reduction was made.

2.3.3.3 Point pattern maps

Point pattern maps were generated using the geographical boundary for the Waitākere Ranges survey study area to plot two point pattern maps using the R package ggplot2 (Wickham et al., 2016). The first map plotted the point location of all the surveyed kauri trees with points coloured according to their disease status (i.e*.,* symptomatic kauri trees and non-symptomatic (healthy and ill-thrift)) using the case definition. The second map plotted the point location of all the kauri trees from which a soil sample was taken with points coloured according to their *P. agathidicida* detection status.

2.3.3.4 Choropleth maps

The prevalence of symptomatic kauri trees was calculated as the proportion of surveyed trees that were classified as symptomatic while the prevalence of *P. agathidicida* was calculated as the proportion of soil samples in which the pathogen was detected. Crude prevalence estimates were calculated for different natural water drainage sub-catchments or stream sub-catchments and plotted as choropleth maps using the R package ggplot2 (Wickham, 2016). GIS data for sub-catchments were provided by Auckland Council and imported into R using the sf package

(Pebesma, 2018) and plotted using the same projection coordinate system as the point pattern plots (i.e., NZGD2000).

These maps, while useful, are limited by their sensitivity to sub-catchments with a small underlying population at risk. Therefore, to account for the heterogeneous density of kauri trees, a local empirical Bayes (EB) smoothing approach was used to compare the prevalence in each sub-catchment to a local estimate of the mean using the “EBlocal” function in the spdep package (Bivand and Wong, 2018) and plotted as choropleth maps.

2.3.3.5 Relative risk surfaces

In addition to the choropleth maps, four univariate kernel density maps were plotted to show the density of (i) symptomatic kauri trees, (ii) non-symptomatic kauri trees, (iii) *P. agathidicida* detected soil samples and (iv) *P. agathidicida* not detected soil samples using the spatstat package (Baddeley, 2015). The effect of the sample size reduction (after 6 weeks of sampling) on these analyses is to have a slightly higher precision in areas that were sampled early compared to those sampled later, so no adjustment was required. The spatial relative risks for both symptomatic kauri and the presence of *P. agathidicida* after accounting for the varying density of the sampled population were then estimated and plotted. The spatial relative risk represents the ratio of two kernel-estimated densities (i.e., symptomatic vs non-symptomatic and *P. agathidicida* detected vs not detected) after accounting for variability of the underlying population. These can be used to identify regions with significant elevated spatial risk (Davies et al., 2018). The relative risk is estimated on the natural log scale, such that values > 0 depict areas of elevated risk (log(0) = 1, and therefore log relative risk values > 0 equate to relative risks > 1, that is, increased risk). For these plots, an adaptive smoothing technique was used for the density estimates to provide the flexibility of reduced smoothing in densely occupied areas without compromising the stability of the estimate elsewhere. Where detected, tolerance contours delineating statistically significant risk elevations were drawn at a significance level of 0.1 and 0.05. The plots were created using the R package sparr (Davies and Marshall, 2018) using a pilot bandwidth of 609.1, a Gaussian kernel distribution, and an evaluation grid with dimensions of 128 raster cells in the east-west (150 m) and 128 raster cells in the north-south (166 m) directions.

2.4 Results

Ngā hua

2.4.1 Collection of samples

Approximately 4,450 field team hours were spent collecting data for our final dataset which contained 2140 completed observations, including 761 soil sampled trees. This equates to an average of 2 person-hours per observation (1 h per two-person team). This time included training, travel time to the forest, navigating to the tree, sites that were visited but not monitored, 10-30 min of direct observation, hygiene procedures and soil collection (where required).

2.4.2 Host detection

The initial estimate of kauri trees that were >15 m and present in the canopy layer of the study area was 68,420 kauri trees. It is unknown how many kauri shorter than 15 m are within the Waitākere Ranges as they were not easily detectable with remote sensing technologies available in 2020/21.

2.4.2.1 Misclassification of kauri

The positive predictive value for host detection was 86% based on the field data (in that 86% of trees classified as kauri by remote sensing were kauri), which is lower than the estimated mapping accuracy of 90.2%. Not all misclassifications had a record of what the tree species was at the point of interest (n=132), however where these were recorded rimu (n=80) was the most misclassified species, followed by northern rata, rewarewa, kahikatea and exotic pine (detailed results are in Appendix B). Based on an estimated population of 68,420 kauri trees in the study area from remote sensing, and a positive predictive value of 86%, we can estimate that the lower limit of kauri >15 m in height in this population is approximately 58,800 trees. As the diagnostic sensitivity of detecting kauri using the remote sensing methods applied is unknown, it is assumed that the method misses some kauri and therefore the upper population estimate limit is unknown. A cross reference with field data (Meiforth et al., 2019) indicates that the crown segmentation method had difficulties in segmenting crowns with small diameters and declining crowns. Another source of errors was manually distinguishing kauri (especially declining kauri) from other tree species on aerial imagery.

2.4.2.2 Dead or inaccessible kauri

On 21 occasions the tree was located as a kauri, however the survey could not be completed due to accessibility reasons (mostly wasp nests or steep terrain) (n=11), because the tree was dead (n=9) or no recorded reason (n=1). Of the 9 trees that were dead, 5 had been pre-selected for soil sampling, which was instructed to be collected for dead trees, and *P. agathidicida* was isolated from 3 of these 5 samples (consistent with the detection rate reported in the pathogen isolation section).

Where the randomly selected tree was not located or was not suitable for survey, a replacement kauri tree was selected for survey. Only 20% of the sites had a suitable replacement tree present (76 of the 363 sites) and typically this was because there were no kauri trees present within sight of the original point of interest.

2.4.3 Pathogen prevalence

Detection of *P. agathidicida* was assessed at 761 kauri tree sites where soil samples were collected. The baseline pathogen prevalence of *P. agathidicida* detection was 76/761 (10%).

The spatial distribution of *P. agathidicida* from the 761 soil sampled trees showed a greater density of *P. agathidicida* detections in the northern, central-western and southern borders of the study area. There was no detection of *P. agathidicida* in the central interior areas of the Park (Figure 2-8).

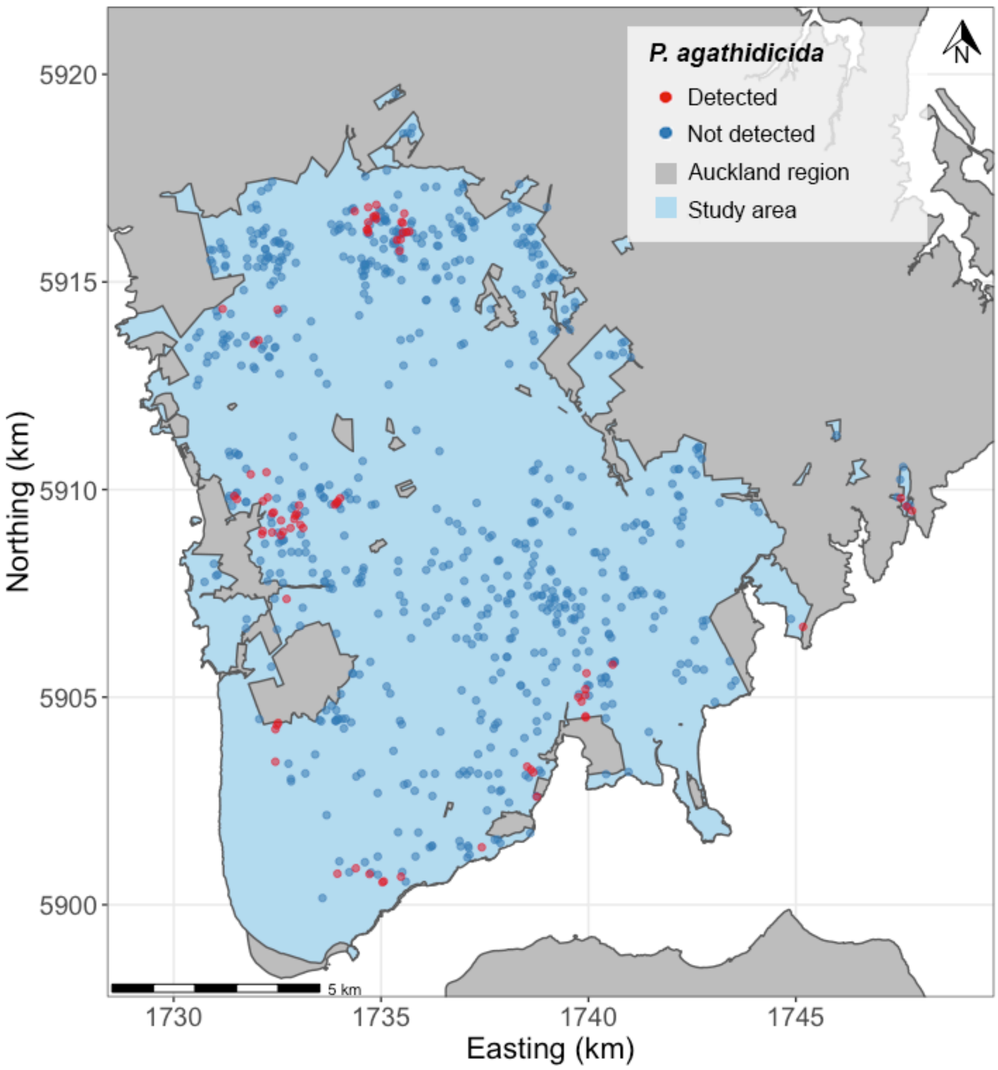


Figure 2-8. Spatial point map showing the location of kauri trees in the study area that had soil samples taken for diagnostic testing (n = 761) with red circles indicating the detection of *P. agathidicida* (n = 76) and blue circles indicating that *P. agathidicida* was not detected (n = 685).

The spatial relative risk surface for *P. agathidicida* detection (i.e., the ratio of positive soil samples to not detected soil samples) shows two regions of elevated detection risk at a significance level of 0.05 in the northern and mid-west areas of the Park (Figure 2-9).

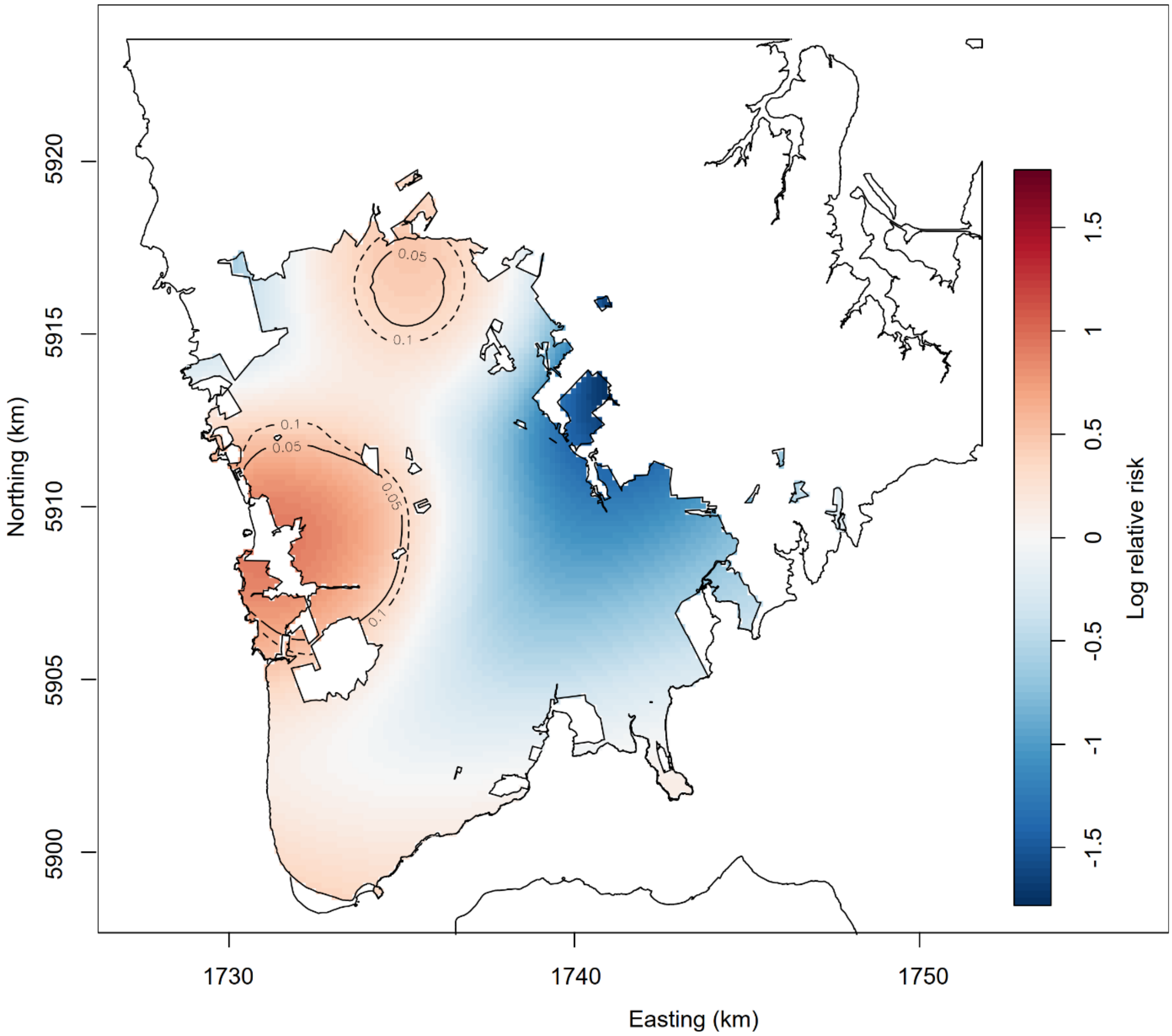


Figure 2-9. A symmetric adaptive bandwidth spatial log-relative risk surfaces map of *P. agathidicida* detection, estimated using kauri trees that had soil samples taken for diagnostic testing (n = 761). The relative risk is estimated on the natural log scale, such that values > 0 depict areas of elevated risk (log(0) = 1, and therefore log relative risk values > 0 equate to relative risks > 1, that is, increased risk). Where detected, tolerance contours delineating statistically significant risk elevations are drawn at significance levels of 0.1 (dashed line) and 0.05 (solid line). White inland spaces indicate areas outside the study area (e.g., Piha village in the central west of the map).

There were 150 small stream sub-catchments included in the study of 761 soil sampled trees. The median number of trees assessed per sub-catchment was 4 trees (25th percentile 2; 75th percentile 7; min. 1 tree; max. 23 trees). A total of 80 stream sub-catchments had 0% *P. agathidicida* prevalence (Figure 2-10).

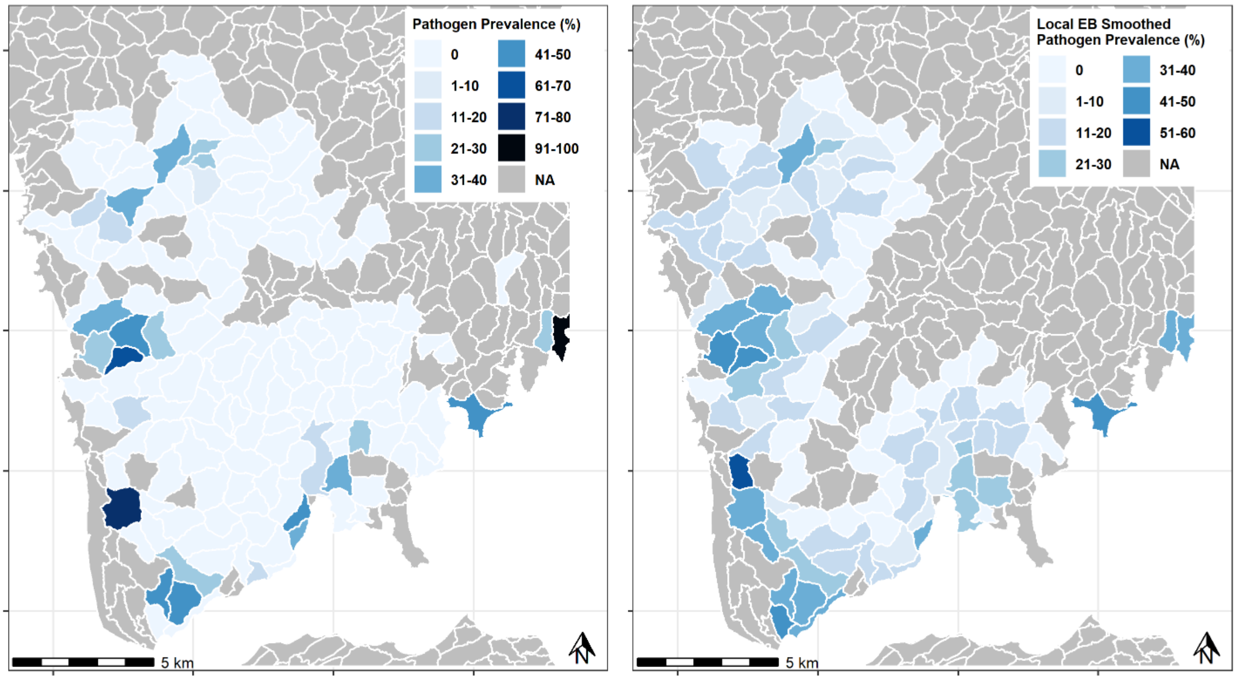


Figure 2-10. Choropleth map showing *P. agathidicida* prevalence (left) and a Bayesian smoothed *P. agathidicida* prevalence (right) calculated using 761 monitored kauri trees in stream sub-catchments. Cells with NA did not have any randomly selected kauri trees within the stream sub-catchment.

Stream sub-catchments provided a useful unit of interest for land management. Empirical local Bayesian smoothing was unable to estimate *P. agathidicida* prevalence in several sub-catchments because of low or zero surrounding sub-catchment prevalence, indicated by the increased number of sub-catchments with missing (NA) values. However, the map still showed a useful visualisation of higher and lower prevalence areas after accounting for differences in the density of kauri trees in each stream sub-catchment.

2.4.4 Symptomatic kauri prevalence

The survey-adjusted symptomatic kauri prevalence across all sites was 16.5% (95% CI: 14.1 to 18.9). This was lower than the overall symptomatic kauri prevalence across all surveyed sites of 19.3% (413/2140 trees) without the weighting adjustment. The symptomatic kauri prevalence within the randomly selected subset of soil sample trees was 17.0% (129/761 trees) which was similar to the adjusted overall symptomatic kauri prevalence of 16.5%. The distribution of symptomatic kauri was wider than the distribution of *P. agathidicida,* which is consistent with a disease which has symptoms that can also be caused by other biotic or abiotic factors. The greatest density of both the symptomatic trees and *P. agathidicida* detections overlap within the northern, central-western and southern coastal borders of the study area (Figure 2-11).

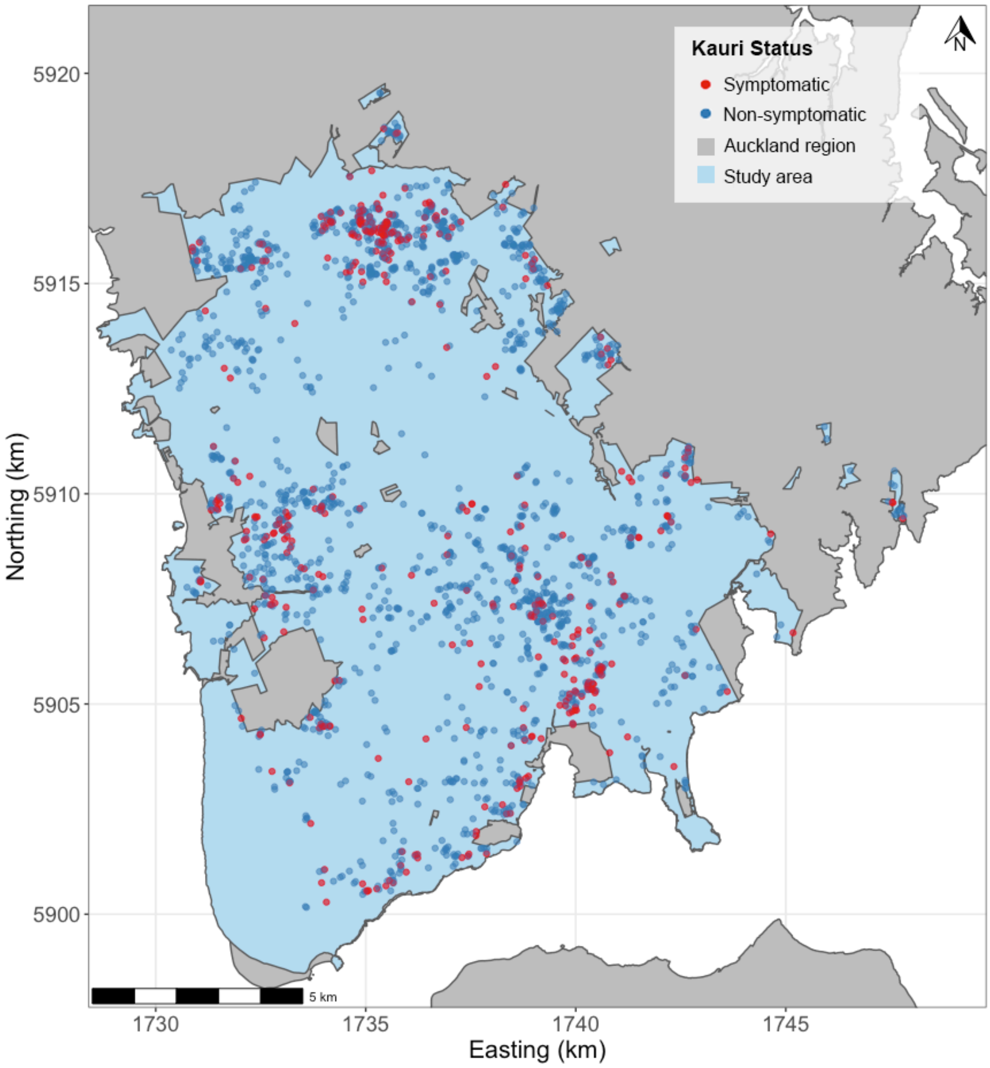


Figure 2-11. Spatial point map showing the location of surveyed kauri trees (n = 2140) with red circles indicating symptomatic kauri (n = 413) and blue circles indicating non-symptomatic kauri (n = 1727) based on the case definition.

The spatial relative risk surface for symptomatic kauri trees consistent with kauri dieback (i.e., the ratio of the density of symptomatic kauri to the density of non-symptomatic trees) shows two regions of significantly elevated symptomatic kauri risk, one in the north which is in the same area as the elevated *P. agathidicida* detection risk and in the south-east of the study area (at a significance level of 0.05) (Figure 2-12). There is an overlap along the western edge of the Park between a trend towards elevated *P. agathidicida* risk and elevated symptomatic kauri risk along with a similar reduced *P. agathidicida* and symptomatic kauri risk trend in the centre of the Park as illustrated by Figure 2-9 and Figure 2-12.

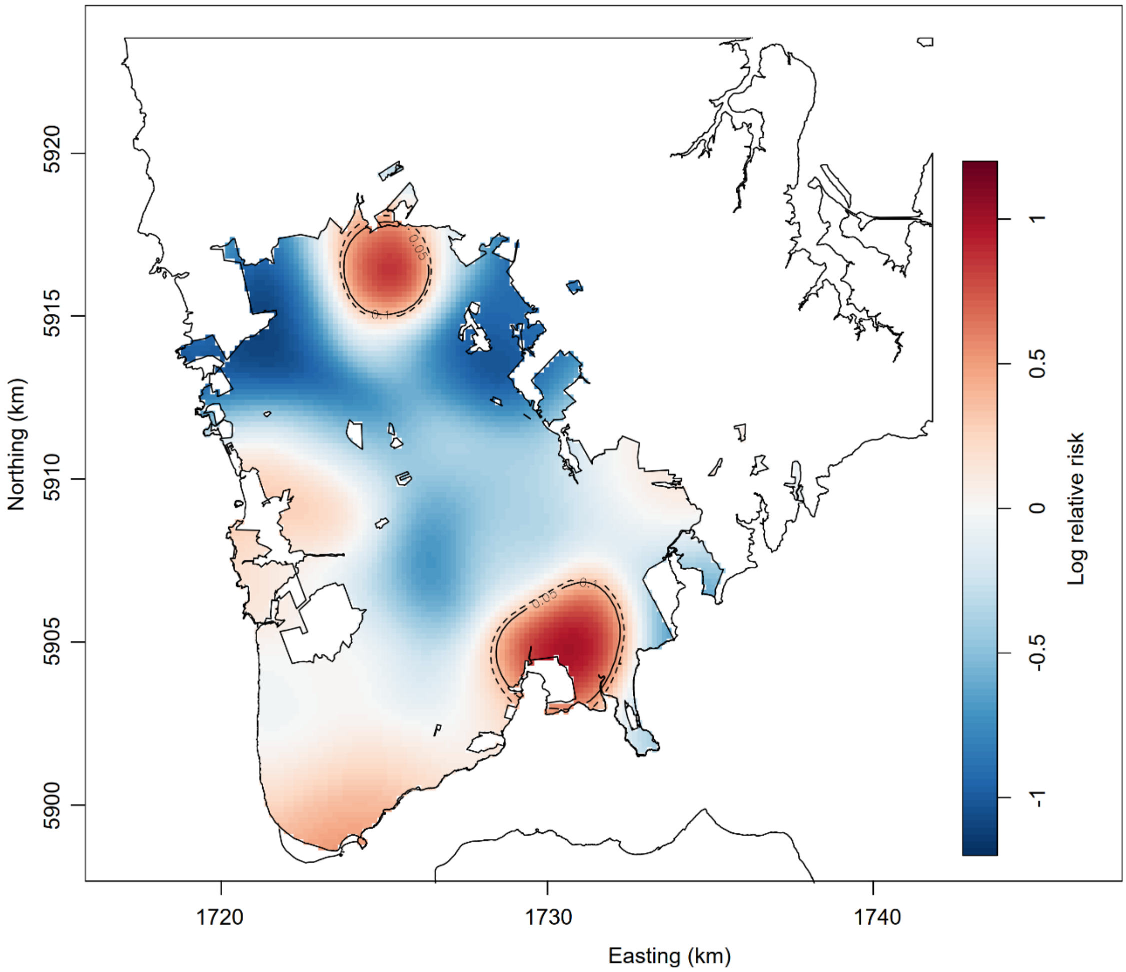


Figure 2-12. Symmetric adaptive relative risk surfaces (Davies et al., 2016) estimated using all the kauri trees included in the study (n = 2140; symptomatic = 413; non-symptomatic = 1727) within the study area. The relative risk is estimated on the natural log scale, such that values > 0 depict areas of elevated risk (log(0) = 1, and therefore log relative risk values > 0 equate to relative risks > 1, that is, increased risk). Where detected, tolerance contours delineating statistically significant risk elevations are drawn at significance levels of 0.05 and 0.1. White inland spaces indicate areas outside the study area (e.g., Piha village in the central west of the map).

We used stream sub-catchment boundaries to assess the proportion of monitored trees within them that were symptomatic. This fine-grained assessment looked at 162 stream sub-catchments. The median number of trees assessed per stream sub-catchment was 7 trees (25th percentile 3; 75th percentile 15; min. 1 tree; max. 82 trees). The median symptomatic kauri prevalence of the stream sub-catchments was 12.5% (25th percentile 0%; 75th percentile 25%). A total of 60 stream sub-catchments had 0% prevalence of symptomatic kauri. The local empirical Bayesian smoothed prevalence was estimated to address unstable raw prevalence estimates because of the small number of trees in some sub-catchments, and these were plotted, alongside the raw prevalence estimates. These plots indicate that symptomatic kauri prevalence was higher in the outer extent of the Park as shown in Figure 2-13. Note that stream sub-catchment areas outside the Waitākere

Ranges Regional Park and those without surveyed kauri are indicated by missing (NA) values in the figure. Additionally, urban areas outside the study boundary, e.g., Piha, which were not surveyed may have higher prevalence. Stream sub-catchments are useful as a way of visualising the data and could be considered as a practical management unit for land managers.

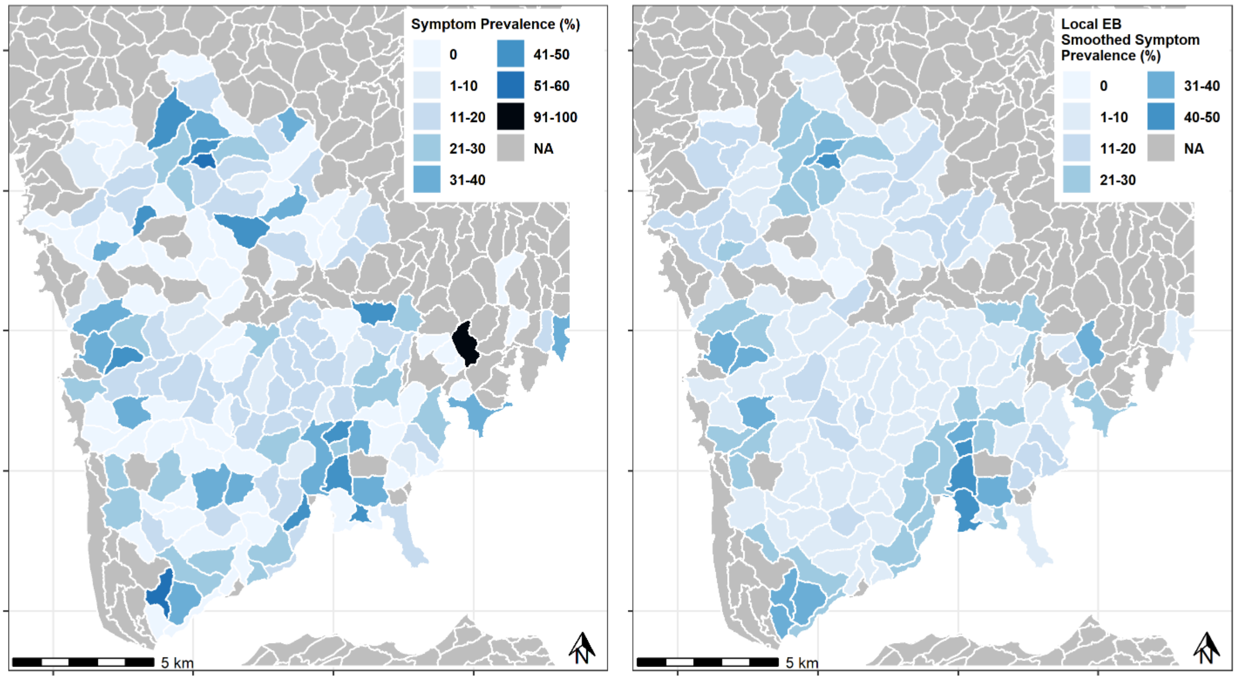


Figure 2-13. Choropleth map showing the spatial distribution of symptomatic kauri prevalence (left) and Bayesian smoothed symptomatic kauri prevalence (right) within discrete stream sub-catchments in the Waitakere Ranges Regional Park. Cells with NA did not have any randomly selected kauri trees within the stream sub-catchment. Note that stream sub-catchment areas include urban areas outside the study boundary e.g., Piha which were not surveyed and may have higher prevalence.

The classification of symptomatic kauri against the different classes of the Stevenson and Froud (2020) case definition (using the modified cut-points for classification) with an epidemiological criteria of 50 m from a *P. agathidicida* detection site (point location of a *P. agathidicida* detected test) is provided in Table 2-3. The large number of suspect cases are likely to contain both trees with kauri dieback and trees with other causes of symptoms. Likewise, the non-symptomatic ill-thrift group will contain a mix of trees with early-stage kauri dieback and trees with other causes of ill-thrift.

Table 2-3. Number of trees that meet the kauri dieback case definition stratified by the different classes within symptomatic kauri and non-symptomatic kauri. Where confirmed is on a *P. agathidicida* site, probable is within 50 m and suspect is >50 m of a *P. agathidicida* site. Note this is the total prevalence of symptomatic kauri, which is higher than the survey adjusted prevalence.

Symptomatic criteria status	**Epidemiological criteria class**	**Number of trees**	**Prevalence**
Symptomatic kauri	Confirmed	30	1.4%
	Probable	52	2.4%
	Suspect	331	15.5%
Non-symptomatic kauri	Ill-thrift	588	27.5%
	Healthy	1139	53.2%

2.4.5 Pathogen isolations

Phytophthora agathidicida was detected in 10% of soil samples (76 sites) (Table 2-4). In contrast, *P. cinnamomi* was detected more widely in 53% (401) of soil sample sites, which were much more spatially distributed across the study area (Figure 2-14). *Phytophthora multivora* was tentatively identified in only two soil samples and is reported, along with all other *Phytophthora* not identified to species level, as *P.* spp. These other *P.* spp. were detected in 10% (79) of soil samples. No *Phytophthora* were detected in 38% of sites (291). In just under half of the *P. agathidicida* detections (49%; 37/76), *P. cinnamomi* was also detected (5% of all sites), and a further 8% (6) of the *P. agathidicida* sites also had *P.* spp. present (0.8% of all sites).

Table 2-4. Detection of *P. agathidicida*, *P. cinnamomi* and *P.* spp. alone or in combination in the culture bioassay tests from 761 sites where soil samples were collected.

***Phytophthora* species detection**	**Percent of sites**	**Number of sites**
P. agathidicida only detected	5%	36
P. cinnamomi only detected	43%	324
P. spp*.* only detected	4%	30
P. agathidicida and *P. cinnamomi*	4%	31
P. agathidicida and *P.* spp.	0.4%	3
P. cinnamomi and *P.* spp.	5%	40
P. agathidicida and *P. cinnamomi* and *P.* spp.	0.8%	6
No *Phytophthora* detected	38%	291
Total sites		**761**

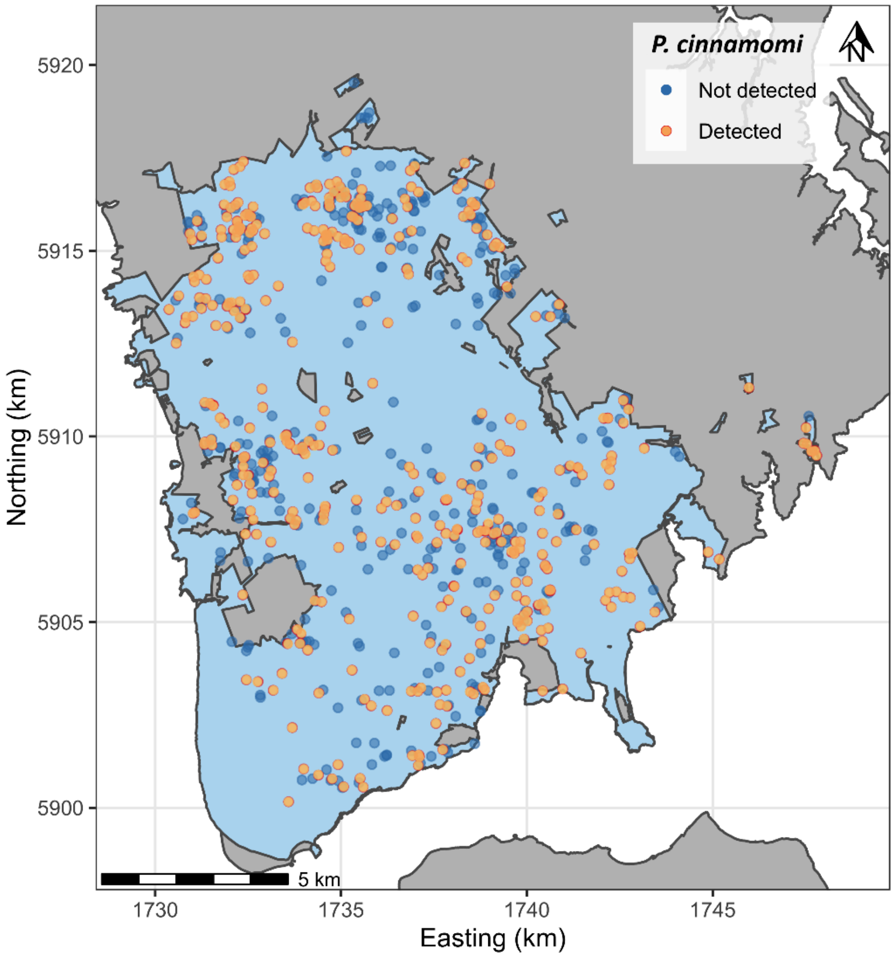


Figure 2-14. Spatial point pattern plot showing the location of kauri trees in the study area that had soil samples taken for diagnostic testing (n = 761) with orange circles indicating the detection of *P. cinnamomi* (n = 401) and blue circles indicating that *P. cinnamomi* was not detected (n =360).

P. agathidicida was detected by the culture bioassay in 23% (30/129) of the soil sampled trees that were assessed as being symptomatic kauri (consistent with kauri dieback), which was significantly ($p<0.001$) more than the 7% of non-symptomatic trees (46/632). Detection of *P. agathidicida* in the non-symptomatic trees were split between 10% in non-symptomatic – unhealthy kauri and 6% in non-symptomatic – healthy kauri (Table 2-5). In contrast, there was no significant difference ($p=0.63$) between *P. cinnamomi* detection in symptomatic tree soil samples 50% (65/129) and non-symptomatic samples 53% (336/632), nor between *P.* spp. detection in symptomatic versus non-symptomatic tree soil samples ($p=0.75$ with 12 versus 67 detections, respectively).

Table 2-5. Detection status of *P. agathidicida* within soil samples taken from 761 trees stratified by whether the trees were symptomatic or non-symptomatic under the case definition for kauri dieback.

Disease classification	*P. agathidicida* detected	*P. agathidicida* not detected	Total	Proportion with *P. agathidicida* detected
Symptomatic kauri trees	30	99	129	23%
Non-symptomatic – ill-thrift	22	198	220	10%
Non-symptomatic – healthy	24	388	412	6%

There were 20 symptomatic kauri trees that were soil sampled and were greater than 2 km from the nearest *P. agathidicida* detection. Of these 20 symptomatic trees, 8 had *P. cinnamomi* detected. In addition, two symptomatic trees that were not selected to be soil sampled with severe basal bleeds and an approved observer assessment of severe kauri dieback were over 3.5 km from the nearest *P. agathidicida* detection.

2.4.6 Severity of symptoms

Every monitored kauri tree (n=2140) was assessed for disease severity symptoms, which included canopy health scores and presence or absence of lesions, along with lesion activity, height and percent of the base affected. These will be used as a baseline for repeated monitoring assessments. Brief results are presented, and detailed results are in Appendix B.

2.4.6.1 Basal lesions

A total of 22% (463) of trees had either basal or lateral root lesions (including those where the observer was unsure). Basal lesions were observed on 19% (n=412) of trees and an additional 2% of trees (n=43) may have had basal bleeds, but the surveyor was unsure. In contrast lateral root bleeds were rare and observed on only 1% of trees (30) with an extra 4 trees where the surveyor was unsure. Of the 34 lateral root bleed trees, 26 were recorded on trees that also had a basal lesion. Basal or lateral root lesions can be caused by *P. agathidicida* or other biophysical injuries.

2.4.6.2 Disease lesion activity

Bleed activity was assessed for all 453 basal bleeds (including unsure bleeds) and 12% (254) had an active or semi-active basal bleed and 9% of trees (199) had an inactive basal bleed. Within the trees with basal bleeds (n=453), there was a higher rate of inactive bleeds in the unsure bleeds group with 56% not active, compared to the basal bleed 'Yes' group with 43% not active, indicating that inactive bleeds were harder to assess. Of the 34 lateral root bleeds, 5 were active, 5 were semi-active and the remaining 24 were not active (including all the unsure bleeds).

Within the trees with basal lesions (including the unsure ones), the height up the tree trunk to the apex of the lesion was measured for 453 trees. Height of lesions were left-skewed with a median of 40 cm (inter-quartile range of 17-103 cm) with a minimum of 0.4 cm and maximum of 600 cm high.

Of the 453 trees with basal lesions, the percent of the basal circumference that was affected by a basal bleed was measured for 449 trees and was strongly left skewed with most within 1-10% of the basal circumference affected. This indicates that the severity of basal bleed symptoms was towards the lower range in most affected trees.

2.4.6.3 Canopy health

The most common canopy score was 1.5 (between healthy crown and foliage thinning) which was observed for 39% of trees (845), followed by a score of 2 (foliage thinning) from 30% of trees (652), and 8% of trees had canopy scores of 3 or higher which was the cut-point for meeting canopy dieback for the symptomatic kauri case definition.

2.4.6.4 Canopy colour

There was a strong relationship between canopy colour and canopy scores with the majority of monitored trees having green canopy 72% (1544), or green-yellow 26% (559); few trees had yellow-green 1.5% (33) or copper-brown canopies 0.09% (2), (Figure 2-15).

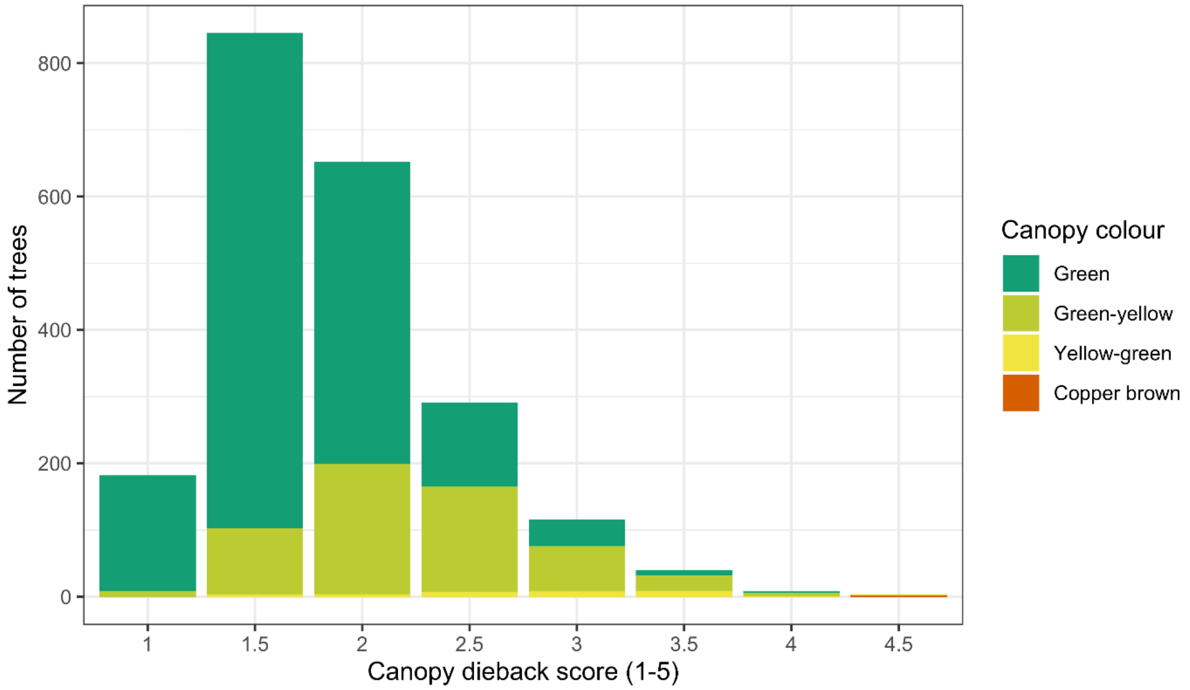


Figure 2-15. Bar chart showing the number of monitored trees within each canopy score class with a score of 1 being healthy and 4 significant dieback, stratified by canopy colour. Dead trees (canopy score of 5) were reported separately.

2.4.7 Host-related factors

The smallest tree that was surveyed had a DBH of 11 cm and the largest was 317 cm DBH. DBH was left skewed with a median DBH of 66 cm (25th percentile 48 cm; 75th percentile 99 cm). Most trees were in the intermediate size class (1388 (150-450 cm)), followed by rickers (527 (<150 cm)) and mature trees (218, (>450 cm)), 7 trees with missing circumference values were excluded. Our results reflect the use of remote sensing to detect our sample frame with taller (larger) canopy trees more likely to be included.

The presence of small (<15 cm) and established (15 cm – 1.35 m) kauri seedlings and saplings (>1.35 m tall and <10 cm DBH) was assessed at 1452 of the kauri monitoring sites. Seedlings and saplings were detected at 55% (794) sites. A total of 14% (199) of sites had all three size classes present along with the surveyed kauri tree. Immature kauri seedlings and saplings' presence or absence was not significantly associated with sites where *P. agathidicida* was detected (p=0.224, Fisher's exact test) (Table 2-6). Likewise immature kauri presence or absence was not significantly associated with sites where either *P. cinnamomi* or *P.* spp. were detected (p=0.380 and p=0.231 respectively) (Table 2-6).

Table 2-6. Counts and percent of sites where kauri seedlings and saplings were present or absent stratified by *Phytophthora* species detection status from 761 soil sampled sites.

***Phytophthora* status**	**Kauri seedlings and saplings**	
	Present	**Absent**
***P. agathidicida* detected**	48 (63%)	28 (37%)
***P. agathidicida* not detected**	380 (55%)	305 (45%)
***P. cinnamomi* detected**	232 (58%)	169 (42%)
***P. cinnamomi* not detected**	196 (54%)	164 (46%)
***P.* spp. detected**	39 (49%)	40 (51%)
***P.* spp. not detected**	389 (57%)	293 (43%)

Further results are in Appendix B.

2.4.8 Anthropogenic risk factors

Detailed results are available in Appendix B.

A total of 65% of the trees in the Waitākere Ranges survey were located within old logging areas with regenerating kauri forest, with just over a fifth (21%) in mature forest stands.

The distance to the nearest track was recorded for all 2140 trees and showed that the median distance from a track was 155 m (25th percentile 64 m; 75th percentile 299 m) and the most remote tree was 1.2 km from a track in any direction. The nearest tree was 0.1 m from a track.

Uphill distance to track is subtly different to the closest track which is based on an “as the crow flies” measurement. This variable is dependent on whether there is a track uphill of the monitored tree within the same sub-catchment of the tree, therefore 245 trees without a track uphill from them had no measurement leaving 1895 observations. Of these the median distance uphill to the closest track was 213 m (25th percentile 100 m; 75th percentile 375 m; min 0.6 m; max 1420 m).

2.4.9 Distance to closest *P. agathidicida* site

The distance to the closest current or historic confirmed *P. agathidicida* site (a point location of a positive *P. agathidicida* test), was recorded for all 2140 trees and showed that the median distance from a *P. agathidicida* site was 842 m (25th percentile 228 m; 75th percentile 1596 m) and the most remote tree was 4.07 km from a confirmed *P. agathidicida* site (Figure 2-16). A total of 1216 of the monitored trees (57%) were within 1 km of a confirmed *P. agathidicida* site.

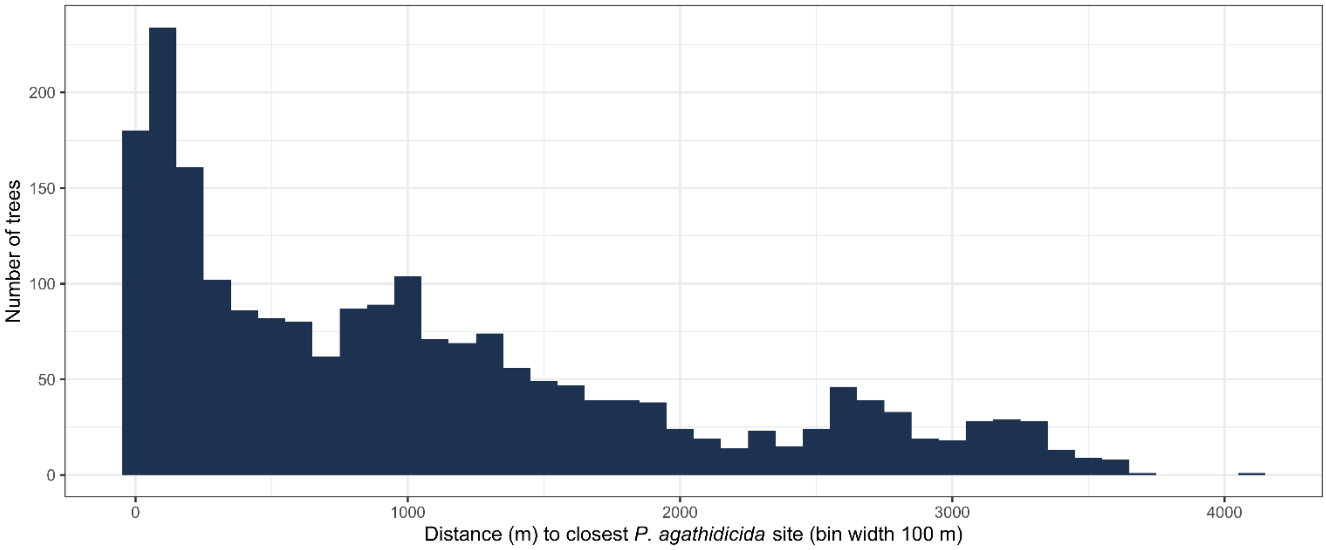


Figure 2-16. Frequency histogram showing the distribution of distance to the closest confirmed *P. agathidicida* site for 2140 monitored trees with a bin width set at 100 m.

2.4.10 Baseline ecological impact factors

2.4.10.1 Closest neighbour species

The closest neighbour tree species and DBH were recorded at 2080 monitoring sites. The DBH of each monitored kauri was compared to the nearest neighbouring tree species to calculate which was the larger and dominant tree. In most sites, the monitored kauri tree was the dominant tree at 91% (1945) of sites with only 9% (182) of the monitored kauri trees being smaller than the neighbouring tree and classified as subdominant. Kauri was both the most common dominant and subdominant neighbouring species at 62% (110/117) and 18% (334/1903) respectively. This is consistent with the remote sensing method used detecting the larger canopy occupying kauri trees. Full details and species are given in Appendix B.

2.4.10.2 Common species

A survey of the presence of kauri-associated plant species was conducted at 1406 sites, including all soil sampling sites and provides a detailed baseline dataset for repeated monitoring (data in Appendix B). Nine species (rewarewa, lancewood, mapou, kauri grass, shining karamu, rimu, mamangi, kanuka, and mingimingi) occurred near to 50% of these monitored kauri.

2.4.10.3 Forest floor depth (soil organic layer)

The forest floor depth was measured for 1452 of the monitored kauri. A mean from the left and right-side forest floor depth measurements per tree was calculated and used as the individual tree forest floor depth value. The population median forest floor depth was 16.5 cm (25th percentile 11.5 cm; 75th percentile 23.5 cm), with a minimum of 1.5 cm and maximum of 69.3 cm. Forest floor depth was positively correlated with DBH ($p<0.001$, Pearson correlation coefficient), with mature trees having much deeper organic layers than smaller ricker trees (Appendix 3). Change in forest floor depth is classified as a potential impact from kauri dieback, rather than a risk factor for kauri dieback, so the associations between symptomatic trees and forest floor depth and *P. agathidicida* and forest floor depth were tested. There was no significant association between forest floor depth and symptomatic kauri trees ($p=0.80$, Mann – Whitney test), however there was a significant association between *P. agathidicida* and forest floor depth ($p<0.001$, Mann – Whitney test) with much shallower depths under trees where *P. agathidicida* was detected with a median of 11.5 cm (25th percentile 7 cm; 75th percentile 15.5 cm) than not detected with a median of 16.5 cm (25th percentile 11 cm; 75th percentile 23.5 cm). This relationship was stratified against size class and shows an interesting pattern of lower organic layer depth where *P. agathidicida* was detected, regardless of kauri size class (Figure 2-17). However, the temporal and therefore causal nature of this relationship cannot be determined from these cross-sectional data.

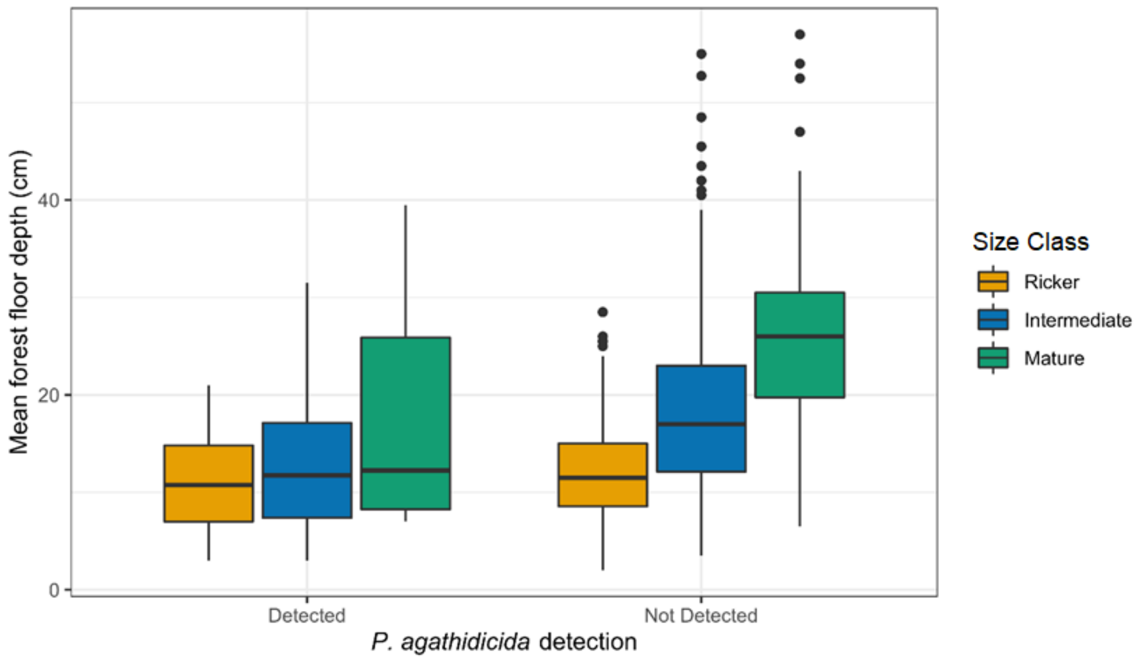


Figure 2-17. Box and whisker plots of mean forest floor depth (cm) per tree where *P. agathidicida* was detected or not detected, stratified by kauri tree size class from 759 monitored trees that were soil sampled and where the size class value was recorded (2 observations missing). Showing the median value (horizontal line), interquartile range (within box), maximum and minimum values (excluding outliers, vertical bars) and outliers (dots) for the population.

2.5 Discussion

Te matapaki

This study had 5 objectives: i) operationalise new remote sensing methods to develop a kauri sample frame; ii) spatially describe the baseline (in 2021) prevalence of *P. agathidicida*; iii) spatially describe the baseline (in 2021) prevalence and severity of symptomatic kauri in the Waitākere Ranges; iv) identify and collect data on key factors that could affect disease risk for hypothesis generation; and v) collect baseline (in 2021) data on ecological factors as possible indicators of ecosystem impacts from kauri dieback. These aims and findings are discussed in order of importance for understanding kauri dieback and kauri health in the Waitākere Ranges.

2.5.1 Prevalence and distribution of *P. agathidicida* and symptomatic kauri

The most important finding of this study was that *P. agathidicida* is currently (2021) in localised areas around the periphery of the Waitākere Ranges parkland, and this is consistent with historical *P. agathidicida* detections (Jamieson et al., 2014, Hill et al., 2017). This distribution is consistent with that of a slow-moving invasive soil-borne pathogen, which aligns with the hypothesis of the likely introduction of *P. agathidicida* from the Asia/Pacific region (Weir et al., 2015). It shows a pattern of point source introduction with initial long-distance (presumably human-assisted) spread into distinct foci, and natural spread (including via short distance vectoring) around those foci. The pattern of spread also indicates that *P. agathidicida* has not yet achieved its full potential range. This contrasts with the observed widespread distribution of *P. cinnamomi,* which is also an introduced pathogen into New Zealand. With a centre of origin in Taiwan, *P. cinnamomi* has spread widely worldwide (Shakya et al., 2021). An important difference of *P. cinnamomi* is its extensive host range, with more than 3000 susceptible hosts worldwide (Socorro Serrano et al., 2019) and at least 25 native species in New Zealand forests (Podger and Newhook, 1971), which likely has contributed to its extensive spread.

Spatially, the relative risk surface showed two regions of elevated *P. agathidicida* detection risk, one in the northern area and one in the mid-west area of the Park. It is possible that *P. agathidicida* has been present and spreading longer, or more efficiently, in these two elevated risk areas, and additional genomic analysis (Winkworth et al., 2021) of these *P. agathidicida* isolates may provide evidence for this observation. *Phytophthora agathidicida* is an Unwanted Organism and any areas where it is present are important for operational management. This study provides evidence to support the continuation of strategies to slow the spread of *P. agathidicida.*

The baseline pathogen prevalence of *P. agathidicida* detection in soils across the forest was 10% of sampled trees. In comparison the symptomatic kauri prevalence was higher at 16.5%. The majority (80.7%) of trees surveyed were either healthy (53.2%) or ill-thrift (27.5%) which is encouraging. The prevalence of symptomatic kauri in this study is not directly comparable to historical surveys as they used different methods.

In contrast to *P. agathidicida* distribution, symptomatic kauri showed a broader spatial distribution. Symptomatic kauri overlapped the same outer extent of the Park where *P. agathidicida* was present, but were also observed across the south-east region, where no *P. agathidicida* detections were made. This disease distribution was consistent with aerial detection of suspected kauri dieback symptoms in 2011 by Jamieson et al. (2014) and with the findings in Hill et al. (2017). The relative risk surface showed an elevated relative risk of disease in the north, which matched that for *P. agathidicida,* and in the south area of the Park, which, while not matching an area of higher relative risk for *P. agathidicida*, did overlap with *P. agathidicida* detection. In addition, the relative risk of disease was elevated, but not significantly, in the mid-west area where there was an elevated relative risk for *P. agathidicida*.

The observation of symptomatic kauri trees consistent with kauri dieback, including some trees with severe symptoms, in the south-east area of the Park in the absence of *P. agathidicida* detection indicates that these symptoms are caused by other abiotic factors such as drought, disturbance or another pathogen such as *P. cinnamomi.* With the number of samples taken in this area it is most likely that *P. agathidicida* is absent. This indicates that the symptomatic criteria of the case definition are over-estimating presence of kauri dieback and detecting symptoms caused by other factors.

It was also interesting that elevated disease risk (in conjunction with *P. agathidicida* detection without an elevated risk) was also present on the southern border of the Park. These trees may have contributing factors that are making them more vulnerable. Beever et al. (2010) state that similar canopy symptoms are observed with natural stand thinning on drought-prone sites and the Waitākere Ranges have recently (2019-2021) experienced a prolonged drought (NIWA, 2022).

Phytophthora cinnamomi has been reported widely in native forest, as it was in this study, and has been associated with ill-thrift of trees, particularly in regenerating stands (Beever et al., 2009, Podger and Newhook, 1971). However, no association between symptomatic kauri and *P. cinnamomi* was found in this study, in that, *P. cinnamomi* was just as common under non-symptomatic trees as symptomatic ones. Johnston et al. (2003) also found no such association in a study in Waipoua forest in Northland. Future research on these monitored trees using DNA-based tests (McDougal et al., 2014, Winkworth et al., 2020) or lesion samples of those with basal bleeds (Beever et al., 2010) may provide evidence to explain what is causing these symptoms away from *P. agathidicida* areas. More detailed examination of specific disease severity symptoms (data collected in this study) in relation to detection of *P. agathidicida* in soils below symptomatic, ill-thrift and healthy trees is also warranted.

Chapters 3 and 4 of this report provide further insight into the other factors that may be contributing to these symptoms and the limitations of the visual assessment and soil test to estimate *P. agathidicida* distribution.

This survey was focused on kauri health and understanding the other factors that could be contributing to driving kauri dieback symptoms in the forest in addition to *P. agathidicida* will be important to inform how best to manage unhealthy kauri trees in conjunction with managing the spread of *P. agathidicida.*

The results in this study showed that while over half of all monitored trees were within 1 km of a current (2021) or historic *P. agathidicida* site, 43% were more than 1 km away, some of which were classified as symptomatic kauri, and this risk factor will be explored further in Chapter 3. Historical detections of *P. agathidicida* follow a similar spatial distribution to those detected during this study (Jamieson et al., 2014, Hill et al., 2017). *Phytophthora* species are known to persist for years in the environment using dormant resting stages (Jung et al., 2018). *Phytophthora agathidicida* has persistent oospores with thickened walls that have been found to remain viable in stored soil for 10 years (Bradshaw et al., 2020) so it would be reasonable to assume that viable *P. agathidicida* remains in areas where it has been previously detected. Pathogen testing to confirm the cause of symptoms when kauri dieback is suspected will be important in the future, particularly in areas where *P. agathidicida* has not been detected.

There was a significant association between observation of symptoms and *P. agathidicida* detections, with 23% of the symptomatic kauri trees that were soil sampled detecting *P. agathidicida.* This relationship is explored further in Chapter 3. In contrast, within the non-symptomatic group there were more detections in the ill-thrift group (10%) than the healthy group (6%), both significantly lower than the symptomatic group. The relatively low recovery rate of *P. agathidicida* from symptomatic trees is consistent with earlier investigations such as McDougal et al. (2014) which found only 31% of soil samples detected *P. agathidicida* from known infected trees and this is investigated further in Chapter 4. It is recommended that DNA-based detection methods are implemented alongside the soil bioassay to improve detection, however they will require diagnostic sensitivity and specificity parameters to be assessed too.

Phytophthora agathidicida detection in the healthy and ill-thrift groups indicates firstly that *P. agathidicida* is present where we cannot visually detect disease, and secondly that the cut-point for canopy score and yellowing may need to be reassessed, particularly within different size classes as there are indications that smaller trees are more likely to show canopy symptoms than lesions (Beever et al., 2010). This is further supported by the discussion among experts when the symptomatic criteria were agreed that there are some unusual developing symptoms that may be associated with *P. agathidicida* infection (Stevenson and Froud, 2020). Future research into the cut-points for the symptomatic criteria will be useful. Repeated cross-sectional monitoring of the same cohort of kauri to observe the development of symptoms over time will provide information that could improve early visual disease detection. Any modifications to the cut-points for the symptomatic criteria, informed by repeated monitoring, would require re-scoring of the baseline trees so that they can be compared using a consistent definition.

The baseline prevalence and spatial distribution results for *P. agathidicida* and for disease in the forest are valuable to help inform which intervention strategy or combined strategies could be applied to different areas of the Waitākere Ranges. To date several kauri dieback interventions have been developed, firstly to control vectoring aimed to stop spread of the pathogen (pest control, hygiene stations, track closures, track upgrades and rāhui (cultural restrictions)), to restrict access to the forest to rebuild forest health (rāhui, weed and pest control and track closure and upgrades) and to treat symptomatic trees to stop decline and tree death (phosphite and rongoā (cultural health measures)). These strategies are applied within a wider decision-making framework which includes consideration of tikanga, natural values, biosecurity risks and impacts, geological and landscape values, historic and cultural heritage values, cumulative effects on any values, recreational values and accessibility, visitor safety, climate change risk and the feasibility and whole-of-life cost. Areas with *P. agathidicida* may require proactive management alongside a continued strategy to stop or slow the spread of *P. agathidicida*. In contrast, where *P. agathidicida* has not been detected, there is now additional evidence to support a protective management strategy to maintain absence through stopping the spread of *P. agathidicida* particularly in areas where *P. agathidicida* was not detected but trees are showing signs of disease, such as the south-east section of the Waitakere Ranges parkland, as these trees may be even more vulnerable.

This study showed that stream sub-catchments are a useful way of visualising data and have potential as a practical land management unit for assigning areas for different kauri health management strategies. These could be used with buffers around stream sub-catchments with high *P. agathidicida* prevalence or no *P. agathidicida*. It is also important to note that estimated prevalence in some stream sub-catchments near urban areas is based only on a small part of the sub-catchment, e.g., around Piha village in the central west. The bush blocks of private land in these areas are known to have kauri dieback disease and positive *P. agathidicida* detections that may be at a higher prevalence than that observed within the Park boundary.

It will be useful to apply the classes within the kauri dieback case definition in the future for operational management. Particularly the distinction between probable (symptomatic and close to known *P. agathidicida* detection sites) and suspect (symptomatic and away from known *P. agathidicida* sites). A probable kauri dieback classification is useful for land managers to effectively fill in the gaps between tested and untested trees that are symptomatic and 'close' to each other. The definition of 'close' is currently 50 m, but this may be too conservative to be practical for land management decisions. An example of use would be in a semi-urban environment where confirmed kauri dieback (*P. agathidicida* positive, symptomatic kauri trees) could confer a probable kauri dieback tree status to neighbouring symptomatic trees, enabling landowners to access treatments without the expense of testing. It also aids management decisions, where land managers may decide to manage suspect trees in a different way to confirmed or probable trees. An example of this would be to consider an area in which there are many suspect symptomatic kauri trees but no positive soil tests. This may indicate that trees have cryptic disease, and the use of specific *P. agathidicida* treatments like phosphite injections may not be beneficial or warranted in that area.

2.5.2 Host detection

The first operational use of new remote sensing methods to identify kauri trees for inclusion in the sample frame and cross-validation of randomly selected trees was successful. Most misclassifications were against other native tree species which were consistent with previous kauri detection research (Meiforth et al., 2019). Tree species that are commonly confused with kauri are species with conical growth forms (in younger stages) like rimu, tanekaha, rewarewa and kahikatea, as well as species with needle like leaves and rough foliage surfaces like tōtara and pine trees (Meiforth et al., 2019). Pine trees were the most common misclassified exotic tree species both within the monitored sample (1% of misclassifications) and during cross-validation of trees randomly selected for inclusion. These exotic trees have been misclassified as kauri due to no prior algorithm training, as exotic trees were absent from the Meiforth et al. (2019) research sites. Some exotic tree misclassifications were easily dealt with during the manual confirmation process that was applied. However, this was time-intensive and future research to train the classifier with more evenly spaced data across the forest area would improve the predicted kauri extent map, particularly for use in areas with higher density of exotic species such as parts of the Hunua Ranges.

The method used to detect the kauri extent map was constrained by tree height, presence in the canopy and remote sensing algorithms that may have biased our host detection estimates. The accuracy to detect kauri trees with remote sensing depends on the size of the crowns, the symptom stages and the type of other tree species present in the forest area. Previous on-ground validation on an independent field reference dataset in three study areas within the Waitākere Ranges showed the detection accuracy using the methods of Meiforth et al. (2019) was dependent on tree size and disease expression. Large non-symptomatic kauri were detected with a high accuracy of 93% while detection of smaller trees was far more limited. For the remote sensing methods applied to this study, host detection accuracy would have been highest for larger non-symptomatic kauri and lowest for small crowns and dead and dying trees (J. Meiforth unpublished results). These underlying host detection accuracy conditions may have biased our sample frame towards larger and healthier trees, which means we may have underestimated the baseline prevalence of symptomatic kauri in the population. Extrapolating the study results to smaller size classes needs to take account of this potential bias. The host detection methodology used in this study can be improved in the future with more manual crown segmentation, especially for dead and dying and small trees, a consistent cloud-free HiRAMS dataset with high sun elevation, and a balanced reference crown set that includes kauri and other tree species in all symptom stages and size classes. In addition, it would be valuable to undertake a diagnostic test performance evaluation on the sensitivity and specificity of the remote sensing method of kauri detection as they are the preferred measures of test validity (Vallee and Cogger, 2019). Unlike accuracy measures, diagnostic sensitivity and specificity do not vary with the prevalence of the hosts in the forest and will not vary between sites with differing densities of kauri trees (Vallee and Cogger, 2019).

The estimated kauri population map layer for trees above 15 m, along with the calculated positive predictive value of 86%, can be used as an estimate to plan management interventions across the forest and to estimate the lower limit of tree numbers within management areas. However, regenerating areas where trees are not yet above 15 m will have been missed from our sample frame and population estimates. Remote sensing improvements to detect smaller kauri could provide additional sample points for repeated monitoring and to assess if disease or pathogen prevalence differs in these populations.

2.5.3 Disease severity

The percent of the tree trunk base affected by a basal bleed is an indication of the extent of girdling of the trunk, which affects the transfer of water and nutrients to the canopy due to vascular dysfunction (Bellgard et al., 2016). The baseline of this severity measure showed that half the trees with basal bleeds covered less than 10% of the trunk and 80% of the trees with basal bleeds covered less than 30% of the trunk. This measure will be important to collect in repeated monitoring to determine if disease is progressing over time. This severity measure indicates that most trees will be good candidates for phosphite treatments, as mildly affected trees have a better response and survival than severely affected trees (Horner and Arnet, 2020, Horner et al., 2019a).

The basal bleed age results show in that 44% of bleeds were not active, which is a similar rate to the untreated controls in the Horner et al. (2015) phosphite trials. There was no apparent trend in lesion activity over the 4-month survey period, but they may change across seasons and more intensive studies such as those planned by the researchers within Ngā Rākau Taketake would be required to understand this. Repeated monitoring of these trees will show if inactive lesions remain inactive over time.

A correlation between baseline disease severity measures such as higher canopy health scores and basal bleed height, percent and activity scores with subsequent tree decline and death from repeated monitoring could be used to predict the extent of tree loss over time. These baseline disease severity measures provide evidence of areas where interventions are best targeted, in that discrete spatial areas with high prevalence of severe symptoms can be prioritised. The data can also be extrapolated (within the limitations described) to estimate the number of affected trees within areas to assist with intervention planning and costing. Ongoing monitoring of disease and severity measures will provide incidence rate data to quantify the efficacy of interventions. In addition, analysis of kauri dieback symptoms and severity classes to validate remote sensing stress detection methods for the future would assist in identifying stands of trees for management interventions.

2.5.4 Frequency of potential risk factors

Our study aimed to identify and collect data for factors that could contribute to or protect from disease for hypothesis generation (Chapter 3). Once associations between risk factors and disease are understood, the frequency and distribution of potential risk factors (detailed in Appendix B) will enable land managers to calculate a population estimate of trees with specific characteristics within the forest and to spatially apply risk maps based on their distribution. For example, if mature trees have a higher disease prevalence, a population estimate of the proportion of mature kauri in the population could be estimated, e.g., 10% of 68,000 trees would be approximately 6800 trees with 60% located within mature forest stands. These estimates can then be used to plan and budget for protection measures. Further research into host detection of smaller size class kauri using remote sensing will be important to accurately estimate trees at risk for planning.

2.5.5 Baseline ecological impacts

One of the key findings from the collection of baseline data was the observation of kauri seedlings and saplings at 55% of monitored sites. These seedlings and sapling observations were aimed at monitoring if recruitment was occurring, especially under symptomatic trees. It also set a baseline to measure if disease may be reducing reproduction even when it is not killing the trees. *Phytophthora agathidicida* is thought to be particularly lethal to seedlings from glasshouse trials (Gadgil, 1974, Horner and Hough, 2013, Horner and Hough, 2011), however, kauri seedling and sapling presence was not significantly associated with *P. agathidicida* (or with *P. cinnamomi*) detection. These observations provide evidence that kauri can germinate and grow in association with *P. agathidicida.* However, the survival rate of these seedlings is unknown and multiple factors will influence their survival, including different environmental conditions under diseased compared to healthy kauri stands. Future monitoring will be needed to see if that extends to kauri regeneration and replacement of lost trees at a rate sufficient to maintain a kauri dominant forest.

A consideration in interpretation of this measurement is the potentially confounding effects that i) *P. agathidicida* may be causing canopy loss, leading to increased light favouring seedling germination and growth; ii) seedling and sapling roots may not extend deep enough into the soil layer to encounter *P. agathidicida* zoospores; and iii) very healthy trees may not have any seedlings nearby due to the Janzen-Connell effect (Packer and Clay, 2000), which, in brief, implies that seedling survival is greatest further from the parent. However, how well the Janzen-Connell effect is supported in temperate species has been questioned (Hyatt et al., 2003). Further analysis of the presence of kauri seedlings and saplings with different soil characteristics and tree health/disease severity would be a valuable extension of this dataset. These monitored sites could also potentially be used to select sites to further investigate *P. agathidicida* virulence and host resistance under natural conditions to augment *in vitro* research where some variability in pathogen virulence and host susceptibility has been observed (Herewini et al., 2018).

The results showed that kauri was the dominant tree in 91% of sites surveyed, which is consistent with a kauri-dominated forest. However, our host population at risk detection method, where only trees greater than 15 m high and visible in the canopy were eligible for selection to be monitored, is likely to have biased us towards dominant trees as they were easier to detect using remote sensing.

P. agathidicida mostly infects the distal feeder and secondary roots of kauri within the upper 20 cm of soil layers (Bellgard et al., 2013). The difference in forest floor depth between sites with and without *P. agathidicida* detected was an interesting finding, especially as there was no relationship between symptomatic trees and forest floor depth. Because of the cross-sectional nature of this baseline study, it is not possible to determine the direction of a causal link between *P. agathidicida* presence and a reduced forest floor depth. In that is, a shallower organic layer may be more hospitable to *P. agathidicida* than deeper organic layers or that *P. agathidicida* may be causing shallower organic soil layers through slow or no tree growth causing a reduction in tree litter input (Wyse et al., 2014). Higher microbial populations may be present in deeper organic layers, which may be antagonistic to *P. agathidicida* (Bradshaw et al., 2020). It is possible that on sites with restricted forest floor depths there is a higher concentration of both kauri roots and *P. agathidicida* which would increase the probability of isolation from the soil bioassay. Future monitoring of this kauri population within the Waitākere Ranges Regional Park may explain a causal link between *P. agathidicida* and shallow organic layers. The potential impact of a reduction in forest floor depth, if that is proven to be caused by *P. agathidicida*, could lead to loss of kauri-associated species (Bradshaw et al., 2020), a change in the composition of the forest (Wyse et al., 2014) and will have implications for the carbon and nutrient cycling within the forest (Schwendenmann and Michalzik, 2019). The addition of plot surveys in combination with repeated monitoring would be valuable for understanding these ecological processes.

2.6 Conclusion

Te whakatau

This study found *P. agathidicida* in localised areas within the outer periphery of the Waitākere Ranges parkland, which suggests that *P. agathidicida* has not yet achieved its full potential range and provides evidence to support the continuation of strategies to slow or stop the spread of *P. agathidicida.*

Elevated disease risk overlapped areas where *P. agathidicida* was detected.

Kauri trees with visible symptoms similar to those of kauri dieback were found scattered throughout most areas of the Park, including in areas where *P. agathidicida* was not detected, indicating that other factors can cause poor health in kauri, which need to be identified.

The description of symptomatic kauri and of *P. agathidicida* prevalence in space and time can be used to inform different forest health strategies within a wider decision framework.

The study also showed that new remote sensing techniques to detect hosts could be operationalised and were a practical, accurate and efficient method to build a sample frame for a large-scale native forest survey of a canopy species.

The dataset collected during this study provides a taonga (valued treasure) for future study to explore different variables and develop capability and capacity in researching environmental biosecurity epidemics. The study was designed to provide robust data and a consistent cohort of monitored trees to be remeasured over time using a repeated cross-sectional study design.

It also provides the baseline for ongoing monitoring of a small sub-set of ecological impacts to detect changes in forest composition over time. These results will be used to inform the ongoing and adaptive management of kauri dieback in the Waitākere Ranges and across Tāmaki Makaurau. References are provided at the end of the report.

Chapter 3

Multivariable analysis of risk factors associated with symptomatic kauri and detection of *P. agathidicida* in the Waitākere Ranges

Te Mātatini o te tātari i ngā whakaputanga tūraru e hāngai ana ki kauri e whai tohumate ana, i te kitenga hoki o te puruheka patu kauri i Te Wao Nui ā Tiriwa

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3.1 Abstract
Te whakatūporotanga

The aims of this study were to generate and test hypotheses about the associations of environmental, host and pathogen-related risk factors with i) symptoms in kauri consistent with kauri dieback and ii) the presence of *Phytophthora agathidicida*, the causal agent of kauri dieback.

Multivariable logistic regression models and spatial modelling were used to investigate symptomatic kauri and detection of *P. agathidicida* in separate models from data collected from a cross-sectional survey and GIS-generated landscape variables. Data from 2140 randomly selected kauri were used to investigate the risk factors associated with the binary outcome of symptomatic vs non-symptomatic kauri, based on the symptomatic criteria of the case definition for kauri dieback disease (Chapter 2). Data from a subset of 761 kauri with soil samples analysed for *P. agathidicida* using a soil bioassay were used to investigate the risk factors associated with a *P. agathidicida* detection vs not detected.

This study identified three factors that were significantly associated with presence of symptomatic kauri and four factors that were significantly associated with presence of *P. agathidicida* in spatial models.

For the symptomatic kauri model, the strongest association was between symptomatic kauri and proximity to *P. agathidicida* sites (point locations of *P. agathidicida* detections). Prevalence was highest close to *P. agathidicida* sites and reduced with distance away from *P. agathidicida* sites. Symptomatic kauri prevalence was also higher closer to historic timber sites (timber mills and saw pits) (reducing with distance away from them) and increased with increasing tree size (DBH).

For the *P. agathidicida* model, pathogen prevalence was higher with decreasing elevation, and with decreasing distance from historic timber sites and from the coastline. It was also higher as the distance to the closest neighbouring tree decreased. The results generated hypotheses for further investigation into understanding or managing these relationships, such as managing the distribution of *P. agathidicida.* In addition, our results found several associations of note (where the associations had wider credible intervals) between symptomatic kauri prevalence and distance to the coast, neighbouring tree distance, and distance to the closest uphill track; and *P. agathidicida* prevalence and distance to the closest track and presence of tanekaha (*Phyllocladus trichomanoides).* These require further investigation.

Both modelled outcomes had potential misclassification bias, in that effect sizes for risk factors may have been pushed towards no effect (towards the null hypothesis). Misclassification bias may have been present due to the low sensitivity of the diagnostic test for *P. agathidicida*, missing true positives, and the potential misclassification of symptomatic trees as non-symptomatic, using a conservative symptom-based cut-point.

These results can be used to prioritise future surveillance and research, as well as inform potential management interventions to reduce the spread of *P. agathidicida* and development of disease through appropriate biosecurity and ecosystem protection measures.

3.2 Introduction

Te whakataki

There is a strong relationship between *P. agathidicida* and kauri dieback disease, with both pathogenicity and Koch's postulates having been demonstrated (Bellgard et al., 2016, Gadgil, 1974). The presence of *P. agathidicida* is necessary to cause kauri dieback but a pathogen is rarely sufficient to cause disease in the absence of other factors, in that other component causes such as a vulnerable host and particular environmental conditions (e.g., drought, rainfall, disturbances) are required for disease to develop (Rothman and Greenland, 2005, Martin, 2008). In addition, it is uncertain how many kauri with symptoms that look like kauri dieback observed in the forest are caused by *P. agathidicida* compared to other abiotic or biotic causes. All potential causes of disease and tree death are important when the aim is a healthy forest.

An observational study design was used to identify and collect risk factors for symptomatic vs non-symptomatic kauri and for *P. agathidicida* detection vs non-detection as separate outcomes as described in Chapter 2. These potential risk factors will be assessed using an analytical cross-sectional study. The cross-sectional study design is a type of observational study, which is a commonly applied in human and animal health investigations, with only recent application in plant health (Rothman et al., 2008, Dohoo et al., 2009, Froud and Cogger, 2015). This is a novel approach for investigating kauri dieback, which has previously followed a pathogen-centric approach (Bradshaw et al., 2020). A key difference between observational and experimental studies is that extraneous factors, called confounders, are not able to be managed through randomisation. These are therefore typically controlled for during the analysis stage of an investigation using multivariable statistical models (Dohoo et al. 2009e). Cross-sectional studies have robust guidelines for their application (Sargeant et al., 2016, O'Connor et al., 2016, Vandenbroucke et al., 2007).

The type of observational study design selected depends on the research question. Ideally, a longitudinal study such as a cohort study would be used to obtain the strongest evidence for a causal link between risk factors and disease. However, when disease is already widely distributed, as in the New Zealand kauri dieback outbreak (Hill et al., 2017), a cross-sectional study is a more appropriate approach, because it collects outcome and risk factor data at a single point in time with the aim of identifying factors that are associated with an increased or decreased prevalence of the outcome. In this case symptomatic kauri or *P. agathidicida* detection. The risk factors identified in a well-designed cross-sectional study may not be causal, however, as long as results are interpreted with caution around temporality (in that a cause precedes an outcome) and potential confounding, they should be interpreted as factors that contribute significantly to an increased or decreased prevalence of disease (Maes et al. 2001). Results can be used to prioritise which factors should be investigated further, using either experimental studies or more comprehensive observational studies (e.g., a cohort study or case-control study) to determine causal relationships (Mann 2003).

This study investigated a range of environmental, anthropogenic, host and pathogen-related risk factors to generate and test hypotheses on associations with i) symptoms in kauri consistent with kauri dieback and ii) *P. agathidicida* detected in soil beneath kauri in Te Wao Nui ā Tiriwa / the Waitākere Ranges parkland. The intended outcome of this study is to inform kauri dieback control measures to reduce the presence of *P. agathidicida* and the development of disease symptoms in kauri to enhance kauri health.

3.3 Methods

Ngā tikanga

3.3.1 Dataset

Trees were randomly selected from a sample frame of trees classified as kauri using remote sensing, based on the Meiforth et al. (2020) methodology and detailed in Chapter 2. A total of 2140 randomly selected trees were surveyed and a subset of 761 trees were soil sampled for *P. agathidicida*.

3.3.2 Outcome variables

Each surveyed tree was visually assessed and classified as symptomatic or non-symptomatic (which included healthy and ill-thrift trees) as described in Chapter 2. Dead trees were excluded from the study.

Soil samples were collected around the base of pre-selected trees at the time of visual assessment and tested using the soil sampling bioassay as described in Chapter 2 and classified as *P. agathidicida* detected or not detected.

3.3.3 Initial risk factor variable selection

Individual kauri tree health factors were identified through two hui involving kauri ecosystem health experts from mana whenua and research organisations.

For each tree, potential risk factor variables were either collected during the ground-based survey (Chapter 2, Appendix A) or derived by later Geographic Information System (GIS) analyses based on existing Auckland Council or national datasets (Chapter 2, Appendix A, Appendix G). Among the aggregated data, over 100 variables (Appendix C) were collected which were potentially associated with the presence of symptomatic kauri or detection of *P. agathidicida*, the outcome variables of this study.

Using the variables identified as potential risk factors, a univariable screening test (simple logistic regression) for each binary (yes/no) outcome (e.g., symptomatic kauri vs non-symptomatic kauri and *P. agathidicida* detected vs *P. agathidicida* not detected) was conducted. Based on the results of the univariable screening test (Appendix C), all variables with a P-value < 0.2 were identified for either outcome for further consideration. Among these, any variables that either (1) contained a large number of missing values (except the variable of the distance to the closest uphill track, which was a variable of interest), or (2) was an (in)direct result of the outcome variables were discarded as they were not on the causal pathway for symptomatic kauri or *P. agathidicida*. Once the variables were identified, any plausible correlations between the variables were manually assessed in turn to select the most biologically meaningful variable among a group of highly correlated ones (e.g., correlated groups of common species) to be included in the multivariable models. A Bayesian network analysis was further conducted to investigate any additional correlations that were missed during the manual examination (Lewis and McCormick, 2012). Based on the correlation between variables, causal path models were constructed for each outcome to aid in variable selection for modelling (Figure 3-2 and Figure 3-3). Finally, the correlations between the variables in the path models were differentiated as either a potential biological confounding effect or simple correlation. The univariable screening and Bayesian network analysis were conducted in R using “glm” and “bnlearn” packages (R Core Team, 2020). The casual path models were developed using the “DAGitty” programme (Textor et al., 2016).

3.3.4 Non-spatial multivariable models

The variables from the screening and initial selection process were investigated using frequentist-based, non-spatial multivariable logistic regression models for symptomatic kauri or *P. agathidicida* detection. As part of the model building process, three key variables of interest that were highly correlated with each other, namely the distance to the closest track, road, or uphill track, were checked separately to identify the variable that best explained the data. Therefore, for each outcome, three models were established with the model building process of each model starting with a full model containing either one of these key variables of interest (i.e., the distance to the closest track, road, or uphill track) and other variables from the initial selection process. From each full model, any non-significant variables with P-values > 0.05 were removed from the model in a stepwise manner with the variable in the order of the largest P-value being removed first. However, regardless of P-value, the distance to the closest track, road, and uphill track for symptomatic kauri and *P. agathidicida* models and the distance to the closest *P. agathidicida* site for the symptomatic kauri models were retained in each model because they were key interest factors and to allow comparison between the three models for each outcome. Also, any biological confounders identified during the discussion with experts remained in the model regardless of the P-value to account for potential confounding when using observational data (refer to glossary). The models were examined for any statistical confounders identified as causing > 20% change in any of the coefficients of remaining variables when they were removed. If identified, they were retained in the final model.

However, there was an exception in the management of statistical confounders in the case of the diameter at breast height (DBH) in the *P. agathidicida* model. This was because (1) DBH was kept in the model even though it had a P-value > 0.50 since it was a biological confounder of the association between the distance to the closest tree and *P. agathidicida* detection, and (2) there were strong correlations between DBH and other risk factors. As the model coefficient for DBH was highly variable following the removal of insignificant risk factors from the *P. agathidicida* model, it needed to be retained.

Once a final non-spatial model was established, potential interactions (refer to glossary) between variables were examined. An interaction term between the distance to the closest timber site and the number of archaeological sites within 500 m significantly decreased the variability of the model, however, the interaction term was not statistically significant in any of the models.

In this study, the final three non-spatial models for each outcome shared the same risk factors except the three different road/track variables. However, due to differences in calculation of the three variables of interest, the final models were based on different numbers of observations. The difference in numbers of observations was due to how the uphill track variable was calculated; in that if a tree had no track above it, no value could be calculated. Therefore, the comparison between the final models for each outcome was based on a reduced dataset without any missing values. The models were compared using standard statistical criteria of the Akaike information criteria (AIC) and area under the ROC (receiver operating characteristic) curve (AUC) with lower AICs and higher AUCs indicating a better model. Once the final multivariable non-spatial model for each outcome was chosen, between the three options, it was re-run using the full observations available depending on the track/road variable that best suited the data. The linearity assumption of any continuous variables for the final multivariable non-spatial model for each outcome was evaluated by converting the variable into an ordinal variable of four groups (based on its quartile values) and visually examining the linearity of the coefficients of the ordinal variable. Also, a Hosmer-Lemeshow test was conducted to examine the goodness-of-fit of the final multivariable non-spatial model for each outcome by splitting the data into eight groups based on percentiles of predicted probability. After confirming the lack of any violation of linearity assumptions or goodness-of-model fitness, standardised residuals (the difference between the observed values and value predicted by the model) were calculated to investigate any remaining spatial dependence in the data that the multivariable models had not adjusted for. The spatial correlation (i.e., the values for trees close to each other may be more similar than the values of those further apart) was examined by assessing covariance in the residual values as a function of distance via computing omnidirectional variograms to a distance of 100 metres.

3.3.5 Spatial multivariable models

Due to evidence of spatial correlation in the standardised residuals from the non-spatial (frequentist) multivariable models, separate Bayesian spatial models were developed for each outcome variable. For a kauri i, the presence of outcome (presence of symptomatic kauri or detection of *P. agathidicida*), Yi, can be mathematically described as

$$Y_i = Bernouilli(P_i)$$

$$logit(P_i) = \beta_0 + BC + W_i$$

where P_i is the probability of a kauri i showing the outcome, β_0 is the intercept, C is a matrix with rows corresponding to the covariate pattern from the non-spatial multivariable model for each sampled location, B is a vector of the covariate coefficients, and W_i is a zero-mean Gaussian spatial random effect term with a Matérn covariance function (Matérn, 2013). By using the formula above, the remaining spatial correlation in the data (i.e., W_i) was expected to be adjusted after considering the result of the final non-spatial multivariable models (i.e., $\beta_0 + BC$).

The covariate coefficients and spatial correlations were inferred based on a stochastic partial differential equation via integrated nested Laplace approximations. In brief, the inferring process relied on a very fine mesh consisting of small triangles, and the value of W_i is determined depending on the location of i within a triangle. In this study, the Waitākere Ranges parkland study area was converted into a fine mesh that consisted of small triangles for where kauri were sampled and large triangles for where the trees were not sampled or outside of the study area boundary (Figure 3-1). For the small and large triangles, the maximum length of triangle edge was set as 1/15 and 1/5, respectively, of the diameter of the study area. All the parameter values for generating the mesh were based on recommendations provided by Moraga et al. (2021). The diameter was calculated as the distance of easting difference between the east-most and west-most kauri sampled. Cut-off values were set as 1/5 of the maximum length of the small triangle. The use of cut-off values was to avoid generating too many small triangles where kauri were closely located to each other to decrease the computational burden. A coefficient of the Matérn covariance function was set as 0.5, which is identical to the exponential covariance function. The modelling was developed in R using the contributed INLA package (R Core Team, 2020).

Once the model was established, the standardised residuals of the models were calculated, and the covariance was examined by variogram to investigate whether the use of a spatial model properly adjusted for the remaining spatial correlation. Also, the standardised residuals were plotted over the study area to visually examine whether there was any distinctive spatial pattern in the residuals. Variables were retained in the final models if the 95% credible intervals (Bayesian equivalent of confidence intervals) for their coefficients did not overlap the null value, if they were significant in the non-spatial model, or if they were considered a biological confounder. Although the measure of association calculated for this study was the prevalence odds ratio (POR), it was presented and interpreted as the prevalence ratio (PR) and assumes that the POR is a good approximation of PR in this study to aid interpretation.

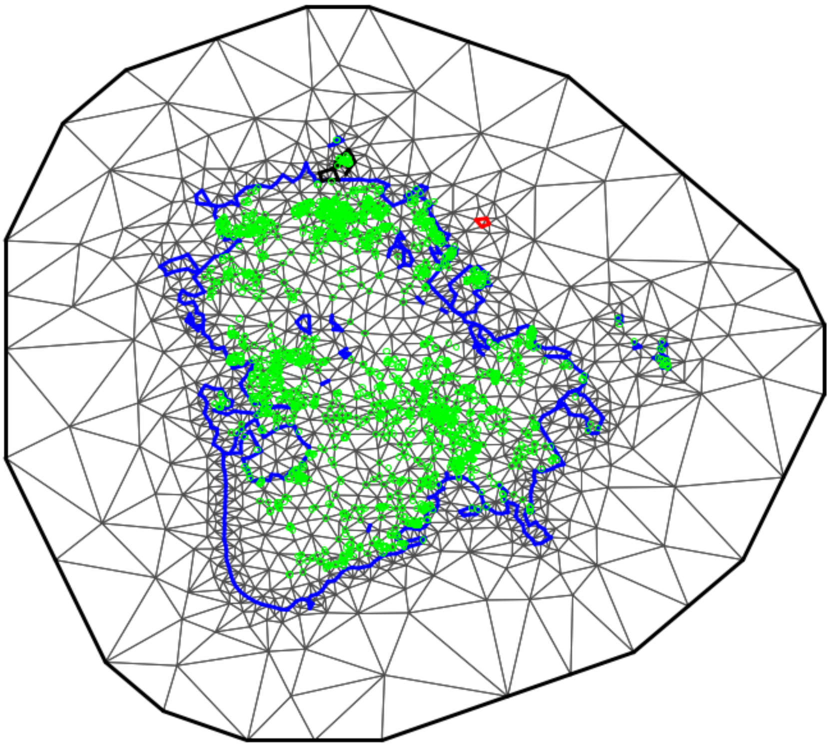

Figure 3-1. A mesh generated for a stochastic partial differential equation via integrated nested Laplace approximations for spatial multivariable models. Blue line indicates the boundary of Waitākere Ranges Regional Park and green dots are the location where kauri were sampled. Red line indicates a disjunct area of Waitākere Ranges Regional Park where no kauri were sampled. The black line denotes areas outside the study area.

3.4 Results

Ngā hua

3.4.1 Initially selected variables

Among 101 potential risk factors for each outcome variable, 39 and 29 variables showed a P-value < 0.2 for the presence of symptomatic kauri and detection of *P. agathidicida*, respectively. The result of the univariable screening tests for the variables with P-value < 0.2 is presented in Appendix C, and the association between the variables are illustrated as a causal path diagram in Figure 3-2 (for presence of symptomatic kauri) and Figure 3-3 (for detection of *P. agathidicida*). In the figures, variables in green with a black triangle are potential risk factors selected for the multivariable model. Variables in white are those omitted from the model due to being highly correlated with the selected potential risk factors, whereas variables in grey are discarded for reasons such as containing too many missing values or being an (in)direct result of the outcome variable. Green lines between any two selected risk factors indicate a potential confounding effect based on discussion with experts.

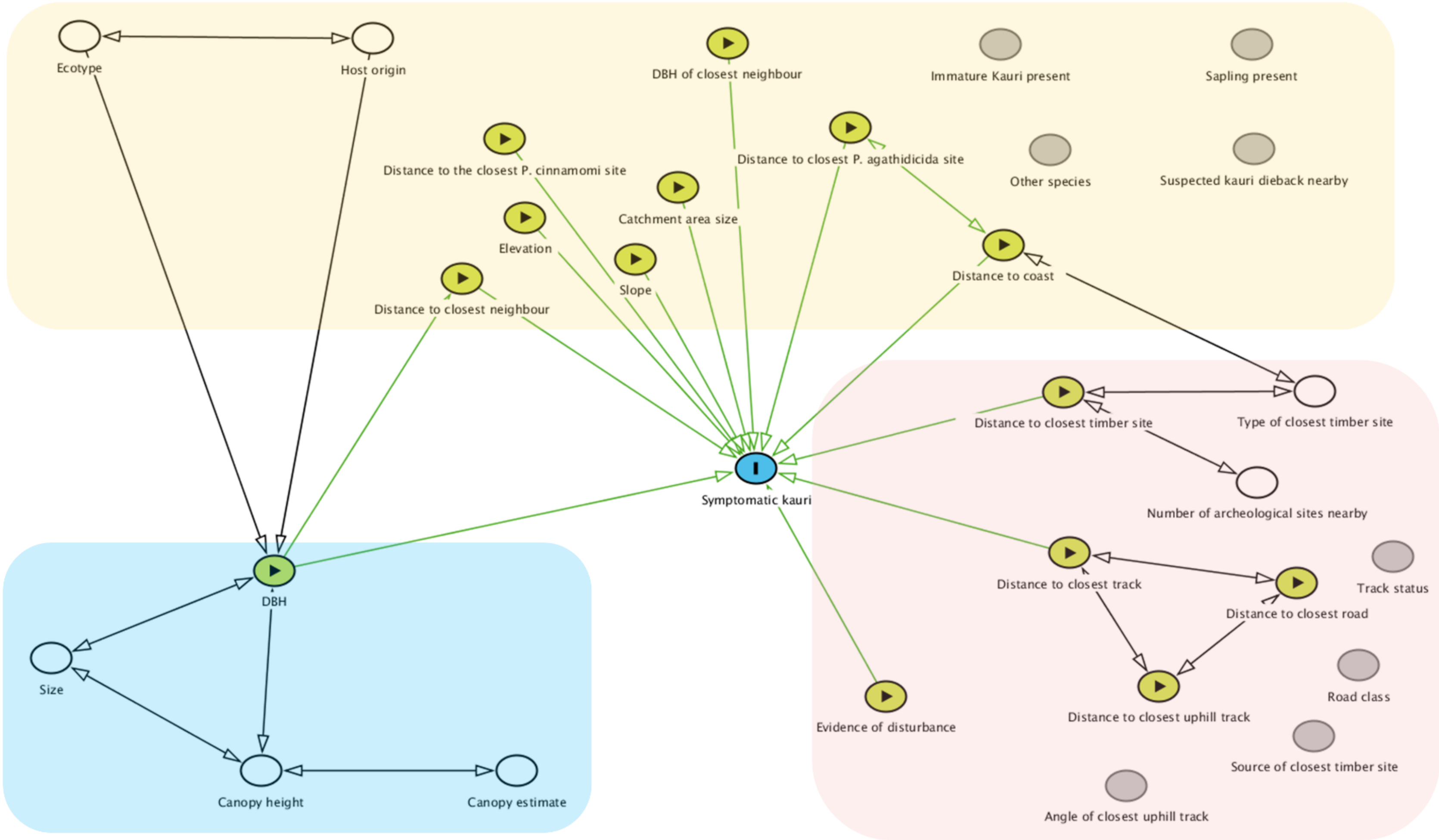

Figure 3-2. A path diagram of potential risk factors for the presence of symptomatic kauri in the Waitākere Ranges Regional Park, Auckland. The variables are grouped in three categories: (1) individual tree factors (blue square), (2) environmental factors (yellow square), and (3) anthropogenic factors (red square). Please note that not all the correlations between variables are shown to enhance readability.

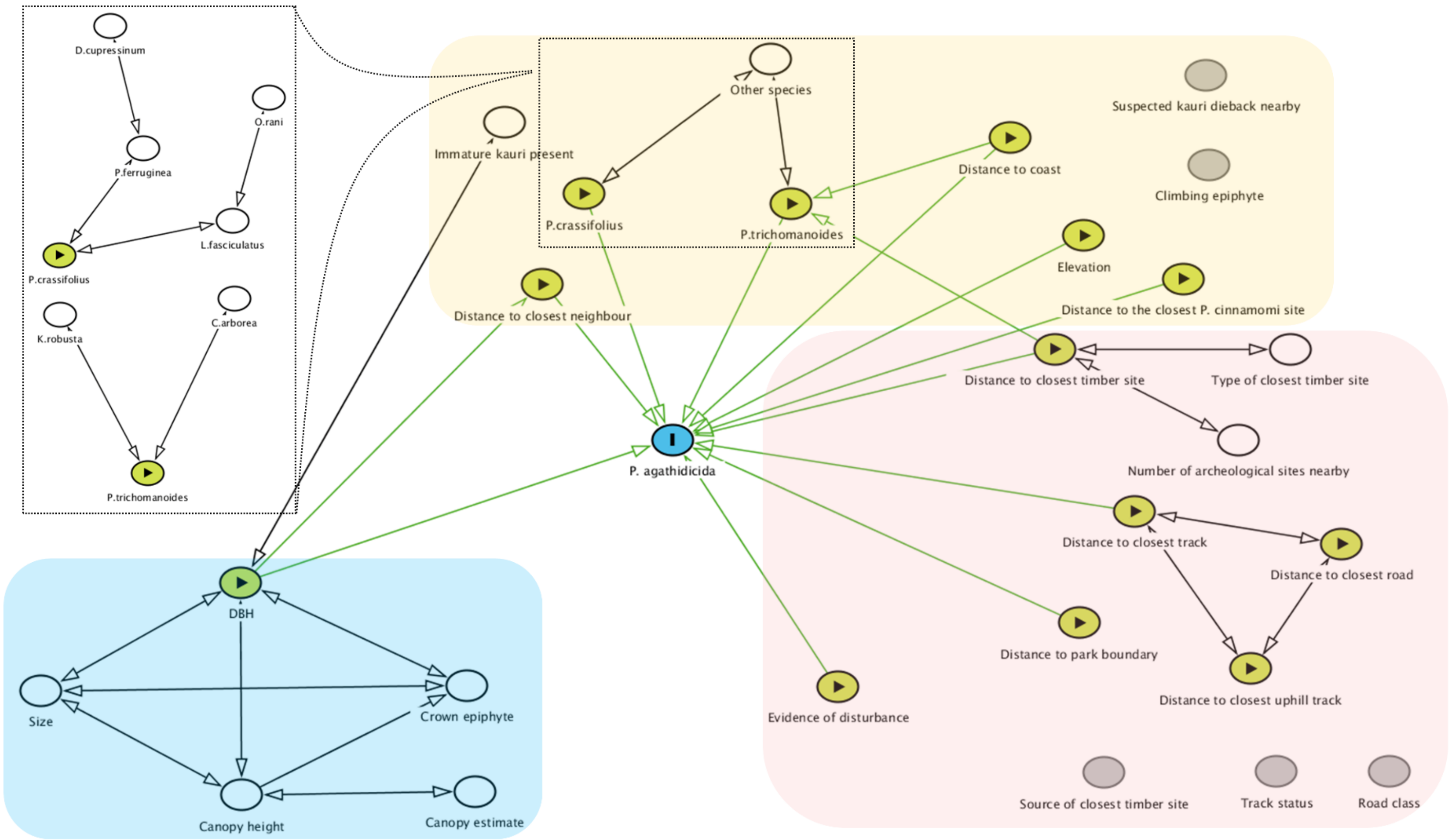

Figure 3-3. A path diagram of potential risk factors for the detection of *Phytophthora agathidicida* in kauri of Waitākere Ranges Regional Park, Auckland. The variables are grouped in three categories: (1) individual tree factors (blue square), (2) environmental factor (yellow square), and (3) anthropogenic factor (red square). Please note not all the correlations between variables are shown to enhance readability. Where *P. crassifolius* is lancewood (*Pseudopanax crassifolius*) and *P. trichomanoides* is tanekaha (*Phyllocladus trichomanoides*).

3.4.2 Results of non-spatial models

For the presence of symptomatic kauri, three models (one for each of the road/track variables) were built. The variables: diameter at breast height (DBH); distance to the closest neighbouring tree; distance to the closest *P. agathidicida* site; distance to the closest coast; distance to the closest timber site and the relevant road/track variable remained across the three final models due to either biological or statistical significance after the variable selection process. The number of observations for the three final models for symptomatic kauri presence with either the distance to the closest track, road, and uphill track was 2094, 2094, and 1856, respectively.

For the detection of *P. agathidicida*, three models (one for each of the road/track variables) were built. The same variables as the disease model (except the distance to the closest *P. agathidicida* site) remained in the final models after variable selection, along with distance to closest *P. cinnamomi* site and elevation. The three final models for the detection of *P. agathidicida* with the distance to the closest track, road, and uphill track were based on 729, 729, and 644 observations, respectively. The results of the final non-spatial multivariable models are presented in Appendix D.

To compare the three models with different key variables, the same dataset for each outcome was used (based on the uphill track variable). It reduced the size of complete datasets to 1862 and 644 observations for the presence of symptomatic kauri and detection of *P. agathidicida*, respectively. Based on these datasets, non-spatial multivariable models were reconstructed and compared. The AIC and AUC values of the reconstructed final models depending on the inclusion of different key variables of interest (i.e., the distance to the closest track, closest road, and closest uphill track) are presented in

Table 3-1. The results indicate that, although small differences in the measure of model fitness occurred, the final models including the distance to the closest uphill track for symptomatic kauri presence and the distance to the closest track for *P. agathidicida* detection best explained the data. Based on this, a final non-spatial multivariable model for each outcome variable was chosen.

Table 3-1. A comparison of final non-spatial multivariable logistic regression models incorporating either the distance to the closest track, distance to the closest road, or distance to the closest uphill track. Values are the Akaike information criteria or the area under the ROC curve for each model. The model with its value underlined indicates the model that best explained the data.

Model outcome	**Distance to the closest**		
	Track	Road	Uphill track
Presence of kauri dieback disease			
Akaike information criteria (AIC)	1721.5	1722.4	<u>1720.4</u>
Area under the ROC curve (AUC)	0.693	0.692	<u>0.695</u>
Detection of *Phytophthora agathidicida*			
Akaike information criteria (AIC)	<u>353.8</u>	356.1	354.6
Area under the ROC curve (AUC)	<u>0.836</u>	0.832	0.836

The variograms of the standardised residuals from the multivariable models for symptomatic kauri presence (**Figure 3-4**) and *P. agathidicida* detection (**Figure 3-5**) indicated a weak remaining spatial correlation at close distance (up to approximately 35 metres), suggesting a need to use a spatial model (Bayesian geostatistical multivariable logistic regression) for symptomatic kauri presence (and potentially *P. agathidicida* detection as well) to account for the remaining spatial correlation. Although the variogram for the detection of *P. agathidicida* did not provide strong evidence of remaining spatial correlation, this may have been due to the smaller sample size compared with the symptomatic kauri outcome.

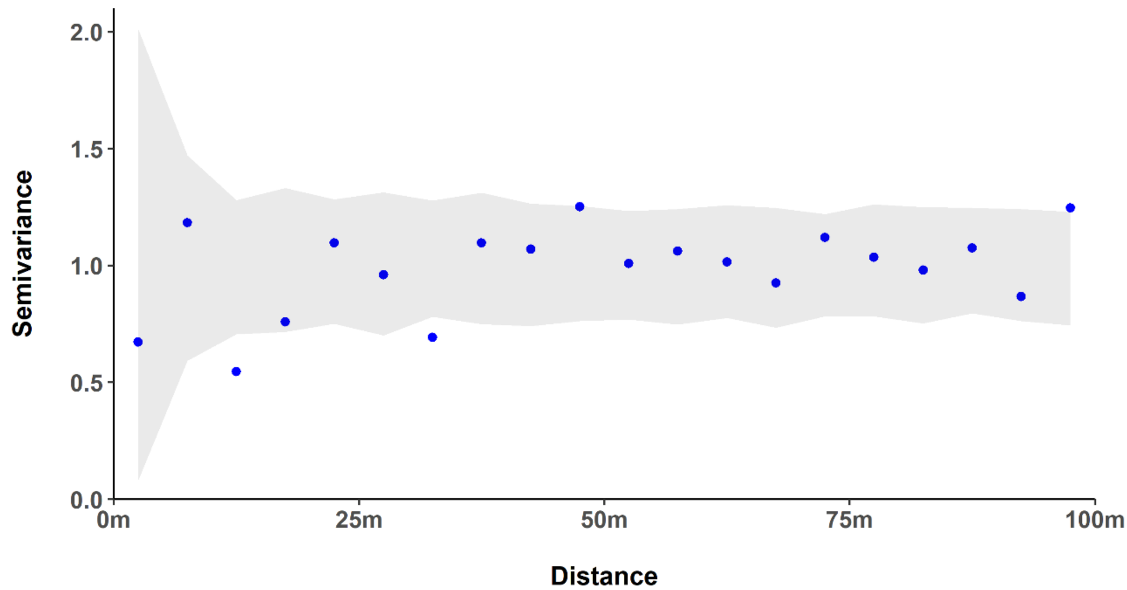

Figure 3-4. A variogram of standardised residuals of a non-spatial multivariable logistic regression model for the presence of symptomatic kauri in the Waitākere Ranges parkland, Auckland (blue points). Any blue points outside of the grey area indicate a spatial correlation, where the grey area was computed by permutation of the standardised residual 500 times**.**

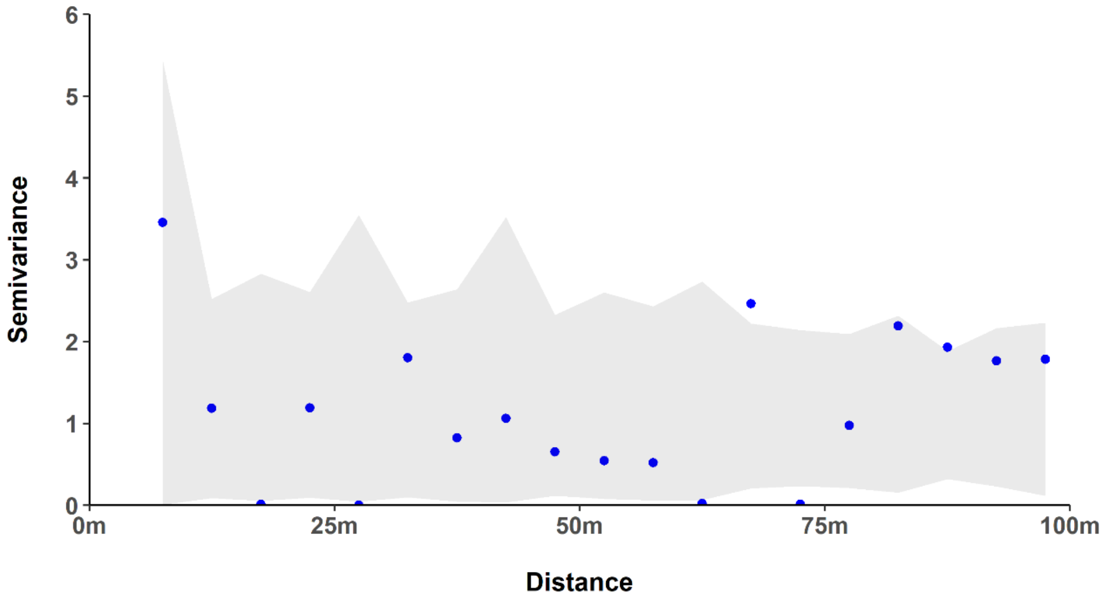

Figure 3-5. A variogram of standardised residuals of a non-spatial multivariable logistic regression model for the detection of *Phytophthora agathidicida* in kauri of the Waitākere Ranges parkland, Auckland (blue points). Any blue point outside of the grey area indicates a spatial correlation, where the grey area was computed by permutation of the standardised residual 500 times. However, this variogram has a low sample size so it could be an impractical indicator of spatial correlation.

3.4.3 Results of spatial models

The results of the spatial multivariable models are presented in Table 2 (for symptomatic kauri presence) and Table 3 (for *P. agathidicida* detection). Note that there is a transition from talking about significance and p-values with the frequentist based non-spatial models to association and credible intervals with the Bayesian spatial models (refer to Kruschke and Liddell (2018) for further reading on how these differ).

There was a small difference of coefficient values between non-spatial and spatial models for both outcomes. This is because only a weak spatial correlation was indicated from the variograms. However, the coefficient of the distance to the closest coast was greatly affected by adjusting the spatial correlation for the *P. agathidicida* model. After adjusting for spatial autocorrelation, the strength of the association between some of the other explanatory variables and either symptomatic kauri or *P. agathidicida* was both reduced (the point estimates were closer to 1) and became more uncertain (i.e., the magnitude of the credible intervals around the association measure increased and included one). For example, in the model for the detection of *P. agathidicida*, after accounting for spatial autocorrelation in the data, the upper band of the 95% credible interval of the prevalence odds ratio for the presence of tanekaha (*Phyllocladus trichomanoides*) nearby, included the value of one. This indicates an association between *P. agathidicida* and the presence of tanekaha, with a small probability (<5%) that the association is either less than or equal to one (i.e., no association). These have been referred to as associations of note in the discussion.

The prevalence of symptomatic kauri decreased in trees with increasing distance from *P. agathidicida* sites and increasing distance from a timber site and increased in trees with increasing DBH of kauri. Examples are provided in **Table 3-2** and **Figure 3-6**. In addition, associations of note were detected with a reduction in prevalence odds of symptomatic kauri with increased distance from the closest neighbouring tree and closest uphill track. A smaller association with distance from coast was observed after adjusting for spatial autocorrelation.

The prevalence odds of kauri detected with *P. agathidicida* reduced with increasing elevation, greater distance to a neighbouring tree, historic timber site or the closest coast (**Table 3-3** and **Figure 3-7**). In addition, associations of note were detected with an increase in prevalence odds of *P. agathidicida* with the presence of tanekaha and a reduction in prevalence odds of *P. agathidicida* with increased distance from the closest track. There was a low probability of an association with *P. cinnamomi* after adjusting for spatial autocorrelation. No association was found with DBH, however it remained in the model as a potential confounder for the closest neighbouring tree relationship.

Table 3-2. A result of spatial multivariable logistic regression model for the presence of symptomatic kauri, consistent with kauri dieback in the Waitākere Ranges Regional Park, Auckland. The median (95% credible interval (CI)) of the coefficients and prevalence odds ratio of the potential risk factors are presented, in order of the strength of association.

Variables	**Coefficient (95% CI)**	**Prevalence odds ratio (95% CI)**
Intercept	-0.805 (-1.317 ~ -0.331)	Reference
Distance to the closest *P. agathidicida* site (100 m)	-0.055 (-0.077 ~ -0.034)	0.947 (0.926 ~ 0.967)*
Distance to the closest timber site (100 m)	-0.027 (-0.046 ~ -0.009)	0.973 (0.955 ~ 0.991)*
Diameter at breast height (10 cm)	0.076 (0.047 ~ 0.106)	1.079 (1.048 ~ 1.112)*
Distance to the closest neighbouring tree (m)	-0.091 (-0.189 ~ 0.005)	0.913 (0.828 ~ 1.005)
Distance to the closest uphill track (100 m)	-0.055 (-0.122 ~ 0.011)	0.947 (0.885 ~ 1.011)
Distance to the closest coast (100 m)	-0.006 (-0.014 ~ 0.003)	0.994 (0.986 ~ 1.003)

Interpretation of factors with the strongest associations (*) after accounting for other variables in the model, demonstrating the effect of one unit difference from the average value of the variable:

- Distance to the closest *P. agathidicida* site: The prevalence odds of symptomatic kauri was 0.95 times (5% less) for each 100 m increase in distance from the closest *P. agathidicida* site. i.e., symptomatic kauri prevalence was higher closer to *P. agathidicida* sites.
- Distance to the closest timber site: The prevalence odds of symptomatic kauri was 0.97 times (3% less) for each 100 m increase in distance to the closest timber site. i.e., symptomatic kauri prevalence was higher closer to historical timber sites.
- Diameter at breast height (DBH): The prevalence odds of symptomatic kauri for trees with a DBH of 70 cm was 1.08 times (8% greater) than that of kauri with a DBH of 60 cm i.e., symptomatic kauri prevalence increased with tree size.

Table 3-3. A result of spatial multivariable logistic regression model for the detection of *Phytophthora agathidicida* in kauri soil samples in the Waitākere Ranges Regional Park, Auckland. The median (95% credible interval (CI)) of the coefficients and prevalence odds ratio of the potential risk factors are presented, in order of the strength of association.

Variables	**Coefficient (95% CI)**	**Prevalence odds ratio (95% CI)**
Intercept	1.150 (-1.806 ~ 4.403)	Reference
Elevation (100 m)	-0.906 (-1.907 ~ -0.046)	0.404 (0.149 ~ 0.955)*
Distance to the closest neighbouring tree (m)	-0.456 (-0.777 ~ -0.178)	0.634 (0.460 ~ 0.837)*
Distance to the closest timber site (100 m)	-0.132 (-0.259 ~ -0.034)	0.877 (0.772 ~ 0.966)*
Distance to the closest coast (100 m)	-0.060 (-0.164 ~ -0.005)	0.942 (0.848 ~ 0.995)*
Presence of *P. trichomanoides* (tanekaha)	0.664 (-0.161 ~ 1.566)	1.942 (0.851 ~ 4.787)
Distance to the closest track (100 m)	-0.140 (-0.437 ~ 0.129)	0.870 (0.646 ~ 1.138)
Distance to the closest *P. cinnamomi* site (100 m)	-0.024 (-0.060 ~ 0.007)	0.977 (0.942 ~ 1.007)
Diameter at breast height (10 cm)	0.038 (-0.047 ~ 0.119)	1.038 (0.954 ~ 1.126)

Interpretation of factors with the strongest associations (*) after accounting for other variables in the model, demonstrating the effect of one unit difference from the average value of the variable:

- Elevation: The prevalence odds of *P. agathidicida* was 0.41 times (59% less) for each 100 m increase in elevation. i.e., *P. agathidicida* prevalence was higher at lower elevations.
- Distance to the closest neighbouring tree: The prevalence odds of *P. agathidicida* was 0.64 times (36% less) for each 1 m increase in distance away, i.e., the wider the gap between the kauri tree and its closest neighbour, the lower the *P. agathidicida* prevalence.
- Distance to the closest timber site: The prevalence odds of *P. agathidicida* was 0.88 times (12% less) for each 100 m increase in distance away, i.e., *P. agathidicida* prevalence was higher closer to historic timber sites.
- Distance to the closest coast: The prevalence odds of *P. agathidicida* was 0.94 times (6% less) for each 100 m increase in distance away, i.e., *P. agathidicida* prevalence was higher closer to the coast.

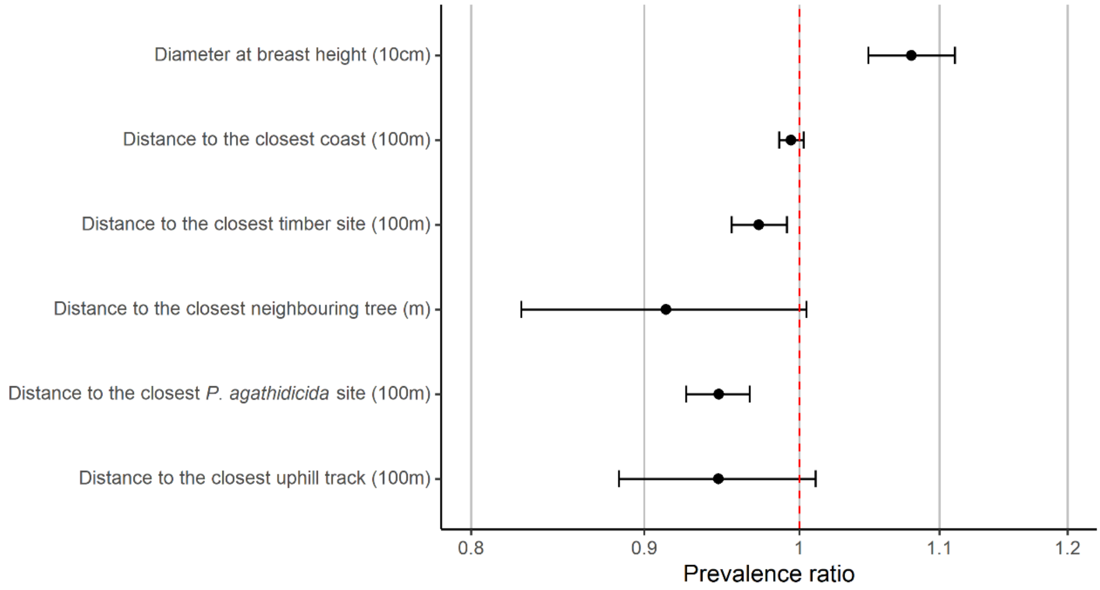

Figure 3-6. A forest plot depicting the prevalence odds ratio (PR) of potential risk factors for the presence of symptomatic kauri in the Waitākere Ranges parkland, Auckland. The black dot and horizontal bars respectively indicate the PR and its 95% credible interval (CI). Risk factors with their PR and 95% credible intervals fully to the left or right of the red dashed vertical line are associated with the outcome, where most of the PR and 95% credible intervals are to the left or right of the red line the association is protective or increases the prevalence odds of symptomatic kauri respectively, and where the black dot and credible intervals are centred on the red dashed line, the strength of the association is low (e.g., distance to coast).

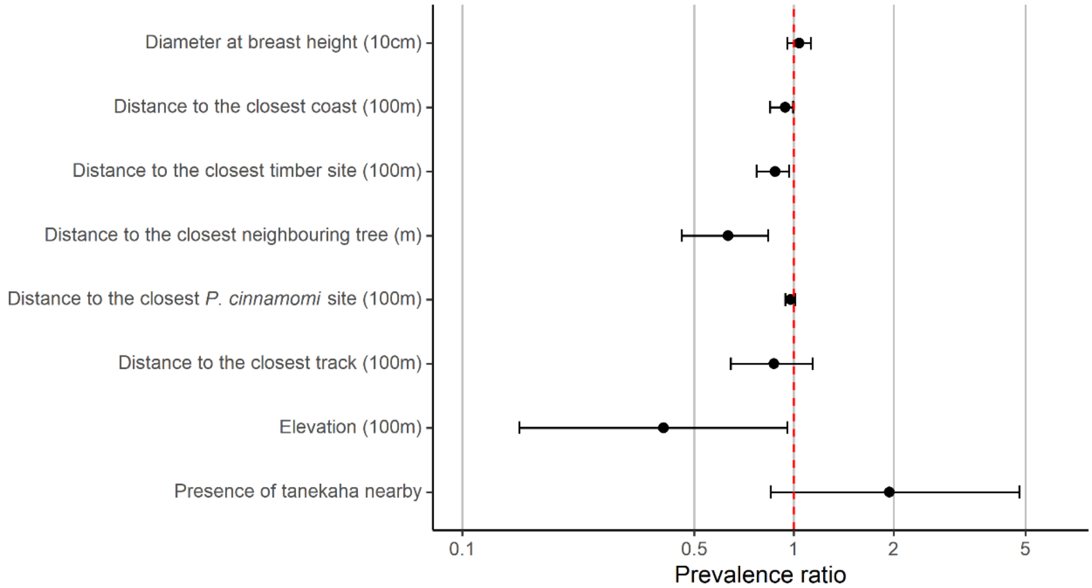

Figure 3-7. A forest plot depicting the prevalence odds ratio (PR) of potential risk factors for the detection of *Phytophthora agathidicida* in kauri in the Waitākere Ranges Regional Park, Auckland. The black dot and horizontal bars respectively indicate the PR and its 95% credible interval. Risk factors with their PR and 95% credible intervals fully to the left or right of the red dashed vertical line are associated with the outcome, where most of the PR and 95% credible intervals are to the left or right of the red line the association is protective or increases the prevalence odds of *P. agathidicida* respectively, and where the black dot and credible intervals are centred on the red dashed line, the strength of the association is low (e.g., diameter at breast height). Note that the x axis is illustrated in a log scale and has a wider range than the symptomatic kauri plot.

3.5 Discussion

Te matapaki

The aim of this study was to identify which environmental, host, anthropogenic and pathogen-related risk factors were associated with either symptomatic kauri or presence of *P. agathidicida*. It also aimed to identify factors much less likely to be causally related to symptomatic kauri or *P. agathidicida* presence. For those that were associated the aim was to generate hypotheses on the possible nature of the relationships. This will inform new studies designed to answer questions about these relationships and identify management interventions to enhance kauri health.

Proximity to *P. agathidicida* sites was strongly associated with symptomatic kauri in the symptomatic kauri model, so discussing the *P. agathidicida* model first will provide insight into the symptomatic kauri model. Below we present the associated risk factors found through the spatial models and discuss potential causal or non-causal hypotheses for these relationships. The strongest associations are discussed first, followed by the associations of note.

3.5.1 *P. agathidicida* model

There were four risk factors that were strongly associated with *P. agathidicida* detection in soil, three of which were environmental factors and one anthropogenic factor. In addition there were three associations of note, two were environmental and one was anthropogenic. It is easier to intervene with anthropogenic factors than environmental factors which tend not to be modifiable; however, they can inform management such as placement of amenities or replanting areas.

3.5.1.1 Elevation

The prevalence of *P. agathidicida* in kauri was higher at lower elevations, after accounting for all other factors. This was an interesting finding, especially as it remained highly associated after coastal proximity was controlled for. Previous reports of a negative relationship between *P. cinnamomi* prevalence and elevation in Southeast Australia support this finding (Wilson et al., 2003). The association may be due to environmental constraints on pathogen survival, such as the warming that occurs with increased solar radiation, or changes in soil pH and moisture. It may also be related to opportunities for vectored or natural spread. As a soil-borne water-mould, it is more likely that prevalence due to natural spread would be greater at lower elevations as water is carried downhill. This is consistent with the direction of effect in the model and with research on other *Phytophthora* species showing that propagules are washed down catchments (Redondo et al., 2018). However, other unmeasured factors such as soil type and chemistry may also affect the presence of *P. agathidicida* in soil and differ with elevation, especially in areas where significant disturbance has occurred. When the soil samples for this study were collected, additional volumes of soil were taken for distribution to a range of collaborating researchers, and soil chemistry or microbiota relationships may become clearer when their research is completed. Elevation is not a modifiable variable, but this result provides information about potentially higher risk areas for future surveillance or replanting.

3.5.1.2 Distance to historic timber sites

The prevalence of *P. agathidicida* was higher closer to historic timber sites, after accounting for other factors. This association could be related to other unmeasured confounding factors but suggests a hypothesis of introduction and spread through increased soil disturbance near these sites. This association was also observed for the disease model, potentially suggesting that inoculum load is greater in these areas, increasing disease risk. It is also reasonable to assume that *P. agathidicida* is easier to detect in soils with a high inoculum load. An increased pathogen prevalence near historic logging has also been observed in other *Phytophthora* diseases (Socorro Serrano et al., 2015, Homet et al., 2019).

3.5.1.3 Distance to coast

The prevalence of *P. agathidicida* was higher closer to the coast. It is possible that the association observed in this study may relate to other unmeasured confounding factors such as higher human habitation and disturbance or climatic differences between coastal areas and the inland forest. Coastal areas are where most modification has happened over time in the Waitākere Ranges (S. Leighton, Auckland Council, pers. comm.) and this association could be related to historic introduction and spread pathways of *P. agathidicida*, a hypothesis supported by the association with historic timber sites. It is also consistent with mātauranga Māori (indigenous knowledge) that when the moana (ocean) is depleted, so too is the whenua (land), making the trees near the coast more vulnerable from this exploitation. Another possible explanation is that rainfall amounts are up to 3 times higher in the centre of the Park compared with the coastal fringe. For example, the range in rainfall is approximately 1 m in Piha through to just over 3 m in the upper Nihotupu Basin (S. Leighton, Auckland Council, pers. comm.). This raises the hypothesis that *P. agathidicida* may be more prevalent in dryer areas or where the host is under increased pressure from dry conditions; future investigation into the relationships between rainfall and other climatic factors on *P. agathidicida* presence would be useful. Depth to water was not associated with an increase or decrease in *P. agathidicida* prevalence (or disease) and typically *Phytophthora* species are more associated with wet soils (e.g., Gyeltshen et al. (2021), Donald et al. (2020), Weste and Ruppin (1975), Weste and Vithanage (1979), Venette and Cohen (2006)), although Sena et al. (2019) found *P. cinnamomi* was more prevalent in drier areas in Kentucky, United States. Another potential hypothesis is that dry areas may have a higher presence of the oospore life stage, which is longer lived and may be easier to detect in the soil bioassay.

The higher prevalence of *P. agathidicida* detection near both the coast and historic timber sites being associated with an introduction pathway is supported by research by Weir et al. (2015) and Winkworth et al. (2021). *Phytophthora agathidicida* is likely an introduced species into New Zealand as Weir et al. (2015) indicate that the centre for diversity of Clade 5 Phytophthora species which includes *P. agathidicida* is East Asia/Pacific. Winkworth et al. (2021) provided some evidence that the limited number of *P. agathidicida* isolates from the Waitākere Ranges they examined (Huia (3) and Piha (1)) were diversifying from the late 1700s onwards, although the authors acknowledge the research requires further sampling. This study raises the hypothesis of historical introduction from the coast and human assisted movement of *P. agathidicida* through timber and other disturbances. This is also supported by the limited distribution of *P. agathidicida* around the periphery of the study area found in the Chapter 2.

3.5.1.4 Distance to closest neighbouring tree

The lesser the gap between the monitored tree and its closest neighbouring tree, the higher the prevalence of *P. agathidicida*. It is postulated that with 20% of neighbouring trees also being kauri, this is likely to indicate enhanced localised spread of *P. agathidicida* between kauri within a stand. In addition, soil samples may be collecting root material from several kauri and maximising the opportunity for *P. agathidicida* detection.

3.5.2 Symptomatic kauri model

There were three risk factors that were strongly associated with symptomatic kauri, one anthropogenic factor, one host related factor and one pathogen related factor. Two other environmental risk factors and one anthropogenic factor were associations of note.

3.5.2.1 Distance to closest *P. agathidicida* site

Trees that were closer to a *P. agathidicida* site had a higher probability of being a symptomatic kauri than trees that were further away from *P. agathidicida* sites, indicating localised tree to tree spread. This finding was not unexpected and is supported by extensive research showing a strong association between kauri dieback disease and *P. agathidicida* (Bradshaw et al., 2020). Both pathogenicity and Koch's postulates have been demonstrated between *P. agathidicida* and kauri dieback (Bellgard et al., 2016, Gadgil, 1974) and the case definition for symptomatic kauri in our model was based on expert agreement on the symptoms of kauri dieback caused by *P. agathidicida*. Not all symptomatic trees were near *P. agathidicida* detected sites, which indicates that while *P. agathidicida* management will be important in reducing disease, some other factors are also contributing to a decline in kauri health and should be investigated.

3.5.2.2 Distance to historic timber site

Symptomatic kauri prevalence was higher the closer the tree was to historic timber sites, after accounting for proximity to *P. agathidicida* and other risk factors.

This indicates that the relationship is beyond that of an introduction pathway of the pathogen. It is hypothesised that proximity to historical timber sites is an indication of soil disturbance and tree damage. Historical logging was extremely destructive to surrounding forest from not only the felling of kauri but the entire process, including the creation of the timber mills, digging of saw pits and then radiating out from these areas, the chutes, bullocks and tramways to move kauri logs to site for processing (Figure 3-8). It is also possible that this association is a proxy for wider disturbance of sites after logging. Often farming was attempted in the wake of logging, leading to full clearance of remaining forest and loss of topsoil. The Manukau, Waitematā and Kaipara harbours are full of silt that would have once been rich soils that were washed away following forest clearance by early Europeans (Hayward et al., 2006).

There is potential to investigate in finer detail the strength of the relationship between timber mills, saw pits and other sites associated with kauri logging and potentially other large soil disturbance activities, such as dam building, using this data and historical records.

It may also be relevant to query and isolate other archaeological features from available datasets (i.e., the cultural heritage inventory, historic tracks and tramlines) to determine the significance of additional archaeological classes (e.g., historic access and transport, historic land use, European and pre-European settlement and activity) in relation to symptomatic kauri and *P. agathidicida* distribution.

Figure 3-8. Historic images of i) a kauri log on a cutting table inside the Piha timber mill (photographer A.P. Godber, Auckland Libraries Heritage Collections JTD-04L-00124) and ii) a felled kauri crown showing surrounding forest devastation after the sawn log has been removed (photographer A.P Godber, Auckland Libraries Heritage Collections JTD-04D-03327).

3.5.2.3 Kauri diameter at breast height (DBH)

The prevalence of symptomatic kauri increased with the size (DBH) of the kauri host. The results were surprising from a physiological viewpoint as *P. agathidicida* infection reduces water uptake in kauri roots, decreasing the infected tree's ability to replace water lost through evaporation at the leaf surface (Killick, 2022). Infected trees are also less conservative of water, operating at a narrower hydraulic safety margin overall (Killick, 2022). While this is true independent of kauri size, larger trees have greater water storage capacitance than smaller trees (Kaplick et al., 2017); therefore, larger kauri should decline slower or later than smaller kauri. On the other hand, increasing tree size affects the availability of soil water, which may also be a factor (Ruess et al., 2021). Bradshaw et al. (2020) state that smaller trees generally decline at a faster rate than larger trees, although it is difficult to measure the rate of decline in individual trees without knowing when they became infected. In a cross-sectional prevalence study, subjects are observed at a single point in time and prevalence can be influenced by the duration of disease (Grimes and Schulz, 2002). If larger trees survive with disease longer than smaller trees, then they are likely to make up a larger proportion of the prevalent population as smaller trees with disease are removed when they die. This survey provides the baseline measure of symptomatic kauri prevalence and repeated surveys on the same cohort of trees will provide more evidence of this relationship by measuring the incidence of new symptomatic kauri developing over time.

It is also biologically plausible that the high proportion of trees that are regenerating from logging that occurred in the late 1800s and early 1900s (i.e., 100-120 year old trees transiting from ricker to intermediate size classes (Bergin and Steward, 2004)) are facing increased competition with higher vulnerability to disease which could be driving this association. The distribution of DBH in trees included in this study was shown to be left skewed towards smaller (average 60 cm) trees, with few very large mature trees (Chapter 2). The association was strongly linear when tested, but this relationship requires more investigation. In addition, large trees within the Waitākere Ranges, especially around the Cascade area where symptomatic kauri risk was high (Chapter 2) were extensively bled for kauri gum in the same period as logging occurred increasing root disturbance and affecting tree health. There may also be a physiological reason for some protection from symptoms in younger or smaller trees, such as greater root growth rates in some younger trees (Rosenvald et al., 2013). The strength of the association between tree size and symptoms was strong and this could be an important finding for the long-term management of kauri. The size classes of kauri cannot be manipulated for management, however trees at greater risk could be prioritised for protection and enhanced monitoring to inform early treatment.

It is possible that the association between symptomatic kauri prevalence and DBH was an unmeasured confounding factor, for example, trees with a DBH of less than 10 cm were deliberately excluded from the study because symptoms are hard to detect on very small trees. It is also possible that symptoms, in particular basal lesions are more obvious on larger trees, which may have contributed to the observed association.

3.5.3 Associations of note

3.5.3.1 Distance to tracks

The distance to tracks (closest or uphill) was significantly associated with *P. agathidicida* detection and disease in the non-spatial models. However, the association reduced (the point estimates were closer to 1) and became more uncertain (i.e., the magnitude of the credible intervals around the association measure increased and included one) after adjusting for spatial autocorrelation. It is biologically plausible that an association exists and additional analysis of different track types, historic tracks, and whether there is a similar association between ridgelines and *P. agathidicida* and symptomatic kauri prevalence will provide a more complete picture of the relationships with track and transport networks. It would also be possible to undertake quantitative bias analysis on the non-spatial model results to investigate if misclassification of the outcome variables is masking a greater effect.

3.5.3.2 Distance to closest neighbouring tree

The association towards a lower prevalence of disease as the distance between monitored trees and their closest neighbour tree increases contrasts with the relationship between an increase in symptomatic kauri prevalence as tree size increases. As mean tree size increases, it would be expected to see a decline in density suggesting greater distances between trees. It is possible that these relationships are confounded by whether the nearest neighbour is a kauri or not, which was the case in 20% of trees (Chapter 2). Further investigation of the data to understand size classes in relation to closest neighbouring tree species and the importance of this relationship is possible with the data collected during this study using different outcome variables.

3.5.3.3 Presence of tanekaha

An interesting association between *P. agathidicida* and the presence of tanekaha (*Phyllocladus trichomanoides*) nearby (within 10 m of the monitored tree) was found. During screening, 8 of the 15 common plant species showed an initial association and formed into two distinct groupings (**Figure 3-3**) when inter-variable correlations were investigated. One was represented best by lancewood (*Pseudopanax crassifolius*) and the second was best represented by tanekaha. The groupings are well aligned with the developmental phases of kauri forest, i.e., mature, old-growth forest and newer regenerating forest respectively (Ahmed and Ogden, 1991, Ogden and Stewart, 1995). Presence of tanekaha could be a proxy for forest characteristics differentiating these two forest types that may favour *P. agathidicida* or be related to increased disturbance and spread. Tanekaha are also more common on drier ridges and in areas with extreme conditions (Kaplick et al., 2018). Another potential biological association could be related to the possibility of tanekaha acting as an alternative host for *P. agathidicida*. To date there have been some laboratory indications that tanekaha may be an alternative host for *P. agathidicida* (Ryder et al., 2016), however no field evidence exists as yet. As with the other factors of note, the relationship remains uncertain and further investigation is warranted. The data collected in this study will aid researchers to locate kauri sites with tanekaha where *P. agathidicida* has been detected for future studies.

3.5.3.4 Distance to closest *P. cinnamomi* site

There was no association between symptomatic kauri and *P. cinnamomi,* however, there was a weak initial association between *P. agathidicida* and distance to the closest *P. cinnamomi* site in the non-spatial model, with a very small decrease in *P. agathidicida* prevalence with increasing distance from *P. cinnamomi* sites. However, this relationship became very weak in the spatial model. It does raise an interesting hypothesis that the introduction pathways of *P. agathidicida* and *P. cinnamomi* may have been similar, however from the *P. cinnamomi* distribution results in Chapter 2, historically in New Zealand (Podger and Newhook, 1971) and internationally (Sena et al., 2019) it is clear that *P. cinnamomi* is much more efficient at spreading within the landscape, most likely due to a much wider host range.

3.5.4 Variables of interest with no association found

There were several variables of note that were found to have no association to symptomatic kauri and/or detection of *P. agathidicida* in our models.

P. cinnamomi was not associated with symptomatic kauri in this study, a factor that has been uncertain in the past (Podger and Newhook, 1971, Bellgard et al., 2013, Beever et al., 2010), although Beever et al. (2009) also found no association with disease in kauri within the Waipoua Forest in 2003. Podger and Newhook (1971) concluded *P. cinnamomi* was important in disease observed in older 80-100-year-old regenerating stands (now 120-150 years old), however when the site was revisited in 2006, remaining trees appeared healthy (Beever et al., 2009).

It was also surprising that the depth to surface water index which gave an indication of areas more prone to being moist or dry was not associated with increased symptomatic kauri prevalence or *P. agathidicida.* It may be that the depth to water index used was not a good model for wet or waterlogged sites (Davison, 2018) which are postulated to enhance infection through weakened roots, higher sporulation and mobility of the motile zoospores as has been observed in other native tree-*Phytophthora* pathosystems (Donald et al., 2020, Jung et al., 2018).

Similarly, it was postulated that the distance to hydrological features would be an associated factor. However, distance to overland flow path (watercourses) did not indicate a relationship with symptomatic kauri or with *P. agathidicida* detection. Despite this, it is considered important to investigate this relationship which could consider stream order or detailed watershed analysis to determine whether a tree's location in the sub-catchment influences *P. agathidicida* or symptomatic kauri prevalence.

It is also important to note that disturbance at the tree base by pigs and other hoofed animals was included in the initial model building but was not significant in the non-spatial model. However, the study design was not optimal to collect data on pig and other potential soil-disturbing and pathogen vectoring pest animal species and no existing geospatial datasets were suitable for investigation. It may be useful to obtain pig surveillance data similar to that used for Bovine TB (*Mycobacterium bovis*) in New Zealand (Nugent et al., 2015). Further research to understand pig density and pest animal relationships with *P. agathidicida* and symptomatic kauri would be helpful.

3.5.5 Study limitations

The symptomatic criteria of the case definition (Chapter 2) used to classify symptomatic and non-symptomatic trees relies on set cut-points for canopy scores (greater or equal to 3 out of 5) and more yellow than green canopy colours, along with the presence of trunk or lateral root basal lesions, which can be caused by physical damage or biological factors. The Stevenson and Froud (2020) case definition we applied states that the symptoms need to be consistent with kauri dieback, as assessed by approved observers. The survey was undertaken by experienced and well-trained observers that were familiar with kauri dieback to reduce the level of misclassification. However, the non-symptomatic class contains trees that can be either healthy or showing a level of ill-thrift below the case definition cut-points. Therefore, the ill-thrift trees will contain both stressed trees from other causes which might recover, and trees that may transition into the prevalent (symptomatic) population. Misclassified ill-thrift trees into the non-symptomatic class are most likely to push prevalence odds ratios towards 1 (the null) and may have reduced effect sizes. Further research looking at modelling specific symptoms with *P. agathidicida* detection may inform an improved case definition to explore risk factors and improve effect size estimates.

For the *P. agathidicida* model, the diagnostic test sensitivity for the soil bioassay is relatively low (details in Chapter 4). That means that we may have missed over a third of the true positives and misclassified them as not detected. As with the symptomatic kauri outcome, this misclassification would most likely lead to an underestimation of the true effect and pushed effect sizes towards the null. Therefore, risk factors that were associated in the final model, but partly crossed the null value, remain likely to be biologically important and have been considered for hypothesis generation. The sample size for the *P. agathidicida* model was lower than the symptomatic kauri model and this was evident with higher spatial variability and wider credible intervals. Sample sizes for soil sampling in future risk factor studies may need to be increased.

3.6 Conclusion
Te whakatau

For the symptomatic kauri model, the strongest association was between symptomatic kauri and proximity to *P. agathidicida* sites (point locations of *P. agathidicida* detections) which reinforces the need to manage *P. agathidicida* to reduce tree-to-tree spread and symptom development. Symptomatic kauri prevalence was also higher closer to historic timber sites (reducing with distance away from them) and increased with increasing tree size (DBH).

For the *P. agathidicida* model, associations were found showing *P. agathidicida* prevalence was higher with decreasing elevation, and with decreasing distance from historic timber sites and the coastline. It was also higher as the distance to the closest neighbouring tree decreased. In addition, our results found associations of note that are potentially biologically important between symptomatic kauri prevalence and distance to the coast, neighbouring tree distance, and distance to the closest uphill track; and *P. agathidicida* prevalence and distance to the closest track and presence of tanekaha. These require further investigation, particularly around effect size impacts from misclassification bias.

The results generated hypotheses for further investigation into understanding or managing these relationships, such as managing the distribution of *P. agathidicida* and development of disease through appropriate biosecurity and ecosystem protection measures.

Chapter 4

Estimation of the diagnostic sensitivity and specificity of kauri dieback visual assessment and *Phytophthora agathidicida* soil baiting, culturing and morphological identification using Bayesian latent class analysis

Te whakatau tatahanga o te aromatawai ā-tirohanga e ine ana i te tino putanga me te tino korenga o te puruheka patu kauri, te rumaki hoki i te one hei whakatipu i te puruheka patu kauri, hei whakarea hoki i taua puruheka rā, hei tautuhi hoki i te hanga mā tā Bayesian tātari i te momo e torohū ana

Authors

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4.1 Abstract

Te whakatūporotanga

An accurate and precise estimation of *Phytophthora agathidicida* diagnostic tests' performance is needed to design and interpret past and future surveillance work, including the identification of areas free of the pathogen. The tests are: i) an indirect test of visual assessment of trees for symptoms consistent with kauri dieback to predict or extrapolate the presence of *P. agathidicida* in association with a kauri tree and ii) a soil sampling, baiting, culture and morphological identification (referred to as the soil sampling bioassay) to detect *P. agathidicida* in association with a kauri tree. Test performance is measured by the diagnostic sensitivity (the probability of a tree that does have *P. agathidicida* in its soil returning a positive test result) and diagnostic specificity (the probability of a tree that does not have *P. agathidicida* in its soil returning a negative test result) not to be confused with analytical sensitivity and specificity more commonly discussed in plant pathology (refer to terminology). In the absence of a gold standard (perfect) test to determine the true *P. agathidicida* status of a kauri tree, Bayesian latent class analysis (BLCA) is used as a reference method to estimate the tests' performances.

A BLCA model was built using prior expert opinion on the tests' performance and pathogen prevalence where appropriate, and data was collected from 761 trees using visual assessment and the soil sampling bioassay. In total, 159 trees were sampled and visually assessed from an area that was delimited as having a high prevalence by experts and 572 trees from a low prevalence area in the Waitākere Ranges between March and July 2021. The two tests were assumed to be conditionally independent, which means that for a given true infection status, the probability of a given result for one was independent of the other test's result.

For visual assessment, the estimated sensitivity was 41.0% (95% PI 29.8-53.3) and the estimated specificity was 87.0% (95% PI 84.0-89.8).

For the soil sampling bioassay, the estimated sensitivity was 63.2% (95% PI 42.6-88.1) and the estimated specificity was 98.7% (95% PI 96.8-99.8). If we assumed a perfect specificity, i.e., if we assumed it could never give a false-positive result, which is reasonable for a culture test, the sensitivity remains similar at 63.8% (95% PI 43.3-89.1).

Limitations on these results included the fact that the priors were designed using expert elicitation on modifications of the tests (an 8-point rather than 4-point pooled sample) and a low sample size especially in the high prevalence area, leading to large credible intervals for sensitivity estimates.

Using the estimates from the present study to interpret previous surveillance work that used visual assessment and the soil sampling bioassay sequentially, it is likely that the true number of trees with *P. agathidicida* present is around 3.9 times what has historically been recorded.

Finally, the value of sensitivity for the soil sampling bioassay can be used to calculate sample sizes for the definition of areas free of *P. agathidicida*, which can be done easily if we assume a specificity of 100%. For example, if a sample size of 463 trees all test negative in an area with 10,000 kauri trees, we can be 95% confident that if *P. agathidicida* is present, it will be below a prevalence of 1%.

4.2 Introduction

Te whakataki

This study evaluates the diagnostic test performance of two tests that are used in surveillance to estimate the presence of *P. agathidicida* in soils beneath monitored kauri. The two tests are: i) an indirect test of visual assessment of trees for symptoms consistent with kauri dieback to predict or extrapolate the presence of *P. agathidicida* in association with a kauri tree and ii) a soil sampling, baiting, culture and morphological identification (referred to as the soil sampling bioassay) to detect *P. agathidicida* in association with a kauri tree. Obtaining accurate and precise estimates of diagnostic sensitivity (the probability of a truly positive individual to give a positive test result) and specificity (the probability of a truly negative individual to give a negative test result) of the tests used for monitoring is crucial to design and interpret the results of surveillance activities, including those previously completed. Diagnostic sensitivity and specificity refer to the performance of the full methods for a diagnostic test in a population (World Organisation for Animal Health, 2019, Cardwell et al., 2018). In this study we want to know how good our tests (visual assessment and soil sampling) are at diagnosing whether *P. agathidicida* is present or absent. Diagnostic sensitivity and sensitivity differ from, and can be confused with, analytical sensitivity and specificity, which are more commonly calculated for plant pathogen tests. Analytical sensitivity refers to the lowest level of target agent that can be measured accurately by the test (Cardwell et al., 2018) whereas analytical specificity is similar to diagnostic specificity but is concerned with performance around excluding non-target species and cross-reactions (false positives) in the laboratory (Cardwell et al., 2018). Traditionally, the estimation of diagnostic sensitivity and specificity directly follow the estimation of analytical sensitivity and specificity in the development and validation of diagnostic tests (Cardwell et al., 2018).

The diagnostic values are necessary for calculation of true prevalence estimates or sample sizes required to assign a site as *P. agathidicida*-free for management purposes (such as high-value protected areas). The values also allow land managers to compare tests so that the test (or tests) with the best characteristics for the surveillance question can be used. For example, tests with a high sensitivity are suitable for screening for a causal pathogen, and tests with a high specificity are useful for confirming disease caused by a specific pathogen (Dohoo et al., 2009). Possibly because of different disease surveillance designs and control goals, diagnostic sensitivity and specificity have rarely been estimated for tests for plant diseases. The only New Zealand example is (Heuer and Taylor, 2015) who estimated diagnostic sensitivity and specificity for *Pseudomonas synringae* pv. *actinidae* PCR assays in kiwifruit and used the values to provide recommendations to interpret test results and design detection surveys.

The presence of kauri dieback symptoms is assessed visually, aerially (Jamieson et al., 2014) and/or on the ground, or using remote sensing (Meiforth, 2020, Meiforth et al., 2020). The symptoms can resemble manifestations of stress for other reasons. Accurate detection of symptoms and attribution to *P. agathidicida* as opposed to another cause of stress is likely dependent on the observer's experience and knowledge of the location. The visual assessment usually includes an inspection on the ground by trained surveyors, who in addition to checking symptoms, decide if they are compatible with kauri dieback and not just ill-thrift. A five-point scale of disease severity of the canopy ranging from 1 for healthy trees to 5 for dead trees has been created by Dick and Bellgard (2010). Visual assessment is quick and relatively easy for trained observers to use as a test, however, it is uncertain how well visual assessment can predict **presence** of *P. agathidicida* and indicate infection by *P. agathidicida.*

The presence or absence of *P. agathidicida* for surveillance purposes is currently mainly investigated using the soil baiting, culture and morphological assessment described by (Beever et al., 2010). The performance of the assay itself is likely to be dependent on the soil sampling protocol used, and high inter-laboratory variation has been observed in the past (Froud, 2020), but efforts to standardise testing have been made (Beauchamp, 2016, Kauri Dieback Programme, 2017). However, any estimation of sensitivity and specificity will be specific to the sampling protocol and laboratory used to provide the data. Current surveillance activities use either a four (Auckland Council) or eight (Department of Conservation, Ministry for Primary Industries) cardinal points sampling protocol, and samples are tested at one or two of three approved research laboratories. The soil sampling bioassay is relatively expensive, causes direct disturbance to kauri roots and it is uncertain how well it can confirm the **absence** of *P. agathidicida.*

Traditional methods to estimate diagnostic sensitivity and specificity require the use of a gold standard, which is defined as a perfect test that never gives false-negative and false-positive results. In most cases, however, such a test does not exist. Bayesian latent class analysis for diagnostic test evaluation in the absence of a gold standard (Johnson et al., 2019, Cheung et al., 2021) allows estimation of test sensitivity and specificity even when no perfect test is available for comparison. This report estimates the diagnostic sensitivity and diagnostic specificity for *P. agathidicida* detection of the kauri dieback visual assessment test and the soil sampling bioassay (soil sampling, baiting, culture and morphological identification) used by Auckland Council using Bayesian latent class analysis. Additionally, it provides true prevalence estimates for two sets of sampling areas in Te Wao Nui ā Tiriwa / the Waitākere Ranges, North Island, New Zealand. This report follows the STARD-BLCM (Standards for the Reporting of Diagnostic accuracy studies by the use of Bayesian Latent Class Models) reporting guidelines (Kostoulas et al., 2017).

4.3 Objectives
Ngā whāinga

The objectives of this work were to undertake diagnostic test performance evaluation using latent class models of the following two tests:

i. Visual assessment of trees to detect symptoms of disease against a case definition
ii. Soil sampling bioassay involving baiting, culturing, and morphological identification

4.4 Methods
Ngā tikanga

This study closely followed the protocol detailed in (Vallee et al., 2019), with some modifications as detailed in this section. This study uses a latent class analysis methodology, described below. The following assumptions were made and deemed reasonable:

- The diagnostic sensitivity and specificity of both tests are constant across the different areas and trees sampled
- The two tests are conditionally independent, which means that for a given true infection status, knowing the result of one test would not change the chance of the other test to return a positive result
- The high and low prevalence areas have prevalence different from each other, and different from 0% and 100%. In other words, both areas have truly infected and truly healthy trees.

4.4.1 Data
The diagnostic test evaluation was done retrospectively using data previously collected from the cross-sectional prevalence study described in Chapter 2.

4.4.2 Tree selection
Trees were selected independently of disease status in the Waitākere Ranges (Figure 4-1) as described in Chapter 2. High and low prevalence sites were informed by previous surveillance activities. Possible high prevalence areas were assessed by Alastair Jamieson (Auckland Council), a kauri dieback aerial surveillance expert very familiar with the Waitākere Ranges, who used knowledge gained from two rounds of aerial surveillance looking for canopy ill-thrift in the Waitākere Ranges to inform risk-based ground surveillance in 2012 and 2016 (Hill et al., 2017, Jamieson, 2012b). Areas were identified on a map as apparently high prevalence polygons, including the surrounding contiguous area that was considered likely also to be affected, with all

other areas considered low prevalence (Figure 4-1). These identified areas were cross-checked by local mana whenua who hold mātauranga Māori (cultural knowledge) of the health status of the forest. In total, 189 kauri from the predefined high prevalence area and 572 trees from the low prevalence area were randomly selected.

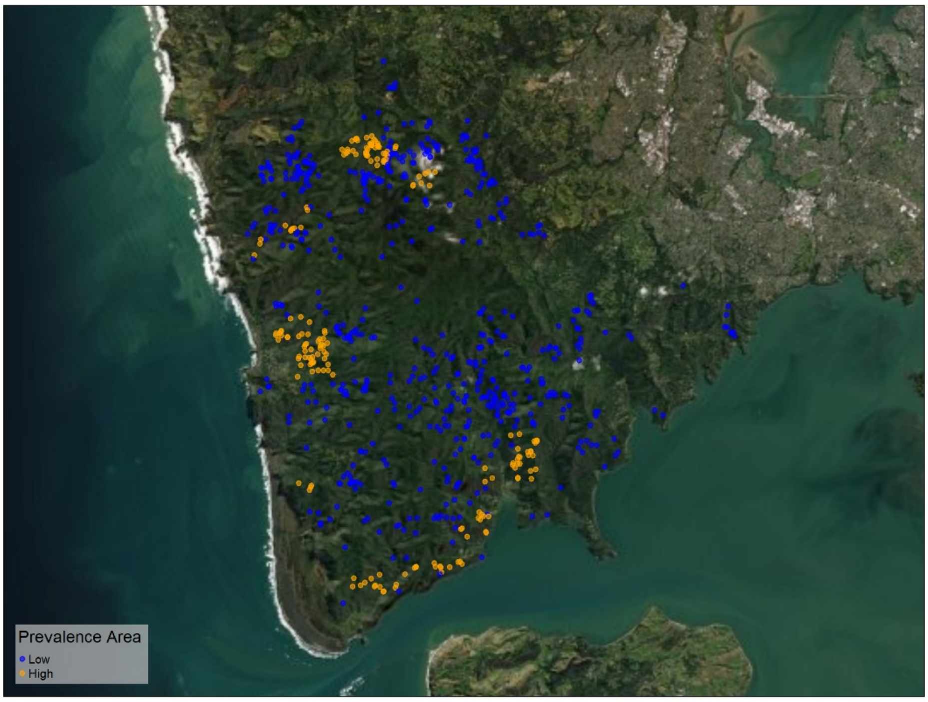


Figure 4-1. Locations of trees sampled in the Waitākere Ranges, North Island, New Zealand, for the evaluation of 2 kauri dieback diagnostic tests. Dots of tree locations from estimated low prevalence areas are in blue and dots for tree locations in estimated high prevalence areas are in yellow.

4.4.3 Visual assessment

Each pre-selected tree was visually assessed on the ground as described in Chapter 2 and using the case definition by Stevenson and Froud (2020). Surveyors observed the trees for the following symptoms: bleeding lesions on the basal trunk or lateral roots, the presence of canopy thinning (canopy score of 3 or higher as defined by Dick and Bellgard (2010)), yellowing of the foliage or copper-brown colour or tree death. Surveyors also observed the tree's surroundings to decide whether the observed symptoms were consistent with kauri dieback or could be attributed to another cause. Symptomatic trees, classified positive by visual assessment, were those showing at least one of the listed symptoms and where the surveyor decided they were consistent with possible or severe kauri dieback.

4.4.4 Soil sampling bioassay

Soil samples were collected around the base of pre-selected trees using the 4-cardinal point protocol at the time of visual assessment. Briefly, four samples were collected and pooled per tree and sent to Plant and Food Research, Havelock North, North Island, New Zealand for the soil bioassay which is described in Chapter 2.

4.4.5 Prior distributions for tests sensitivity and specificity, and prevalence

The method used for this analysis, based on Bayesian analyses, needs "prior" information that is credible, scientifically relevant, and formulated as probability distributions. These prior distributions reflect the knowledge of test performance and prevalence in the study area before this analysis, from recent studies and expert opinion. The priors used for the soil sampling bioassay (SB) were based on those obtained by (Vallee et al., 2019) using a formal expert elicitation process. The elicitation process followed the method described in Hemming et al. (2018): briefly, eight experts involved in *P. agathidicida* testing and kauri dieback management answered two rounds of an online survey asking for their opinion on the minimum, maximum and most likely value of the diagnostic sensitivity and specificity of the soil bioassay (with a modification of the sampling protocol, using 8 sampling points). Experts discussed the results of the first round face-to-face before doing the second round. Since the plant health discipline does not routinely use the diagnostic sensitivity and specificity concepts and because of the small change in sampling protocol, the intervals were modified before conducting the analysis to increase uncertainty and give more weight to the data. While the model used is identifiable (see 4.4.6 Model below), meaning that estimates of test performance can be obtained from the data only without the need for priors, the priors for SB were considered useful to help improve the precision of the posterior estimates.

"Flat" priors, giving an equal probability for all values between 0 and 100%, were used for the visual assessment (VA), as no reliable information was available. The use of these flat priors ensured that the values of sensitivity and specificity for VA were estimated only from the data, since the model was identifiable (See 4.4.6 Model below). The corresponding beta distribution is beta(1, 1).

Priors for high and low prevalence areas (pi1 and pi2 respectively) were based on previous aerial surveillance and expert opinion. Distributions were generated using BetaBuster, a purpose-built GUI to obtain Beta prior distributions (Su et al., 2012).

They are summarised in Table 4-1 and the distributions can be seen in the figures in Table 4-2 as well as Figure 4-3, Figure 4-5, Figure 4-7, and Figure 4-8.

Table 4-1. Prior belief and corresponding beta distributions for the different parameters needed to estimate the sensitivity and specificity of 2 tests for kauri dieback using BLCA

Parameter name and description	Description of prior belief	Prior distribution	Source
Se_{SB} (sensitivity of SB)	Min 65%, most likely 73% obtained from experts' elicitation; it was assumed this represented a 50% confidence interval	beta(2.89, 1.70)	Modified from Vallee et al. (2019)
Sp_{SB} (specificity of SB)	Min 86%, most likely 92% obtained from experts' elicitation;	beta(8.56, 1.66)	Modified from Vallee et al. (2019)

	it was assumed this represented a 50% confidence interval		
pi1 (high prevalence)	"40%, with some areas at 80%", set as 90% sure than lower than 80% and most likely at 50%	beta(2.06, 2.06)	A. Jamieson, Auckland Council, pers. comm.
pi2 (low prevalence)	50% sure that less than 5%, most likely at 4%	beta(3.42, 59.19)	A. Jamieson, Auckland Council, pers. comm.

The prior for SB specificity was narrower than for sensitivity, indicating that the experts had more confidence in their belief of specificity.

4.4.6 Model

The analysis follows the "two tests, two populations" method described in Branscum et al. (2005) and Johnson et al. (2019) and originally by Hui and Walter (1980). Briefly, the latent class analysis method used here relies on the existence of the true infection status, here the presence of *P. agathidicida* in the soil around a tree, that is unknown (latent) and that the two tests are measuring. It is the reference method to estimate a test's diagnostic sensitivity and specificity in the absence of a perfect, gold standard test and is recognised as such by the World Organisation for Animal Health (World Organisation for Animal Health, 2019). New developments and applications are regularly available (for example, see Cheung et al. (2021)).

The prior information on the parameters listed in Table 4-1, was combined with the data obtained from the tree visual assessment and the soil sampling bioassay in the two populations (Table 4-3) via a likelihood function representing the probability of observing the test results obtained after the tests were conducted as a function of the unknown parameters (sensitivities, specificities and prevalence).

Bayesian estimates of the 2.5th, 50th and 97.5th percentiles of the posterior probability distribution of Se_{VA}, Sp_{VA}, Se_{SB}, Sp_{SB}, high prevalence, low prevalence, the "inference after observing the data" (Johnson et al 2019), were then obtained using Markov Chain Monte Carlo (MCMC) chains with a Gibbs sampler with 50,000 iterations, and the first 10,000 were discarded for results presentations, to avoid any influence of values obtained before model convergence. Three chains were run in parallel, with spread initial values, and convergence was visually assessed on "trace" plots. The Gelman and Rubin's convergence diagnostics and the Gelman-Rubin-Brooks plot are presented in Appendix E. For more information on the Bayesian Latent Class Analysis method please refer to Branscum et al. (2005). The interpretation of the uncertainty intervals (named probability intervals PI) is more intuitive than the confidence intervals generated in a traditional frequentist (non-Bayesian) statistical approach. In other words, the 95% credible intervals presented in the results correspond to the 2.5th and 97.5th percentiles of the total number of iterations of the model. The analysis was conducted in

OpenBUGS (version 3.2.3, OpenBUGS Project Management Group, 2014). More details on the model structure and specification are found in the code in Appendix E.

4.4.7 Sensitivity analysis

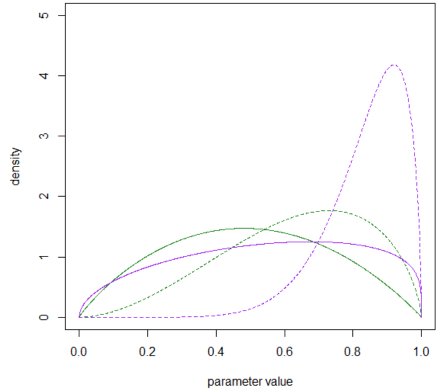
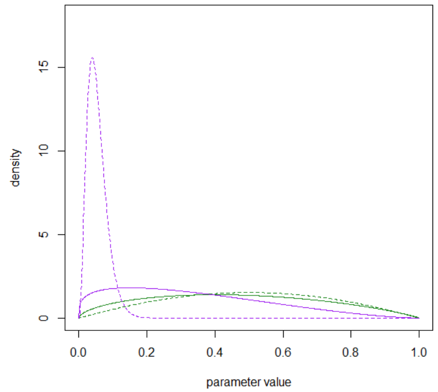
In the model used for this study, we are estimating 6 parameters (Se_{VA}, Sp_{VA}, Se_{SB}, Sp_{SB}, high prevalence pi1, low prevalence pi2). Under the assumption of conditional independence, the model is identifiable, which means that the values could be estimated using the data only, without the priors. Using priors is however often helpful, as it can help increasing the precision of the estimates. It is however important to assess the effect of the priors on the results to understand how they contribute to the final estimate and what effect any misspecification of the priors would have on the posterior distributions of the parameters. To assess the effect of priors on the results, the analysis was repeated seven times, each time with a small, plausible change in the prior distributions. The effect of the priors of VA, SB and prevalence were assessed separately, keeping the others constant. The prior distributions for test performance were obtained by modifying slightly the intervals given by the experts (see Vallee et al. (2019)) and transforming them into beta distribution using the 'prevalence' package in R that implements the method described by (Branscum et al., 2005), assuming an expert confidence of 80%. The priors for prevalence were obtained using BetaBuster (Su et al., 2012).

The following 7 changes to the prior distributions (Table 4-2) were used, in different runs of the model:

- Model run 1: The specificity for SB was fixed to 100%, with no uncertainty. Hence, there were only 5 parameters to estimate: Se_{VA}, Sp_{VA}, Se_{SB}, pi1, pi2
- Model run 2: Changing the most likely values to a value still plausible, and increasing slightly the uncertainty of the prior values for the soil sampling bioassay
- Model run 3: Changing the most likely values to a value still plausible, and increasing slightly the uncertainty of the prior values for prevalence

Sensitivity analyses were conducted using one chain and software-generated initial values.

Table 4-2. Changes in prior distributions used for the 3 different models run for the sensitivity analysis (min = minimum, ML = most likely, max = maximum).

Model run	Original priors	Change in prior assumption	Corresponding change in prior distribution	Plot of change in prior distribution (Se/pi1 in green, Sp/pi2 in purple, sensitivity analysis in plain line, original model in dashes)
1	Sp_{SB}: Min 86%, ML 92%	Sp_{SB}=100%	Sp_{SC}=1	
2	Se_{SB}: Min 65%, ML 73% Sp_{SB}: Min 86%, ML 92%	Se_{SB}: min=35%; ML=48%; Sp_{SB}: min=56%; ML=67%;	Se_{SB} ~ beta(1.90, 1.97) Sp_{SB} ~ beta(1.52, 1.25)	
3	pi1: max 80%, ML 50% pi2: max 5%, ML 4%	pi1: max = 60%, ML=40% pi2: max = 30%, ML=15%	pi1~ beta(1.58, 1.86) pi2~ beta(1.28, 2.58)	

4.5 Results and discussion

Ngā hua me te matapaki

4.5.1 Observed test results

The cross-classified test results for the two areas are presented in Table 4-3.

Table 4-3. Number of trees testing positive or negative for *P. agathidicida* by visual assessment (cases) and by soil baiting, culture and morphological identification (*P. agathidicida* detected vs not detected), stratified by population

		P. agathidicida detected (SB positive)	*P. agathidicida* not detected (SB negative)
High prevalence areas (n=189)	Cases (VA positive)	22	26
	Non-cases (VA negative)	35	106
Low prevalence areas (n=572)	Cases (VA positive)	8	73
	Non-cases (VA negative)	11	480

The apparent prevalence, defined as the proportion of tested trees that return a positive test result, of *P. agathidicida* measured by visual assessment were 25.4% in the high prevalence area and 14.1% in the low prevalence area (Figure 4-2 A). The apparent prevalence measured by soil baiting, culturing, and morphological identification was 30.2% in the high prevalence area and 3.3% in the low prevalence area (Table 4-3; Figure 4-2 B).

A

B

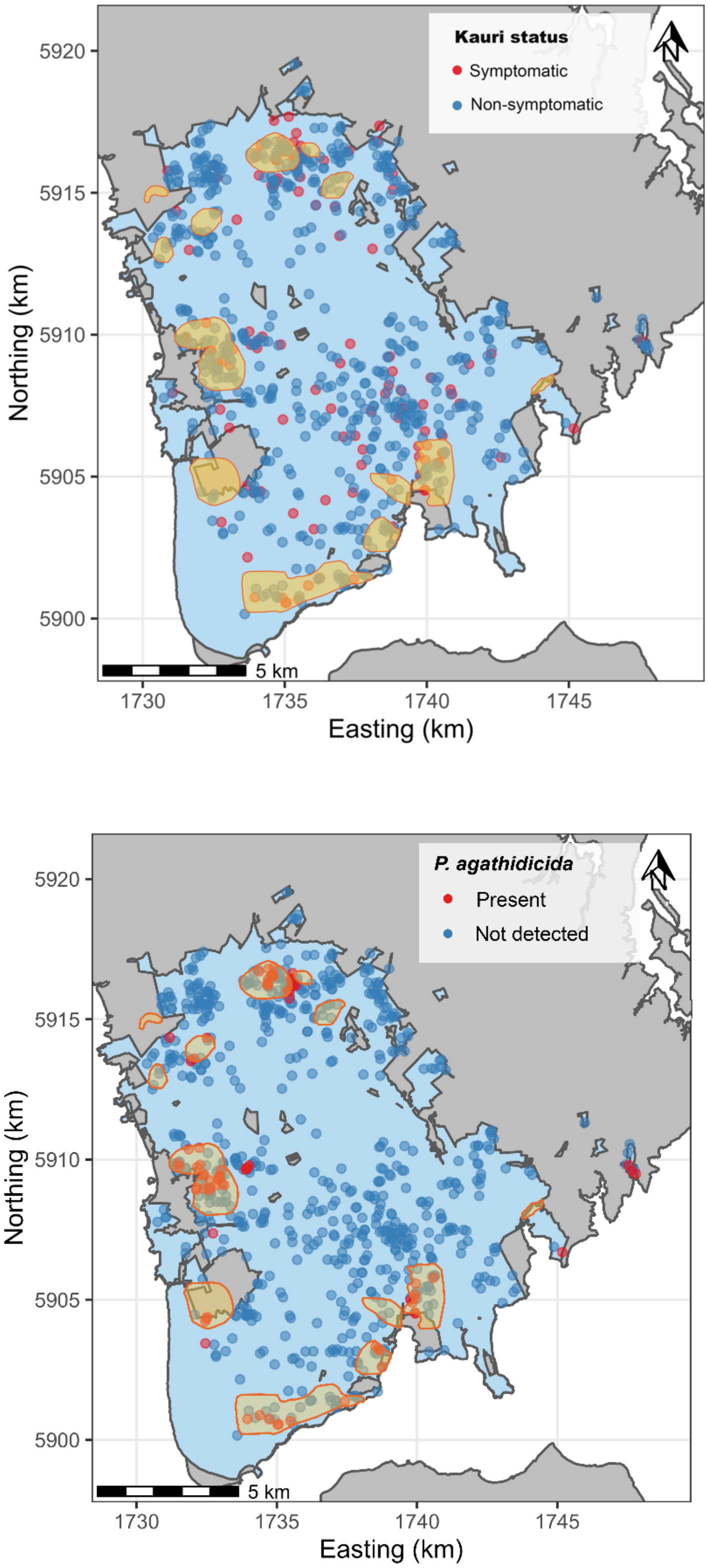


Figure 4-2. Point maps of the 2021 Waitākere Ranges survey showing the prior expected high prevalence areas (yellow-coloured polygons) and A) where *P. agathidicida* was predicted based on the visual assessment test and B) where *P. agathidicida* was detected based on the soil sampling bioassay.

4.5.2 BLCA results

The summary statistics of the posterior distributions for the six parameters are summarised in Table 4-4 and detailed in the following subsections.

Table 4-4. Summary statistics and Monte Carlo error for the six diagnostic test performance and prevalence parameters estimated using Bayesian latent class analysis.

	2.5 percentile	**Median**	**97.5 percentile**	**Mean**	**Standard deviation**	**Monte Carlo error**
Se VA	0.2977	0.4096	0.5333	0.411077	0.060471	0.000244
Sp VA	0.8395	0.8699	0.8981	0.869671	0.014984	0.000829
Se SB	0.426	0.6321	0.8809	0.637753	0.116273	0.000059
Sp SB	0.968	0.9872	0.9982	0.986171	0.007943	0.000035
Prevalence (high)	0.3145	0.4641	0.6745	0.471908	0.092095	0.000655
Prevalence (low)	0.01567	0.03804	0.07118	0.039414	0.014253	0.000074

The Monte Carlo error represents the random error that arise because the model takes random draws from probability distributions. In this model they are small, representing less than 1% of the standard deviation of all parameters except the VA specificity for which it is 5.5%. Overall, this means that the summary statistics presented in Table 4.4 are reliable.

4.5.2.1 Visual assessment performance evaluation

The estimated sensitivity for visual assessment was 41.0% (95% PI 29.8-53.3) (Figure 4-3A), which means that less than half of the trees with *P. agathidicida* in the root zone will be recorded positive by visual assessment.

The estimated specificity for visual assessment was 87.0% (95% PI 84.0-89.8) (Figure 4-3B), which means that 13% of trees without *P. agathidicida* in the root zone will be recorded positive by visual assessment.

To help with the interpretation of prevalence studies conducted using visual assessment as described above, the relationship between apparent prevalence (the proportion of trees positive by visual assessment, in other words, the proportion classified as symptomatic trees) and true prevalence (the proportion of truly infected trees, defined here by having *P. agathidicida* in the root zone of the tree) is presented in Figure 4-4. It can be calculated as follows:

TP = (AP+Sp-1)/(Se+Sp-1)

With TP the true prevalence and AP the apparent prevalence (Dohoo et al., 2009). For example, if 30% of trees are positive by visual assessment, the true prevalence of *P. agathidicida* in the soil is 60.7%.

This should, however, be interpreted with caution, as the presence of *P. agathidicida* is spatially clustered, and an estimation of the true prevalence in areas free of *P. agathidicida* would be erroneous. This relationship only applies when apparent prevalence lies between 13% and 41% (Dohoo et al, 2009, p103). If a value outside of these boundaries is observed, it is likely that the sampled trees come from kauri populations that differ from the current study, and the estimated values of sensitivity and specificity don't apply. This is likely to occur frequently with the visual assessment, as in areas (or time points) where dieback is present for other reasons the specificity of visual assessment to detect *P. agathidicida* will decrease.

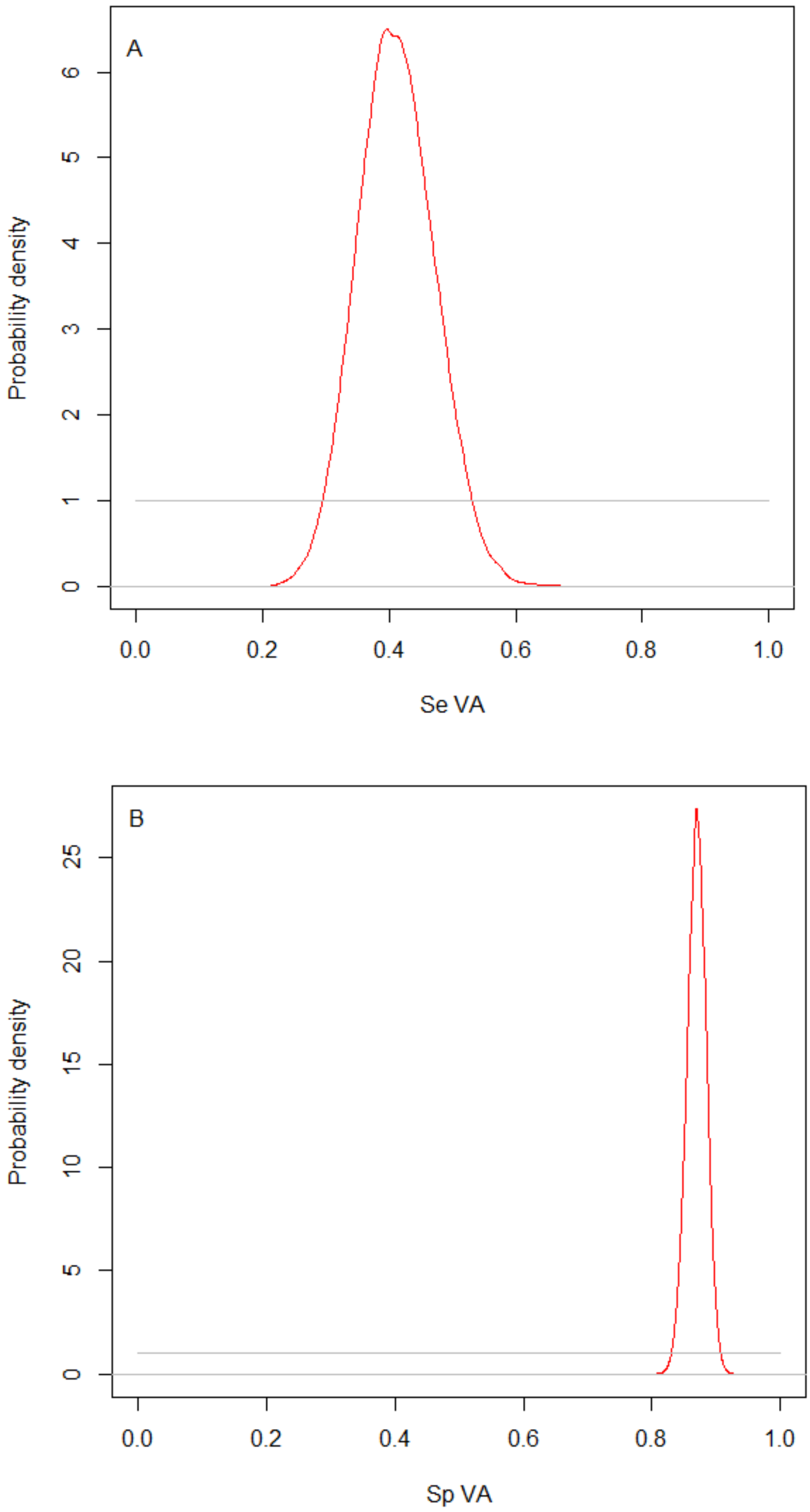


Figure 4-3. Prior (grey) and posterior (red) distributions of the sensitivity (A) and specificity (B) of the visual assessment test for *P. agathidicida*.

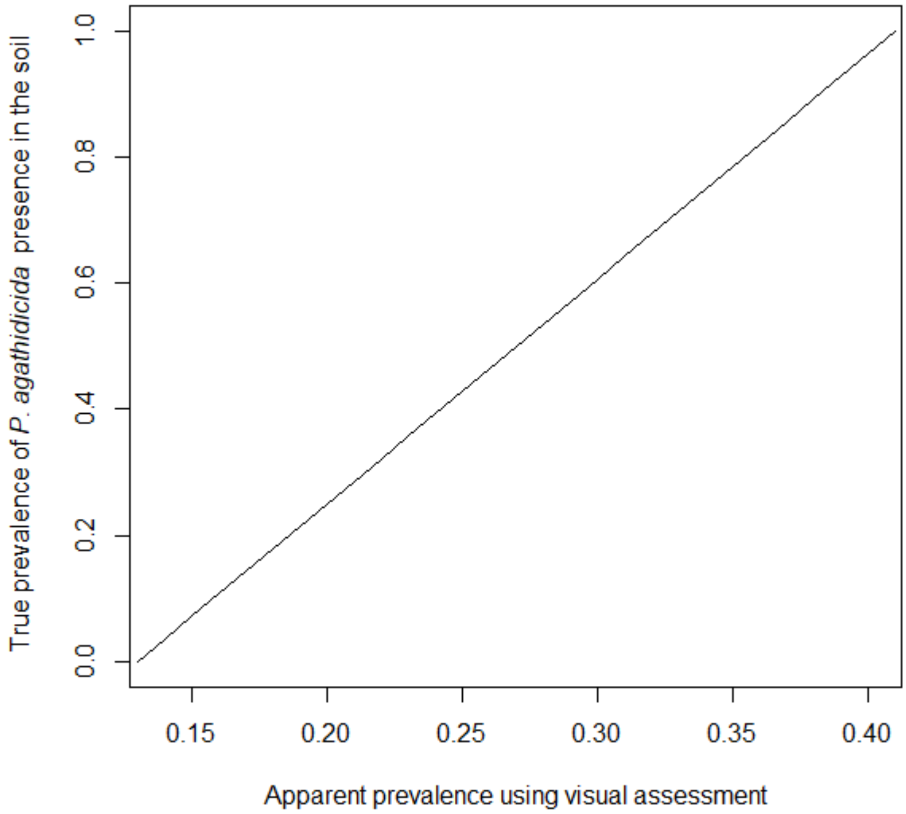


Figure 4-4. Relationship between the apparent prevalence of *P. agathidicida* using visual assessment of disease symptoms, and the true prevalence of *P. agathidicida*.

4.5.2.2 Soil sampling bioassay performance evaluation

The estimated sensitivity for the soil sampling bioassay was 63.2% (95% CI 42.6-88.1) (Figure 4-5A), which means that 63 out of 100 trees with *P. agathidicida* in the root zone will be recorded positive by soil bioassay. This was lower than the value obtained during experts' elicitation.

The estimated specificity for the soil sampling bioassay was 98.7% (95% CI 96.8-99.8) (Figure 4-5B), which was higher than the value obtained during experts' elicitation.

To help with the interpretation of prevalence studies conducted using the soil sampling bioassay as described above, the relationship between apparent prevalence (the proportion of trees returning a positive test result) and true prevalence (the proportion of truly infected, defined here by having *P. agathidicida* in the root zone of the tree) is presented in Figure 4-6. This relationship only applies when apparent prevalence lies between 1.3% (or 0 if we assume a perfect specificity) and 63.2%. In other words, because of the imperfect sensitivity, if the true prevalence is 100%, the apparent prevalence would be 63.2% at the maximum. If a study estimates a prevalence above this number, then the values of sensitivity and specificity calculated here do not apply.

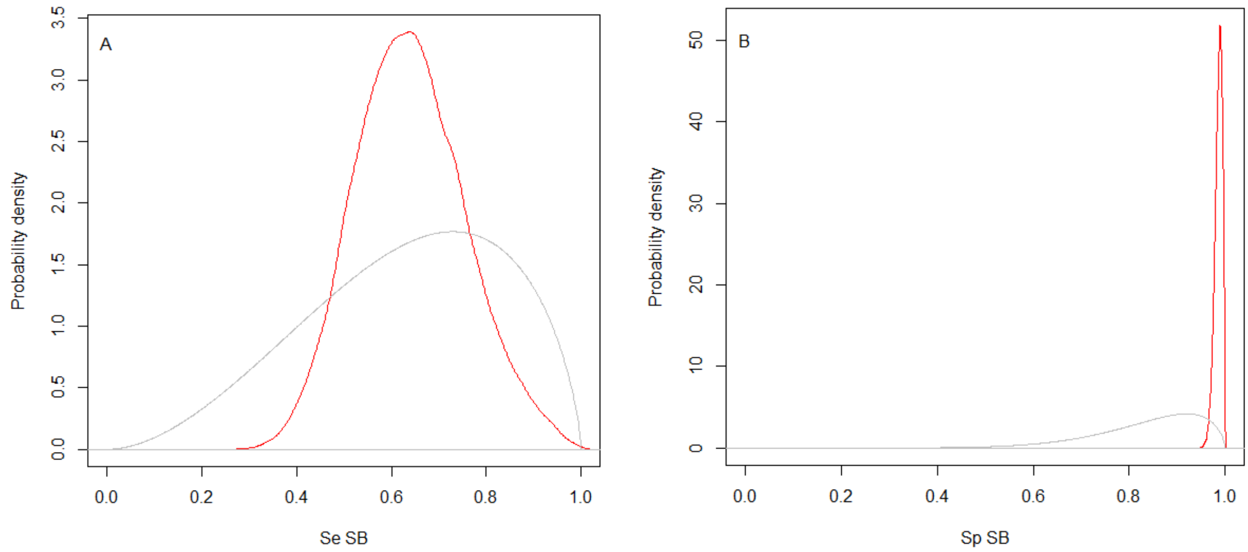


Figure 4-5. Prior (grey) and posterior (red) distributions of the sensitivity (A) and specificity (B) of the soil sampling bioassay test for *P. agathidicida*.

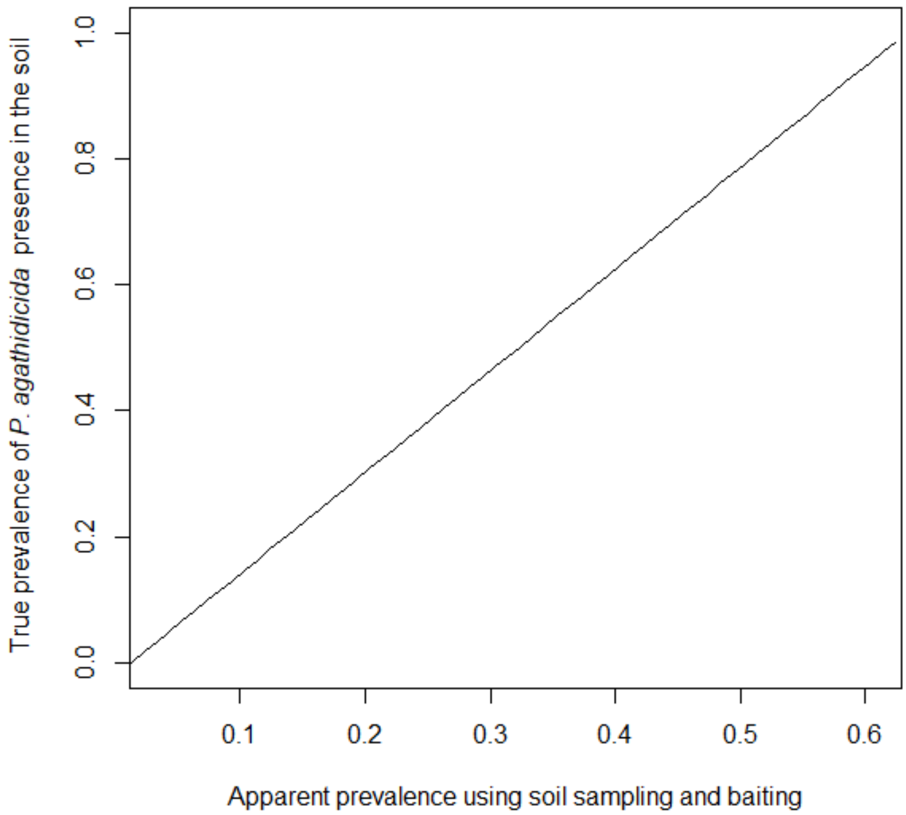


Figure 4-6. Relationship between the apparent prevalence using the soil sampling bioassay, and the calculated true prevalence of *P. agathidicida*

4.5.2.3 Prevalence

The apparent prevalence of *P. agathidicida* measured by visual assessment was 25.4% in the high prevalence area and 14.1% in the low prevalence area (Figure 4-2). The apparent prevalence measured by soil baiting, culturing, and morphological identification was 30.2% in the high prevalence area and 3.3% in the low prevalence area (Table 4-3).

In contrast, the true prevalence estimate, based on the "latent" infection status of the model, for the high prevalence area was 46.4% (95% CI 31.5-67.5, Figure 4-7A), and for the low prevalence area was 3.8% (95% CI 1.16-7.1%, Figure 4-7B). In other words, an estimated 46.4% of the trees in the high prevalence area truly have *P. agathidicida* in their soil. Interestingly, the posterior distribution for the low prevalence area was very similar to the distribution designed from the aerial surveyor's opinion, suggesting that aerial assessment may be an accurate test.

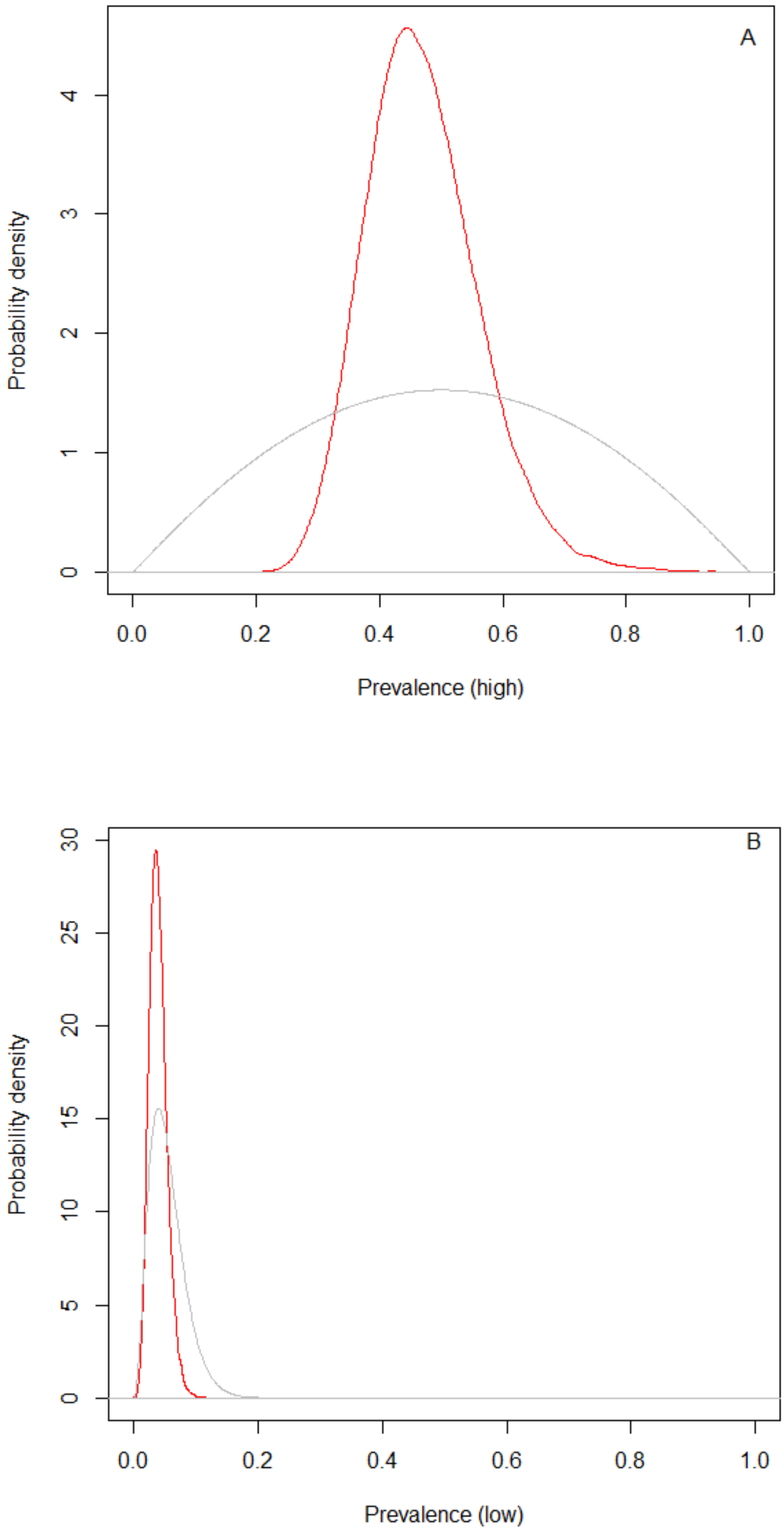
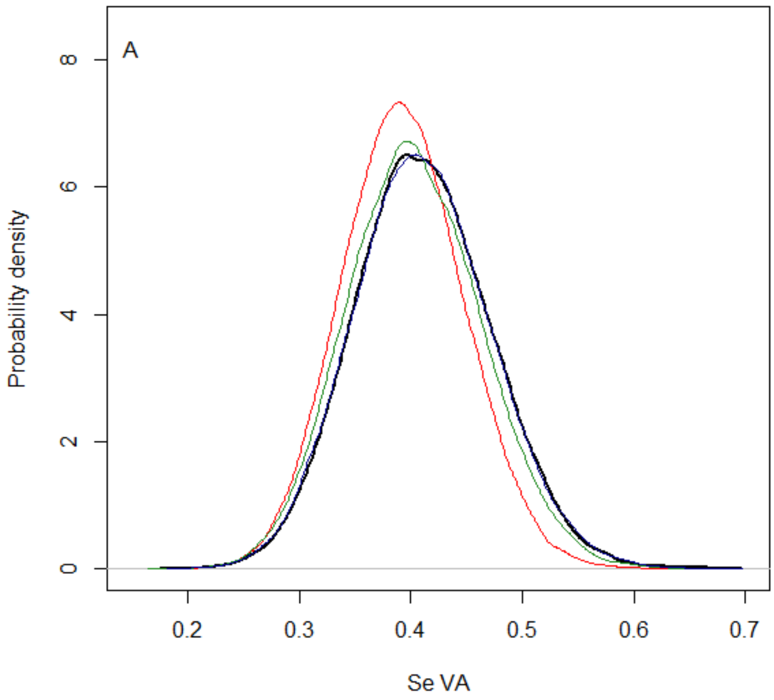
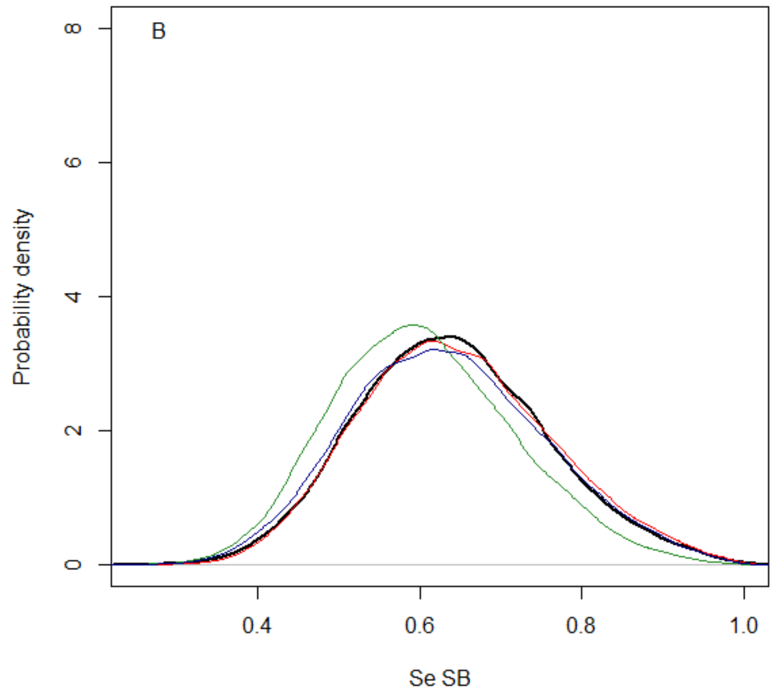


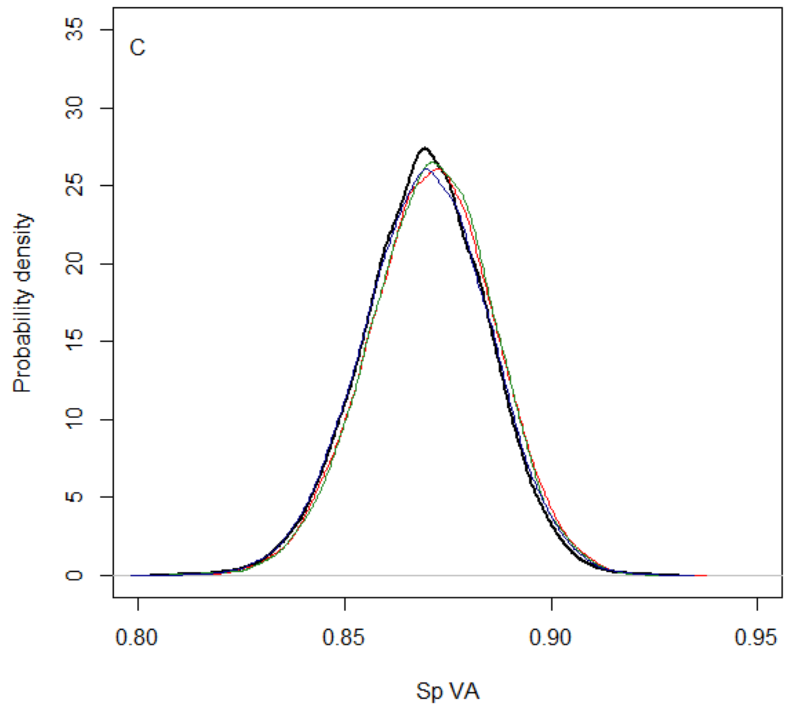
Figure 4-7. Prior (grey) and posterior (red) distributions of the true prevalence of *P. agathidicida* in the high prevalence area (A) and low prevalence area (B).

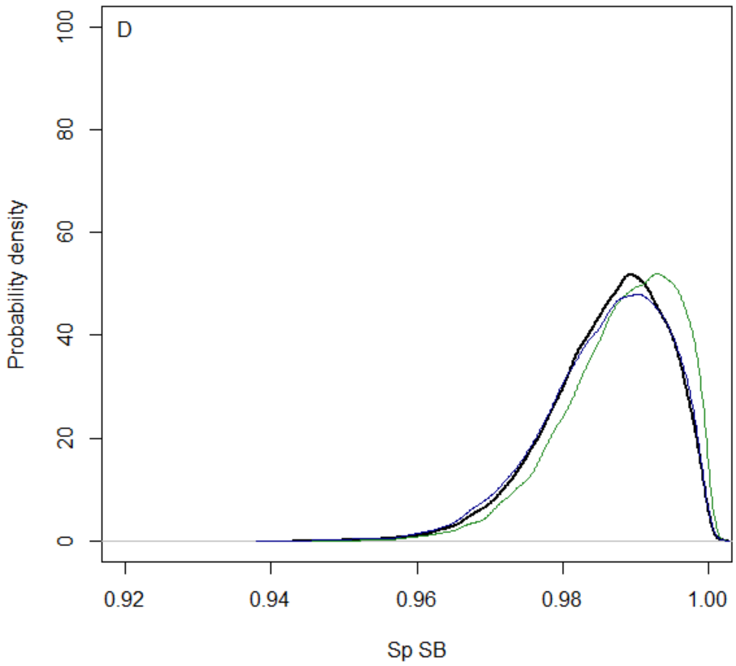
4.5.2.4 Sensitivity analysis

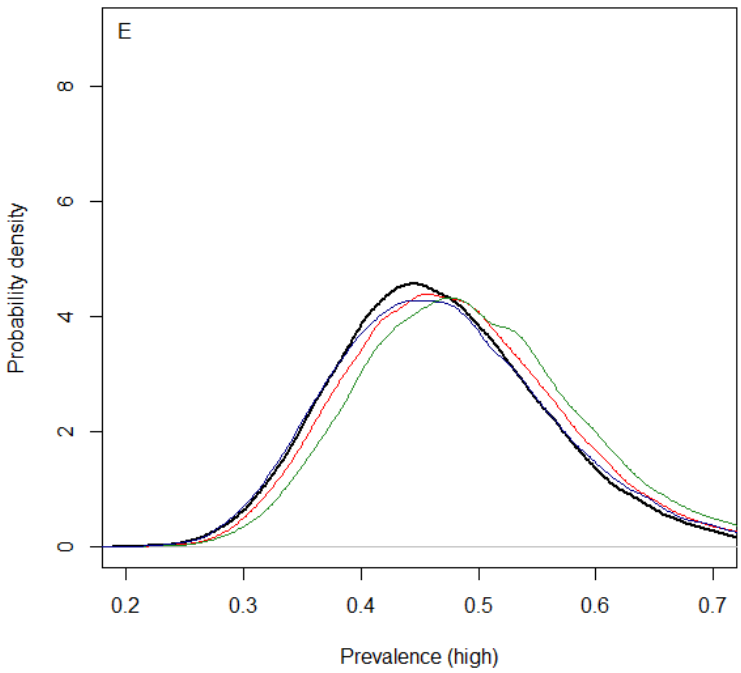
The results of the sensitivity analysis are presented in Figure 4-7. The effect of a change in priors on all the parameters were very small. Assuming a perfect Sp for the soil bioassay (model results shown by a red line on all panels of Figure 4-8) slightly changed the sensitivity of the VA and the prevalence (low), and the soil bioassay sensitivity remained the same, but the precision decreased (63.8%, 95% PI 43.3-89.1). Changing the soil bioassay priors (model results shown by a green line on all panels of Figure 4-8) slightly affected the soil bioassay sensitivity and specificity. A change in the priors for prevalence (in dark blue on Figure 4-8) did not seem to affect any of the parameters.




B
Probability density
0
2
4
6
8
0.4
0.6
0.8
1.0
Se SB


C
Probability density
0
5
10
15
20
25
30
35
0.80
0.85
0.90
0.95
Sp VA


D
Probability density
0
20
40
60
80
100
0.92
0.94
0.96
0.98
1.00
Sp SB


E
Probability density
0
2
4
6
8
0.2
0.3
0.4
0.5
0.6
0.7
Prevalence (high)

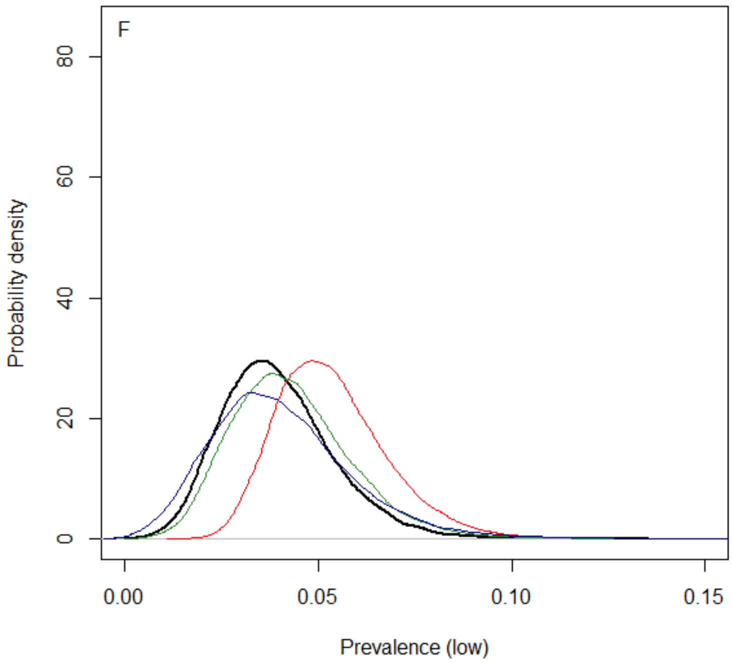


Figure 4-8. Posterior distributions for the sensitivity analysis of the visual assessment sensitivity (A), specificity (B), soil sampling bioassay sensitivity (C), specificity (D), true prevalence in the high prevalence area (E) and low prevalence area (F). The black line was the posterior distribution for the main result using the original priors, the red line for model 1, the forest green line for model 2, the dark blue line for model 3. See Table 4-2 for details on the change in priors for the different sensitivity analysis models.

4.5.3 Limitations

The following methodological limitations were identified and should be considered when using the results of this study.

4.5.3.1 Sampling protocol for soil sampling

It should be highlighted that the results are estimates from the whole procedure from soil sampling to baiting, culture and morphological identification, and not just the laboratory procedure. The methods used to conduct the standard morphological test do not have a standardised measurement of soil for baiting and uses 'about half a zip-lock sandwich bag of soil' for baiting. In addition, soil collection in the field used a minimum weight which had high variability due to soil moisture differences on different days (after rain vs long fine periods) and soil composition. It is likely that the test sensitivity depends on the quality of the sample, for example the quantity of fine roots, the composition of the soil, the experience of the person conducting the sampling, storage conditions of the soil along the process, and the volume of soil used in baiting.

4.5.3.2 Assumption of independence

One of the assumptions of the model was that the two tests, visual assessment and the soil sampling bioassay, were conditionally independent. This means that it was assumed that for a kauri tree with *P. agathidicida* in the soil, the knowledge of the visual assessment result would not affect the probability of the soil culture to be positive, and vice-versa; similarly for a tree free of *P. agathidicida*. This assumption is very likely satisfied.

4.5.3.3 Assumption of sensitivity and specificity constant across the study areas

Another important assumption of the model was that the diagnostic sensitivity and specificity of both tests are constant across the different areas and trees sampled. Spatial and temporal variability of the pathogen presence around the tree and soil conditions could affect the sensitivity of the soil sampling and baiting. While there is possibly variability in the samples due to the fact that 16 persons collected soil samples, this was mitigated by specific training and the fact that a large number of trees were sampled. The sensitivity and specificity of visual assessment are also likely affected by other factors such as visibility of the canopy from the ground, experience in using the canopy score scale, in identifying the lesions and in attributing the symptoms to kauri dieback rather than other causes of symptoms around the tree.

4.5.3.4 Sample size

The sample size used in the present study utilised samples from a planned randomised cross-sectional prevalence study (n=189 in the high prevalence area, n=572 in the low prevalence area) and therefore was lower than the recommended sample size in (Vallee et al., 2019). Vallee et al. (2019) recommended at least 800 trees, ideally 1200 across both sites for a specific diagnostic test evaluation study. In addition, only a quarter of the trees in the sample come from the high prevalence area, and the rest come from areas with an overall prevalence estimated at around 4%. This means that the total number of truly infected trees in the sample is likely low, which would have contributed to the higher credible intervals around the sensitivity estimates.

If refining the test sensitivity and specificity estimates was seen as a priority, then a further study could use the current estimates as priors. Indeed, one of the strengths of the Bayesian approach used here is that it can utilise new information to continually refine and improve parameter estimates.

4.5.3.5 Prior distributions

The tests evaluated here differ slightly from the tests for which the prior distributions were established though experts' elicitation (see Vallee et al. (2019)). Because of this, flat priors were used for VA. The SB priors were obtained for soil culture following an 8-point soil sampling protocol, not four points. In addition, the priors for prevalence, were not obtained via formal elicitation, but rather based on the opinion of a single expert, potentially making them more prone to bias. In this study the expert opinion for prevalence was however informed with results from previous studies in the area and was assumed to be reliable. Additionally, the sensitivity analysis showed that a misspecification of the priors for prevalence is unlikely to have affected the results.

4.5.3.6 Implication for interpretation of the tests in series in previous studies

In this study trees were tested using both test methods based on random selection from a sample frame and regardless of disease status. However, previous passive surveillance work has first identified ill-thrift trees during aerial surveillance or as part of a ground survey and then used the two tests sequentially. The trees were first assessed visually and only those with symptoms consistent with kauri dieback were tested by the soil sampling bioassay. Hence, to be considered positive, a tree had to test positive for both tests. Interpreting test results sequentially results in a decrease in diagnostic sensitivity and an increase in diagnostic specificity. This means that a higher proportion of trees with presence of *P. agathidicida* would have been missed by using the two tests in series than by using only one test, notably those that had no symptoms, the "non-symptomatic", but also because of the relatively low sensitivity of the soil sampling bioassay. As an example, in the dataset used for this analysis, in the high *P. agathidicida* prevalence area (where an estimated 189*45.7% = 88 truly infected trees were sampled), *P. agathidicida* was detected using the soil bioassay for more non-symptomatic trees (n=35) than symptomatic trees (n=22); if we had used the two tests in series, we would have classified 35 infected trees as healthy at the visual assessment stage, and thus not tested them for *P. agathidicida*.

If we maintain the original assumption of conditional independence (see Methods section), the sensitivity and specificity of the whole historic sequential testing procedure can be calculated (see Dohoo et al, 2009, p.111). Using the median values obtained from the model with the expert-elicited priors, we obtain the following values:

Se = 25.9%, which means that for 100 trees with a presence of *P. agathidicida*, only 26 would be detected using the sequential procedure

Sp = 99.8%, which means that for 100 trees without *P. agathidicida*, all would almost always test negative using the sequential procedure; in other words, the sequential testing is not expected to have produced any false positives

The previously stated limitations will also apply to these Se and Sp estimates, including the large uncertainty around sensitivity estimates.

These values could in theory be used to calculate the true prevalence of *P. agathidicida* using the apparent prevalence (i.e., the proportion of trees assessed that were positive using the sequential testing; this includes all trees that were visually assessed as not having kauri dieback signs). Some of the historic surveys do not provide the total number of trees visually assessed. If this proportion can be calculated, for example using an estimation of the number of kauri trees in the area, the following formula could be used:

$P = (AP + Sp - 1) / (Se + Sp - 1)$

With P the true prevalence and AP the apparent prevalence. Assuming that Sp = 1, this simplifies as

P = AP/0.259, which is roughly equivalent to multiplying the observed proportion or number of trees by 3.9.

4.5.3.7 Implications for sample size calculations for freedom of P. agathidicida

Using the sensitivity estimate (63.8%) assuming perfect specificity (100%) for the soil sampling and bioassay obtained from Model 1 in the sensitivity analysis, the number of trees to be sampled from an area to demonstrate freedom of *P. agathidicida* can be easily calculated, for example using a calculator such as https://epitools.ausvet.com.au/freedomss.

For example, in an area with 10,000 kauri trees, you would need to test 47 trees by the soil sampling bioassay to detect *P. agathidicida* at a prevalence of 10%, 94 at a prevalence of 5%, or 463 at a prevalence of 1%. If all trees return a negative result, we would be 95% confident that if the pathogen is present, it would be below this "design" prevalence. Note that the design of such a study would need to focus on areas that are small enough to assume a homogenous distribution of truly infected trees. The sample size will change depending on the level of confidence desired (the "required population sensitivity") and the population size of kauri trees in the area.

4.6 Conclusions and recommendations

Te whakatau me ngā tūtohunga

This study used data from a cross-sectional study to estimate diagnostic sensitivity and diagnostic specificity of visual assessment and soil sampling bioassay to detect the presence of *P. agathidicida* in the soil around kauri trees, using Bayesian latent class analysis. The study area was divided into presumed high and low prevalence areas.

For visual assessment, the estimated sensitivity was 41.0% (95% PI 29.8-53.3) and the estimated specificity 87.0% (95% PI 84.0-89.8). For the soil sampling bioassay, the estimated sensitivity was 63.2% (95% PI 42.6-88.1) and the estimated specificity 98.7% (95% PI 96.8-99.8). If we assumed a perfect specificity, the sensitivity for the soil sampling bioassay was 63.8% (95% PI 43.3-89.1). These values can be used to calculate the true prevalence of *P. agathidicida* in past and previous studies that used visual assessment or the soil sampling bioassay using the same procedures, or a sequential use of both tests. When both tests were used in series, it was estimated that the true prevalence was underestimated by a factor 3.9 in historical studies. These values, especially the diagnostic sensitivity of the soil sampling bioassay assuming a perfect specificity, can be used to calculate the required sample size for a proof-of-freedom survey.

The pre-defined high prevalence area had an estimated true prevalence of *P. agathidicida* of 46.4%, and the remaining low prevalence area had an estimated true prevalence of 3.8%.

The values obtained in this study are valid only for tests conducted using the same test methodology, i.e., with visual assessment following the exact same procedures, by skilled operators, or the soil sampling bioassay using the exact same soil collection methodology and laboratory procedures. An assessment of operator agreement would also be useful in deciding if an overall value is sufficient or if operator or laboratory specific values are needed. These results can be used as informed priors for future refinement of the sensitivity and specificity parameters. It is also recommended to interpret test results for prevalence studies on limited areas where the distribution of pathogen presence can be considered homogenous.

It is recommended that current and future tests' accuracy are also evaluated using Bayesian latent class analysis, which allows demonstrating a higher sensitivity of new tests, that the gold standard method does not allow.

Chapter 5

Key findings of the 2021 Waitākere Ranges survey

Ngā kitenga matua o te Rangahau i ngā Rākau Rangatira o Te Wao Nui ā Tiriwa 2021

The 2021 Waitākere Ranges survey has provided extensive new information about the state of kauri dieback within Te Wao Nui ā Tiriwa / Waitākere Ranges. The key findings of the three studies are detailed.

5.1 Key findings from the prevalence study

Ngā kitenga matua i te mātaitanga o te horapatanga o te mate

This study had 5 objectives i) operationalise new remote sensing methods to develop a kauri sample frame; ii) spatially describe the baseline prevalence of *P. agathidicida*; iii) spatially describe the baseline prevalence and severity of symptomatic kauri; iv) identify and collect data on key factors that could affect disease risk for hypothesis generation; and v) collect baseline data on ecological factors as indicators of ecosystem impacts from kauri dieback.

The key findings from this study are:

- The most important finding of this study was that *P. agathidicida* is located in localised areas around the periphery of the Waitākere Ranges parkland.
- It shows a pattern of point source introduction into distinct foci and natural spread (including via short distance vectoring) around those foci.
- It indicates that *P. agathidicida* has not yet achieved its full potential range.
- The relative risk surface showed two regions of elevated *P. agathidicida* detection risk, one in the northern area and one in the mid-west area of the Park. *Phytophthora agathidicida* is an Unwanted Organism and any areas where it is present are important for management.
- The majority (80.7%) of trees surveyed were either healthy (53.2%) or ill-thrift (27.5%) which is encouraging.
- The baseline pathogen prevalence of *P. agathidicida* detection in soils across the forest was 10% of sampled trees.
- The survey adjusted symptomatic kauri prevalence was 16.5% (95% CI: 14.1 to 18.9%).
- Symptomatic kauri overlapped the same outer periphery of the Park where *P. agathidicida* was present, but was also observed across the south-east region, where no *P. agathidicida* detections were made.
- The relative risk surface showed an elevated risk of disease in the north, which matched that for *P. agathidicida,* and in the south area of the Park, overlapped with *P. agathidicida* detection.
- The relative risk of disease was elevated, but not significantly, in the mid-west area where there was a higher risk for *P. agathidicida*.
- The observation of symptomatic kauri trees consistent with kauri dieback in the absence of *P. agathidicida* detection indicates that these symptoms are caused by other abiotic or biotic factors which require further investigation.
- With the number of samples taken in the south-east region it is most likely that *P. agathidicida* is truly absent. This is further supported by results in Chapter 4.
- More detailed examination of specific disease severity symptoms (using data collected in this study) in relation to detection of *P. agathidicida* in soils below symptomatic, ill-thrift and healthy trees is warranted.

- The first operational use of new remote sensing methods to identify kauri trees for inclusion in the sample frame and cross-validation of randomly selected trees was successful.
- Future research to train the classifier algorithm for host detection with more evenly spaced data across the forest area would improve the predicted kauri extent map.
- The method used to detect the kauri extent map was constrained by tree height, presence in the canopy and remote sensing algorithms, which may have biased our sample frame towards larger and healthier trees and may have slightly underestimated the prevalence of symptomatic kauri in the population.
- Baseline disease severity measures provide evidence of areas where interventions such as phosphite treatments are best targeted.
- One of the key findings from the collection of baseline data was the observation of kauri seedlings and saplings at 55% of monitored sites, including *P. agathidicida* sites. Repeated monitoring (over many years) will assess sapling survival and kauri regeneration at a rate sufficient to maintain a kauri dominant forest.
- The dataset collected during this study provides a taonga for future study to explore different variables and develop capability and capacity in researching environmental biosecurity epidemics.
- The study provides robust data and a consistent cohort of monitored trees to be remeasured over time using a repeated cross-sectional study design.
- These results will help inform protection of healthy kauri and ongoing and adaptive management of kauri dieback in the Waitākere Ranges and across Tāmaki Makaurau / Auckland.

5.2 Key findings from the risk factor multi-variable analysis study

Ngā kitenga matua i te mātaitanga o te matatini o te tātari i ngā whakaputanga tūraru

The aim of this study was to identify which environmental, host, anthropogenic and pathogen-related risk factors were associated with either symptomatic kauri or presence of *P. agathidicida*. For those that were associated, the aim was to generate hypotheses on the possible nature of the relationships.

The key findings from the symptomatic kauri and *P. agathidicida* modelling were:

- For the symptomatic kauri model, the strongest association was between symptomatic kauri and proximity to *P. agathidicida* sites (point locations of *P. agathidicida* detections) which reinforces the need to manage *P. agathidicida* to reduce tree to tree spread and symptom development.
- The prevalence of *P. agathidicida* in kauri reduced with increasing elevation. The association may be due to environmental constraints on pathogen survival, be related to

opportunities for vectored or natural spread, or other unmeasured factors such as soil type and chemistry may also affect the presence of *P. agathidicida* in soil and differ with elevation.

- The prevalence of *P. agathidicida* was associated with proximity to historic timber sites, which suggests a hypothesis of introduction and spread through increased soil disturbance near these sites.
- The prevalence of *P. agathidicida* was higher closer to the coast and may relate to factors such as historic introduction and spread pathways of *P. agathidicida,* higher human habitation and disturbance, or climatic differences between coastal areas and the inland forest. It is also consistent with mātauranga Māori (indigenous knowledge) that when the moana (ocean) is depleted, so too is the whenua (land), making the trees near the coast more vulnerable from this exploitation.
- This study raises the hypothesis of historical introduction from the coast and human assisted movement of *P. agathidicida* through timber and other disturbances. This is also supported by the limited distribution of *P. agathidicida* around the periphery of the study area.
- Not all symptomatic trees were near *P. agathidicida* detected sites, which indicates that while *P. agathidicida* management will be important in reducing disease, some other factors are also contributing to a decline in kauri health and should be investigated.
- The prevalence of symptomatic kauri was associated with proximity to historical timber sites, after accounting for *P. agathidicida* proximity. This indicates that the relationship is beyond an introduction pathway of the pathogen and indicates an effect due to soil disturbance and tree damage.
- The size of the kauri host was associated with symptomatic kauri. As the DBH values increased, so did the prevalence of symptomatic kauri.
- The distance to tracks (closest or uphill) was significantly associated with *P. agathidicida* detection and disease in the non-spatial models. However, the association reduced (the point estimates were closer to 1) and became more uncertain (wider credible intervals) in the spatial models and it is possible misclassification of the outcome variables is masking a greater effect.
- *P. cinnamomi* was not associated with symptomatic kauri in this study, a factor that has been uncertain in the past.
- Misclassified ill-thrift trees into the non-symptomatic class are most likely to push prevalence odds ratios towards 1 (the null) and may have reduced effect sizes.
- The diagnostic test sensitivity for the soil bioassay is relatively low and we may have missed over a third of the true positives. This misclassification would most likely lead to an underestimation of the true effect and pushed effect sizes towards the null.

It is easier to intervene with anthropogenic factors than environmental factors which tend not to be modifiable; however, they can inform management such as placement of amenities or replanting areas. The results generated hypotheses for further investigation into understanding or managing these relationships, such as managing the distribution of *P. agathidicida* and development of disease through appropriate biosecurity and ecosystem protection measures.

5.3 Key findings from the diagnostic test performance evaluation study

Ngā kitenga i te mātai arotake i te mahi ā-whakamātau kohura

The objective of the diagnostic test performance evaluation study was to obtain accurate and precise estimates of the diagnostic sensitivity and specificity of the visual assessment and soil bioassay to estimate presence or absence of *P. agathidicida*. Diagnostic sensitivity is the probability of a truly positive individual to give a positive test result and specificity is the probability of a truly negative individual to give a negative test result (not to be confused with analytical sensitivity which is the lowest level of target agent that can be measured accurately by the test (Cardwell et al., 2018)). Diagnostic sensitivity and specificity parameters are crucial to design and interpret the results of surveillance activities.

- For soil sampling and bioassay, the estimated sensitivity was 63.2% (95% CI 42.6-88.1) and the estimated specificity was 98.7% (95% CI 96.8-99.8). If we assumed a perfect specificity, i.e., if we assumed it could never give a false-positive result, the sensitivity was increased to 63.8% (95% CI 43.3-89.1).
- For visual assessment, the estimated sensitivity was 41.0% (95% CI 29.8-53.3) and the estimated specificity was 87.0% (95% CI 84.0-89.8).
- Historical surveillance using visual assessment then soil bioassay in series will have underestimated the true prevalence of *P. agathidicida*. It is more likely to be around 3.9 times what has historically been reported, within the same geographical areas.
- These results will help us interpret future and historic surveillance results and inform the planning of future tree-level monitoring and pathogen freedom surveillance.

Despite the low sensitivity of the soil bioassay test, it is still a vital and important tool for detection of *P. agathidicida*. Knowing these values will allow us to account for low test sensitivity when designing surveillance programmes.

5.4 Conclusions from the 2021 Waitākere Ranges Monitoring Survey

Ngā Whakatau i te Rangahau Aroturuki i ngā Rākau Rangatira o Te Wao Nui ā Tiriwa 2021

P. agathidicida is present in localised areas around the periphery of the Waitākere Ranges parkland indicating a pattern of point source introduction into distinct foci and natural spread, and that *P. agathidicida* has not yet achieved its full potential range.

Symptomatic kauri overlapped the same outer periphery of the Park where *P. agathidicida* was present, but was also observed across the south-east region, where no *P. agathidicida* detections were made. The relative risk surface showed an elevated risk of symptomatic trees in the north and south areas of the Park, which overlapped with *P. agathidicida* detection. The relative risk of symptomatic kauri was also elevated, but not significantly, in the mid-west area where there was a higher risk for *P. agathidicida*. Results of the risk factor analysis provided clear evidence of a strong association between the prevalence of symptomatic kauri consistent with kauri dieback and *P. agathidicida* in the Waitākere Ranges parkland. The causal relationship between *P. agathidicida* and kauri dieback is fully supported by previous research (Weir et al., 2015, Bellgard et al., 2013, Beever et al., 2010).

The risk factor modelling also showed associations between either *P. agathidicida* or symptomatic kauri with low elevation, historic timber sites, the coast, tracks and tanekaha, all of which indicate introduction pathways and disturbance.

The diagnostic test parameters for the soil bioassay were able to be used to estimate that in the centre of the forest where symptomatic kauri were present in the absence of *P. agathidicida* detections, we can be 95% confident that *P. agathidicida* was not present at a prevalence of 3.8% or 90% confident that *P. agathidicida* was not present at a prevalence of 2.9%. This supports our conclusion that *P. agathidicida* is most likely absent in that area. It is also now possible to calculate how many samples would be required to prove *P. agathidicida* freedom in this area to a 95% confidence it is below 1% prevalence.

The strong association between *P. agathidicida* and symptomatic kauri and localised distribution of *P. agathidicida* in the forest reinforces our knowledge that *P. agathidicida* is an 'infectious' disease, in that it is actively spread between hosts, and the first principles of infectious disease control of isolation, hygiene and treatment can be applied. This study provides evidence to support ongoing vector management of *P. agathidicida* in the Waitākere Ranges.

In the future, the soil bioassay should be combined with a more sensitive DNA-based test, such as LAMP, qPCR or, metabarcoding for all species in the *Phytophthora* genus. Samples were collected for LAMP diagnostic testing during the 2021 Waitākere Ranges survey, however due to Covid-19 disruptions, they were not able to be analysed. The LAMP assay and other tests that are in development require diagnostic sensitivity and specificity parameters to be calculated so that they can be compared for operational use in the future. While they are potentially more sensitive, they are likely to have lower specificity (more false positives) and this is important when ruling out the pathogen in *P. agathidicida*-free areas.

These results inform the implementation of the kauri forest, tree level and pathogen freedom sections of the long-term monitoring framework. Specific strategies for each level are discussed in the following section (Chapter 6).

Finally, the 2021 Waitākere Ranges survey results presented in this report are just a fraction of what this data may be able to tell us. Soil samples collected at the same time are being analysed in multiple research labs in partnership with Te Kawerau ā Maki, Auckland Council and Ngā Rākau

Taketake. Data from this survey not only sets up a baseline for repeated monitoring but provides a taonga for future researchers and mātauranga Māori to gain new insights on how we can improve kauri health in our forests.

5.5 Te Ao Māori

The survey of kauri in the regional park component of Te Wao Nui ā Tiriwa provides an important baseline from which to build on in the future. For Te Kawerau ā Maki this is a population and health census of our rākau rangatira (chiefly trees), which also gives us important insights into the mauri (health) of the forest as a whole. From a Te Ao Māori perspective, a number of key findings, questions and hypothesis emerge:

- Property boundaries such as the regional park boundaries used in this survey are arbitrarily placed upon nature and do not reflect the full identity of Te Wao Nui ā Tiriwa which extends from Titirangi to Muriwai. While the regional park boundaries are a pragmatic spatial extent for this first phase of work, other areas (both public and private) within the forest will need to be added to the picture in the future.
- With over 68,000 large kauri identified within the regional park it is likely the population of large kauri across the wider forest is well in excess of 100,000, and the total population including saplings multiple times again. The presence and density of kauri, and in particular rākau rangatira (old kauri), is in and of itself an important tohu (indicator) which comes from the whakataukī that the ngahere is a whānau.
- Of the trees surveyed, 53% were considered healthy, and kauri saplings were present at 55% of monitored sites. The fact that half of the rākau rangatira remain healthy is an indication the ngahere as a whole is fighting the disease but needs continued assistance from kaitiaki. The presence of saplings can be interpreted a number of ways but is seen as a good omen or tohu of regeneration or renewed life.
- This mahaki (*P. agathidicida)* is currently strongly localised to the perimeter of the forest.

Chapter 6

Future steps for the long-term strategy for monitoring kauri health in the Auckland region

Ngā mahi o anamata e pā ana ki te rautaki karioi hei aroturuki ki te hauora o te kauri i Tāmaki Makaurau

6.1 Strategy for implementation of the long-term kauri health monitoring framework

Te rautaki hei whakatinana i te anga karioi e aroturuki ana ki te hauora o te kauri

6.1.1 Landscape-scale kauri forest health monitoring

6.1.1.1 Introduction

The long incubation period of kauri dieback disease means that the temporal relationships between kauri health and the impacts of landscape scale mitigation measures such as rāhui and track closures may not show an association with change in disease for many years. Kauri health may get worse before any benefits of interventions are finally seen.

However, it is essential to obtain information on baseline kauri health so any change over time can be monitored and measurement of management intervention efficacy can be attempted. Understanding kauri forest health over time will allow associations with other potential drivers of kauri health to be monitored and assessed, such as changes in land use, management and climate over the long term.

6.1.1.2 Objectives

The key objectives of kauri forest-level health monitoring are:

- To identify the baseline prevalence of stress symptoms in kauri canopies caused by kauri dieback and other causes (e.g., drought) as a measurement of kauri health
- To monitor the change in kauri health over time against the baseline
- To identify kauri trees and kauri forest areas in the landscape that require management interventions based on these baseline and change measurements
- To measure the results of management interventions over time to inform adaptive management.

There are four key requirements to implement kauri forest-level health monitoring which are i) kauri mapping of the host population, ii) development of a stress index for kauri health monitoring, iii) methods to measure efficacy of landscape scale kauri protection interventions and iv) looking at long-term climate impacts on kauri forest health. There is also a development opportunity for mapping and monitoring the health of other native tree canopy species. The four key requirements and the recommended steps for each are described below.

6.1.1.2.1 Kauri population mapping

Building on the methods developed to detect kauri trees in Te Wao Nui ā Tiriwa / the Waitākere Ranges to monitor kauri health at the landscape scale across the wider Tāmaki Makaurau /

Auckland region, it is essential to map the kauri host population at risk in the forest canopy. The following steps are recommended:

1. Using the techniques developed for mapping the kauri population in the Waitākere Ranges, focus on mapping the kauri population in the Hunua Ranges, which contains the most extensive kauri forest in the Auckland Region where kauri dieback has not been found.
2. Build a kauri population map of kauri tree or stand locations defined by remote sensing and mapped for the forested and remnant kauri areas of greater Auckland. Target a minimum positive predictive value of 80% across size classes and disease statuses using existing and recently acquired remote sensing imagery.
3. Collect validation data on host detection and misclassification and undertake a diagnostic test performance evaluation on the sensitivity and specificity of the remote sensing 'test' for detecting kauri of certain characteristics.

6.1.1.2.2 Kauri stress monitoring

To set the baseline prevalence of landscape scale kauri health, methods to differentiate between kauri dieback induced stress vs drought or other canopy stress are needed. These remote sensing parameters can then be used to monitor change in kauri forest health over time. The following steps are recommended:

1. Develop a comprehensive geospatial kauri stress baseline index over the kauri extent layer (from above) for the Auckland region, where each pixel within a raster has a stress index value.
    a. Apply the Meiforth (2020) and Meiforth et al. (2020) developed methods of stress detection to set a geospatial baseline index of landscape scale kauri health based on this imagery.
    b. Build on the Meiforth et al. (2020) proof of concept methods to analyse canopy for stress symptoms in a wider range of kauri ecosystems.
2. Undertake research to assess change in health over time, acquiring repeated remote sensing imagery to provide the first comparison against baseline. With the aim of the research to assess if a change in stress can be detected, how a change would be measured and to recommend an appropriate frequency of assessment of change in kauri forest health (e.g., annually, two-yearly).
3. Undertake research to test if the Waitākere Ranges survey 2021 monitoring dataset can be utilised for disease vs drought stress validation.
    a. Use recently acquired host detection imagery to match monitored trees spatially.
    b. Use stress detection methods and the 2021 symptomatic kauri data to differentiate between kauri dieback induced stress vs drought or other canopy stress
    c. Use stress detection methods to assess any correlation between diseased trees and stressed trees (it is suspected that host stress increases disease).
4. Future research focus on whether localised periodic change in kauri dieback related stress indices can indicate areas of developing disease for early detection and pro-active management especially in disease-free areas.
5. Develop mātauranga Māori indicators as a complementary dataset to provide a future comparative baseline rooted in Te Ao Māori.
6. Repeat tree stress measurements to allow long-term climate impacts to be monitored across the forest.

6.1.1.2.3 Landscape scale kauri protection efficacy

To measure the efficacy of kauri protection measures over time (e.g., track closures, track upgrades, hygiene stations and phosphite treatments) the following actions are recommended:

1. Collate temporal and geospatial (time and place) data for all future kauri dieback mitigations. For example, hygiene stations are expected to protect forest that is contained within a specific track network. Geospatial layers need to be developed to show areas that are and are not protected by specific mitigations and for how long.
2. Wherever possible, collate historical geospatial and temporal data for kauri protection interventions (track upgrades, closures, rāhui, phosphite areas, pig control areas etc).
3. This data will eventually be able to be used to analyse kauri protection efficacy by modelling change in landscape-scale kauri health where interventions have and have not been applied long term.
4. Fully measuring efficacy of rāhui or other Māori cultural protection measures necessitates the development of mātauranga Māori indicators to supplement and corroborate other measures.

6.1.1.2.4 Long-term climate impacts on kauri forest health

It is reasonable to expect that the change in climate over the last 30-50 years may be contributing to kauri dieback disease (Homet et al., 2019, Aguayo et al., 2014). Extreme weather events such as drought and flooding affecting soil moisture levels may favour the pathogen and disadvantage the kauri host (Homet et al., 2019, Macinnis-Ng et al., 2013). It is recommended that:

1. Botanical epidemiological modelling of climate and kauri dieback are considered using the landscape prevalence of kauri health, knowledge of soil moisture effects (Macinnis-Ng et al., 2013) and the biology of *P. agathidicida.*
2. Climate data are acquired for monitored kauri forests at suitable spatial and temporal scales in conjunction with stress index measurements.
3. Climate data are used to inform the stress index with a view to classifying between disease and drought.

6.1.1.2.5 Mapping and monitoring other tree species at the landscape scale

Outside the scope of this work is the opportunity to utilise the baseline remote sensing data to characterise other forest canopy species within Tāmaki Makaurau that are currently at risk (e.g., from climate change, or *Myrtaceae* species such as pōhutukawa and rātā, susceptible to myrtle rust) or become at risk in future biosecurity events and to assess full forest health.

6.1.2 Implementation of tree-level kauri dieback disease monitoring

6.1.2.1 Introduction

The 2021 Waitākere Ranges survey aimed to refine the methods to set baseline disease and pathogen prevalence values and collect risk factor and ecological impact data. Building on the successful completion of the 2021 Waitākere Ranges survey, baseline tree-level monitoring needs to be extended to other kauri areas within Tāmaki Makaurau. In addition, repeated monitoring of areas with baseline prevalence values to measure incidence (the number of new symptomatic trees developing over time) is required for adaptive management of kauri dieback and to investigate efficacy of management measures.

6.1.2.2 Objectives

The key objectives of tree-level kauri dieback monitoring are:

- To set the baseline kauri host population at risk across Tāmaki Makaurau
- To undertake randomised ground-based monitoring studies in kauri dominant forest areas across Tāmaki Makaurau to:
  - set baseline symptomatic kauri prevalence
  - describe kauri, symptomatic kauri (consistent with kauri dieback) and *P. agathidicida* spatially
  - describe the severity of kauri dieback
  - monitor change in disease incidence (new cases) and disease severity (basal bleed and canopy health scores) over time
- To collect tree-level kauri dieback risk factor and ecological impact data from high priority representative kauri dominant forests within Tāmaki Makaurau
- To use the baseline prevalence and repeated monitoring incidence measurements to inform, prioritise and investigate efficacy of management measures.

There are several key steps required to implement kauri tree-level disease monitoring across Tāmaki Makaurau. These include site selection, considering additions to the unit of interest, kauri mapping, sample size calculations, refinements to field monitoring, analysis of monitoring results and calculation of incidence risk, and additional exploration of risk factors and plot monitoring. The recommended steps are described below.

6.1.2.3 Recommended steps

6.1.2.3.1 Site selection

Priority sites for future baseline monitoring need to be selected in partnership with mana whenua.

6.1.2.3.2 Units of interest and host population at risk

The recommended unit of interest is individual kauri trees that have a diameter at breast height (DBH) of greater than 10 cm and tree height of greater than 15 m. These parameters were tested in the 2021 Waitākere Ranges survey and were concluded to be an appropriate representation of kauri for the purposes of constructing a sample frame using remote sensing to detect the host population at risk. As remote sensing techniques are further refined, it may be possible that shorter ricker trees within dense stands in immature forest areas can be detected. If this technology is validated by Manaaki Whenua – Landcare Research, then shorter trees that are greater than 10 cm DBH could be included in the sample frame for selection and monitoring. This will be particularly useful in areas that have large stands of immature kauri trees that could be represented in baseline monitoring.

6.1.2.3.3 Kauri mapping

To monitor change in symptomatic kauri prevalence over time, it is essential to map the kauri host population at risk in the forest canopy so a sample frame can be built for random selection of monitored trees. It is recommended to:

1. Set the baseline kauri host population at risk using remote sensing as described in section 6.1.1.2.1 (Kauri population mapping).
2. It is recommended that the kauri extent layer is confined to trees >15 m in mature or regenerating forest (i.e., kauri dominant forest) at this stage, due to methodological constraints.
3. If <15 m canopy kauri can be detected in the future (through other research) then it could be added to the kauri extent layer, and smaller trees could be incorporated into future monitoring rounds.

6.1.2.3.4 Field monitoring

The methods deployed during the 2021 Waitākere Ranges survey are recommended for future studies, with the following minor modifications.

1. Mātauranga Māori indicators should be developed to monitor individual trees (using the same trees) noting that this data would form a separate iwi-held but complementary database.
2. It takes two people one hour on average to sample individual trees (including access time), therefore the sample size can be confirmed prior to the start of monitoring. Overall sample time may be reduced if the host detection accuracy can be improved. Analysis of GPS tracklogs from the surveyors will also allow the most efficient trails between trees to be plotted to aid efficient navigation to trees and reduce forest disturbance during repeated surveys.
3. In the future, the minimum sample size should be the starting sample, and if time and resources allow additional samples can be added (through the same random selection process).
4. Observer training, data validation and checking for missing values or inconsistencies should be conducted in real time during a specified training and pre-testing period prior to the start of the main survey.
5. A revised monitoring form has been drafted based on the survey results and excludes variables that were difficult to measure consistently in the field (e.g., new growth flush and seed cones). It should also include distance to closest kauri tree (>10 DBH) to assist understanding the risk and rate of spread (S. Green, Forest Research, United Kingdom, pers. comm.).
6. New tests with known sensitivity and specificity can be incorporated into future monitoring and compared with existing data based on calculated true prevalence values (refer to Chapter 4).

6.1.2.3.5 Sample size

The frequency of potential risk factors (how common they are) and their effect sizes (calculated in the 2021 Waitākere Ranges survey, Chapter 3) informs the future calculation of sample sizes. As does the estimated symptomatic kauri or *P. agathidicida* prevalence of the forests to be monitored and the known sensitivity and specificity parameters of the *P. agathidicida* tests (Chapter 4).

The recommended sample size for future monitoring surveys (both repeated and baseline in new areas) should be based on these criteria:

1. The sensitivity and specificity (Se/Sp) of the visual assessment test and the soil bioassay test, along with the combined Se/Sp if both tests are interpreted in series (refer to Chapter 4).
2. Whether sites will be assessed for baseline disease and *P. agathidicida* prevalence only, or if risk factor analysis is required.
3. Future surveys should consider use of DNA-based testing such as LAMP, qPCR or meta-barcoding, however the sensitivity and specificity parameters should be known in advance or calculated on first use. Note: LAMP testing (Winkworth et al., 2020) and diagnostic test evaluation was planned during the 2021 Waitākere Ranges survey, but was not possible due to sample loss caused by a COVID-19 lockdown part-way through baiting.
4. If the forest ecosystems are very different to the Waitākere Ranges Regional Park, such as the Hunua Ranges and Hauraki Gulf Islands. In these cases collection and analysis of risk factors are recommended to find different contributors to disease or pathogen risk. The factors that are different between forests are of the most interest and their estimated prevalence will inform sample size requirements.
5. Prior estimates of symptomatic kauri prevalence informed by land managers and mana whenua.

6.1.2.3.6 Analysis of monitoring results

The baseline prevalence methods and the R-code to analyse and visualise the results (for *P. agathidicida* sites and for symptomatic kauri trees consistent with kauri dieback) has been developed for future monitoring.

Analysis of incidence risk for repeated monitoring methods are as follows:

Baseline symptomatic kauri prevalence for each survey period is calculated by dividing the number of trees that met the symptomatic kauri criteria by the total number of trees selected in the survey period (Equation 1).

$$\text{Prevalence} = \frac{\text{Symptomatic kauri}}{(\text{Symptomatic kauri} + \text{Not Symptomatic kauri})} \qquad \textbf{Equation 1}$$

Because spontaneous or treatment assisted recovery is not known to occur, the incidence risk (also referred to as cumulative incidence) is calculated by counting the number of new cases of diseased trees (incident cases) that were not diseased (i.e., healthy or ill-thrift) at the start of the period and dividing that number by the number of trees initially at risk (Equation 2). If recovery is found to occur in the future, then that can be incorporated into the calculation as those trees return to the at-risk group when no longer diseased.

$$\text{Incidence risk} = \frac{\text{Number of new symptomatic kauri (incident cases)}}{\text{Number of trees initially at risk}}$$ **Equation 2**

Incidence risk can be compared between management areas such as stream sub-catchments where sufficient samples are available.

6.1.2.3.7 Additional monitoring and exploration of risk factors

The results of the multivariable modelling showed associations with several risk factors both for *P. agathidicida* and symptomatic kauri prevalence. The strongest relationship for symptomatic kauri was distance from *P. agathidicida* sites, confirming the known causal relationship with *P. agathidicida* and kauri dieback. Results from the prevalence study showed that observed disease is likely to be multifactorial and that while *P. agathidicida* is necessary to cause kauri dieback, it is not sufficient to cause disease without other contributing factors. We also found that symptoms consistent with kauri dieback were observed in areas where *P. agathidicida* was not detected. Further research is required to find other causal explanations for these symptoms and to refine the case definition to exclude misclassification of stressed trees from other causes.

Due to the cross-sectional study design (i.e., the dataset only provides information about symptom or pathogen status at a single point in time) in some instances it is not possible to infer a temporal and therefore potentially causal relationship for associated variables. The intent of a cross-sectional study is to describe disease and risk factors in space and time to generate and test hypotheses on associations and discuss what the causal relationship may be to inform possible management interventions. Interventions are easier for anthropogenic risk factors than for non-modifiable environmental risk factors. Therefore, each associated variable (both strongly associated and of note variables) will need to be assessed to decide what, if any, further management or research could be taken based on the evidence. For example:

1. Can the risk factor be managed in any way?
2. Is the association strong?
3. How frequent is the risk factor within the kauri tree population?
4. Is pro-active management of the risk factor warranted to reduce risk?
5. Is further research required to understand the causal relationship of the risk factor?
6. What risk factors were suggested, but not able to be measured?

An example of the latter is pig disturbance. It will be useful to work with ecologists to design a way to collect pig density data for future studies. For example, while we included a monitoring form variable asking if the roots had been disturbed around the monitored tree, this missed the field observation of significant pig sign in some areas of the Waitākere Ranges. One option for measuring this would be to record way-points for every pig sign while navigating to the monitored tree and convert that into a spatial pig-sign density value per management area (e.g., stream sub-catchments), which has been undertaken in earlier studies (Auckland Council, 2010). Collection of pig faeces for laboratory analysis could also be included in field monitoring (e.g., DNA fingerprinting of individuals).

In addition to adding mātauranga Māori indicators to repeated cross-sectional ground monitoring surveys, there is an opportunity for iwi to develop mātauranga Māori indicators that require more frequent or seasonal measurement to monitor individual indicators (e.g., birds) around monitored kauri trees (potentially using a subset of the same trees) noting that this data would also form a separate iwi-held but complementary database.

A mixed-model approach of tree-level and plot-based kauri dieback monitoring was initially proposed, however, due to time and economic constraints, plot-based sampling was not included in the 2021 Waitākere Ranges survey. The advantage of tree-level monitoring was that we could quantify prevalence of *P. agathidicida* and symptomatic kauri across the forest, undertake diagnostic test evaluation and generate hypotheses about risk factors across the entire study region. This made the method more cost-efficient. The Kauri Protection Agency has indicated it may fund plot-based sampling and these results will indicate if it would be useful to extend into Tāmaki Makaurau. If this is not undertaken, then consideration of the value and costs of intensive field plot surveys for the Auckland region should be explored to support ecological impact assessment which is more suited to a plot-based approach. A potential methodology to build on existing data from the prevalence and risk factor surveys would be to apply a forestry plot-based methodology using the central point of the monitored kauri tree to centre a 20 m x 20 m plot. Where monitored plots that contain kauri already exist in the Waitākere Ranges, it is recommended to force their selection during sample selection, so that historical records can be included. These intensive survey plots would provide evidence of ecological change over time which will give a finer understanding of ecosystem impacts such as kauri loss in the forest.

6.1.3 Implementation of pathogen freedom and disease freedom surveillance

6.1.3.1 Introduction

Site-level *P. agathidicida* pathogen freedom and tree-level kauri dieback disease freedom surveillance is aimed at early detection of *P. agathidicida* in areas previously thought to be free of the pathogen (including high value areas), and early detection of kauri dieback in high value areas previously known to have *P. agathidicida* present but not exhibiting significant disease. This will inform protection areas, ongoing pathogen spread prevention, and the investigation and management of new outbreaks.

Freedom surveillance will be useful in three scenarios where:

1. *P. agathidicida* has not been detected and symptomatic kauri trees are absent or rare
2. Symptomatic kauri trees are present but *P. agathidicida* has not been detected from sampling
3. *P. agathidicida* has been detected, but kauri dieback is absent or rare

The key questions that were identified based on these three scenarios were:

- Where are kauri present and absent in the forest area?
- Where is *P. agathidicida* present and where is it absent and how certain can we be about this?
- Where are symptomatic trees and non-symptomatic trees?
- What would risk-informed buffer zones look like?
- Where should vector management be applied (human and animal)?

An example would be the south-east area of the Waitākere Ranges Regional Park where symptomatic kauri trees consistent with kauri dieback were recorded but *P. agathidicida* was not detected. Questions that are raised by this result are:

- What management decisions could be made in this area?
- How could pathogen freedom surveillance support these decisions?
- Should protection from *P. agathidicida* spread into this area be attempted?
- Are trees that are exposed to other component causes of disease (risk factors) more vulnerable to the introduction of a severe pathogen like *P. agathidicida*?
- Could this area be restricted for access other than for pest control and increased pig culling and/or exclusion?
- Would pathogen freedom be needed to continue support for ongoing restrictions, and how often (burden of proof for public support of interventions)?
- Would pathogen freedom surveillance be deployed for early detection of *P. agathidicida* into the area so rapid treatment could be applied to contain spread?

6.1.3.2 Objectives

The ultimate aim of freedom surveillance from a practical management perspective is to provide robust evidence to support protection areas and identify where forest access could be provided safely to maximise the amenity value to Auckland communities.

Freedom surveys build on knowledge from the higher levels of the long-term monitoring framework. They rely on kauri mapping of the host population from the kauri forest level monitoring, and understanding the baseline disease and pathogen prevalence, and risk factors of selected areas from tree-level baseline prevalence monitoring. The key development steps required to implement risk-based freedom surveys include sample selection and sample size calculations and development of risk maps in kauri dieback-free areas.

It is recommended that baseline tree-level disease and pathogen prevalence and risk factor monitoring is conducted in selected sites first and then freedom surveillance is implemented in forests where no disease and/or *P. agathidicida* is detected. Where disease or *P. agathidicida* is detected, then repeated monitoring for incidence is required rather than freedom surveillance. Frequency of monitoring or freedom surveillance will be objective dependant but is estimated to be approximately five yearly.

The development areas and the recommended steps for sample size and selection and risk maps are described below.

6.1.3.3 Recommended steps

6.1.3.3.1 Sample selection and sample size

For kauri dieback, risk-map based freedom surveillance trees for inclusion in surveillance change over time. This is based on the value of the information that they contribute to understanding disease freedom. The risk factors identified from the tree-level cross-sectional observational study will help to identify the trees most susceptible to becoming infected in areas thought to be free of the disease. Sampling would initially focus on these trees, but because we believe kauri dieback spreads and develops slowly over many years, these trees would provide relatively little new information if re-sampled the following year. Therefore, the model for risk of infection will also incorporate the sampling history of individual trees (and stands, if disease is found to cluster) to identify those that contribute the most to proof of freedom.

The diagnostic test performance evaluation has provided estimates of the sensitivity and specificity of visual assessment and the soil sampling bioassay. These parameters, along with results of prevalence surveys for disease and pathogen, along with risk factor frequencies are used to calculate the sample size required to be 95% confident that *P. agathidicida* would be detected if it was present at a set design prevalence such as 5%.

The parameters can be used to estimate the prevalence level of *P. agathidicida* above which there would be 95% confidence of detection in an area that has been surveyed using the soil sampling bioassay test. A real example from an area of the Waitākere Ranges Regional Park where symptomatic kauri were recorded, but no *P. agathidicida* was detected during the 2021 survey can be used to illustrate sample size calculations using the soil sampling bioassay sensitivity value and the AusVet Epitools calculator (https://epitools.ausvet.com.au/herdsensfive) (Figure 6-1). There were an estimated 12,680 kauri trees in the polygon depicted in Figure 8 which were at least 500 m from any known *P. agathidicida* site, of which 125 were soil sampled. Using the Se parameters of the soil sampling bioassay test, we can be 95% confident that *P. agathidicida* was not present at a prevalence of 3.8% or 90% confident that *P. agathidicida* was not present at a prevalence of 2.9%. Note that this assumes random, representative sampling in a study designed for detecting freedom, and where the distribution of positives would be homogenous.

Figure 6-1. Map showing point locations of 125 soil samples collected from an area (inside the polygon) of the Waitākere Ranges Regional Park containing an estimated 12,680 kauri trees where *P. agathidicida* was not detected during the 2021 Waitākere Ranges survey.

6.1.3.3.2 Kauri host and risk maps for sample selection

To undertake risk-based disease or pathogen freedom surveillance, two types of maps are required. Firstly, the host population at risk needs to be mapped. Then, a series of risk map layers should be overlaid onto the host map. The risk maps show the spatial distribution of the risk factors identified in Chapter 3 (refer to Appendix G as an example from the Waitākere Survey). The spatial distribution of risk factors would be collected from field survey or GIS data during ground-based baseline prevalence monitoring. Future research under Ngā Rākau Taketake could inform additional risks and improve selection of sample sites.

An example of predicted probability maps for the Waitākere Ranges were constructed from the multivariable modelling (Chapter 3) and give an indication of what the risk maps may look like for other areas. The predicted probability in Figures 5 and 6 indicates the chance of a representative kauri having each outcome (disease or *P. agathidicida*) if there was a tree with DBH of 80 cm and the distance to the closest neighbouring tree of 2 m for both models and with tanekaha nearby for the *P. agathidicida* model only. These figures should be used as illustrations only as the model predicted probability does not consider any bias, such as the weighted sampling in a pre-known kauri dieback prevalent area at the early stage of sampling (only in the disease map), thus the maps may over- or under-represent the reality.

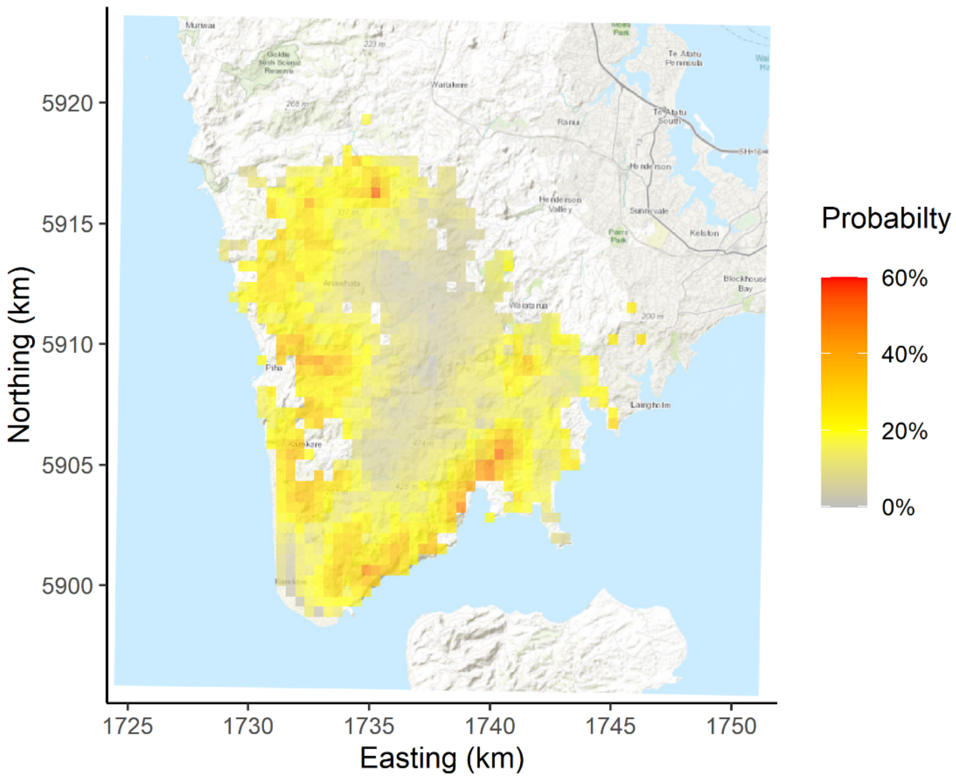


Figure 6-2. Predicted probability of symptomatic kauri presence for a representative kauri across the Waitākere Ranges study area.

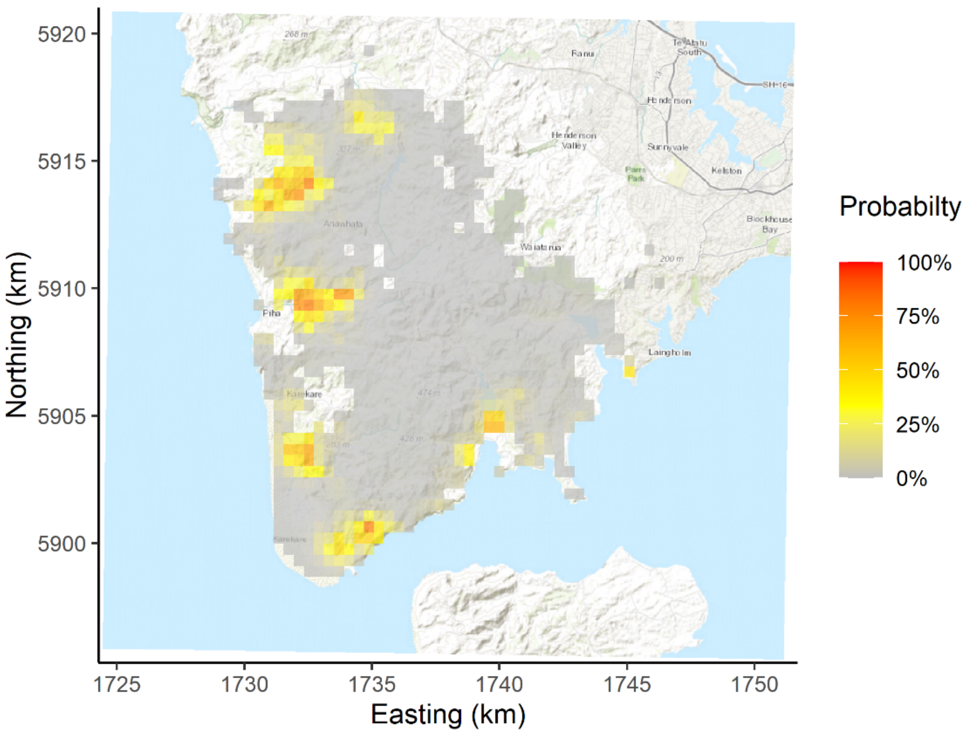


Figure 6-3. Predicted probability of *P. agathidicida* detection for a representative kauri across the Waitākere Ranges study area.

Prevalence ratios inform the surveillance effort and location (high risk sites) and the test performance parameters (sensitivity and specificity) inform the sample size. Samples are taken at the highest risk sites and the results support absence from pathogen or disease at lower risk sites without the cost of surveying them. In the future the kauri health stress index may also contribute to the risk map, identifying areas of higher disease risk.

As an extra step, forest maps should be assessed to see if the host population kauri map and the high-risk areas fully overlap or if the high-risk areas form discrete areas within the extent of kauri forest. Where they are discrete it is most efficient to undertake risk-based freedom surveys. However, where they fully (or mostly) overlap then it is better to undertake repeated prevalence monitoring as there are no target areas of risk to base freedom surveys on. Both use a randomisation of samples across either the host population surface (prevalence survey) or the relative risk surface (freedom survey).

A potential limitation of extrapolating the symptomatic kauri and *P. agathidicida* risk models from the 2021 Waitākere Ranges survey to other areas is if forests have different spread mechanisms. In that, the model may not apply to an area where *P. agathidicida* is absent as it is driven by within forest spread variables that may not be relevant. For example, earthworks introducing *P. agathidicida* vs pigs spreading *P. agathidicida* within the forest. Therefore, the baseline *P. agathidicida* site prevalence and the symptomatic kauri trees consistent with kauri dieback prevalence needs to be known in advance.

6.1.4 Conclusion

Finally, the results of the 2021 Waitākere Ranges survey have moved our understanding of both the presence of *P. agathidicida* in the forest and role it plays in the distribution of symptomatic trees. We have new information on factors associated with higher prevalence which we can apply to new areas to inform risk-based monitoring and we have an estimate of the diagnostic test parameters for our tests, which allow us to estimate the sample size for future surveys. We have also proven the value of using remote sensing to build a kauri extent map as the anchor to build our surveillance designs.

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Appendix A

Monitoring form and detailed methods for study variables

Te puka aroturuki me ngā tikanga whai taipitopito mō te inenga me te tātaitanga o ngā taurangi mātai

A1 Use of monitoring form

Te whakamahinga o te puka aroturuki

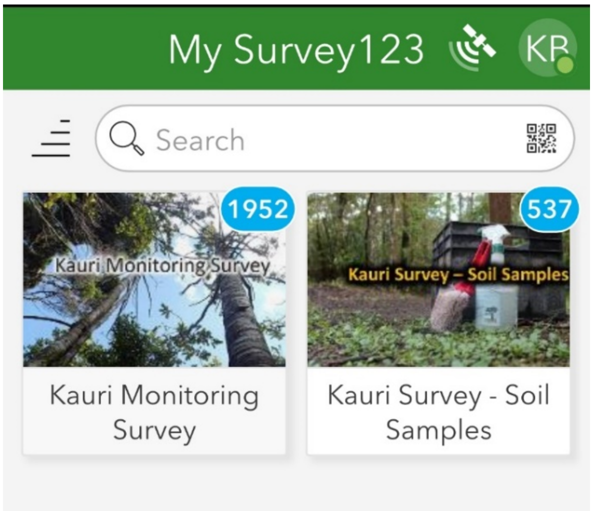
The survey had three form types over the full period of data collection (Table A-1).

From the survey start date of 8/3/2021 through to 23/4/2021, the kauri survey form was completed for all assessed trees. However, following a stop-go point reviewing the time taken to monitor each tree, the sample size was reduced from an original 3500 to 2500 trees on 28 April 2022, which remained within the lower sample size estimate. The number of ecological impact variables assessed per tree were also reduced for all non-soil sample trees following the review (Table A-1).

Table A-1. Survey forms in use during the Waitākere Ranges baseline monitoring survey.

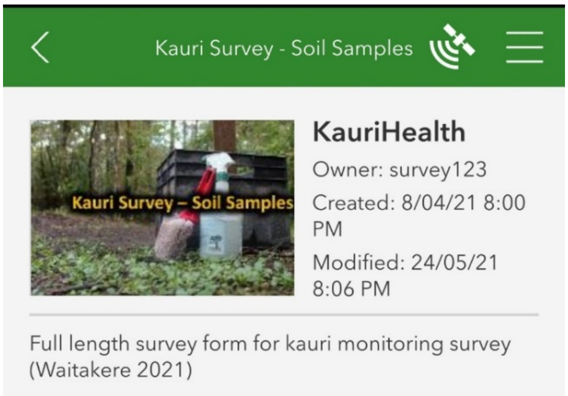
Survey form name	In use period	Usage	Contents
Kauri Monitoring Survey	8/3/2021 to 23/4/2021	Full data collection for all trees	Disease outcomes, potential risk factors, ecological impacts
Kauri Survey – Soil Samples	28/4/2021 to 8/7/2021	Full data collection for soil sample trees only	Disease outcomes, potential risk factors, ecological impacts
Kauri Monitoring Survey	28/4/2021 to 8/7/2021	Partial data collection for non-soil sample trees	Disease outcomes, potential risk factors

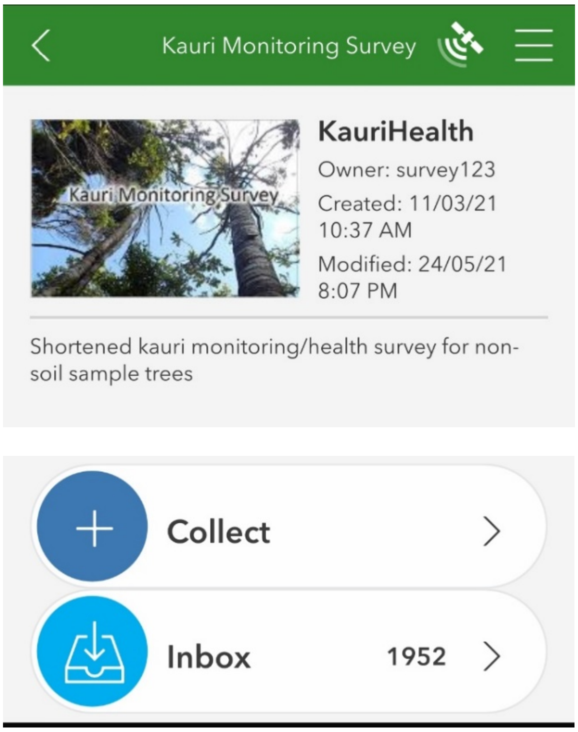
To start the survey, surveyors initially selected the Kauri Monitoring Survey form. After 24 April 2021, they selected either the revised Kauri Monitoring Survey form, or if the Point of Interest (POI) indicated a soil sample was required, the Kauri Survey – Soil Sample survey as below.



The main kauri monitoring survey was used for the majority of trees and collected baseline measurements for potential risk factors and disease outcome variables. The survey entry requirements and measurements for all risk factor and disease outcome variables were replicated in the soil sample survey form. In addition, trees that were selected for soil sampling had additional baseline measurements for ecological impact variables. These additional variables are annotated below as “Soil sample only”.

Upon selection of the correct form, the surveyor could open the inbox and be guided to the nearest tree to their GPS position. If the tree was not an assigned POI, for example when the original POI was found to not be a kauri and the surveyor had to collect survey information on a replacement tree, the surveyor could open a new observation by selecting ‘Collect’.





When opening the 'Inbox', all of the GPS points of the selected nearby trees are shown if 'Map' view is opened. This function of Survey123 did not work all the time, as the map disappeared outside areas with no mobile data reception. When this occurred, the accuracy of locating the preselected POI may have been affected as surveyors had to use a hand-held GPS with no aerial photos of the site to guide them to the specific tree.

It is recommended that all hand-held units are capable of pre-loading all sites and maps, if possible, to enable flexibility of operational deployment into different areas depending on conditions (e.g., potential for rain and terrain constraints).

Areas were assigned to each team for survey based on an achievable planned route through the forest for the day (using large A0 maps and smaller A4 booklets of more detailed topographical maps of each area) and the preloaded GPS points on the surveyors' hand-held GPS unit. The planned route was based on prior knowledge of areas to be visited from experienced BioSense staff, in that if there is known kauri dieback in an area, those trees would be visited later in the day to minimise transmission of *P. agathidicida* to non-symptomatic or unknown disease status areas. Note the existing disease data were not released to the survey teams to avoid biasing their search effort. The route planning also took account of existing tracks and bait lines to guide the most efficient route to the selected tree and minimise time off track.

A2 Survey information

Ngā pārongo mō te rangahau

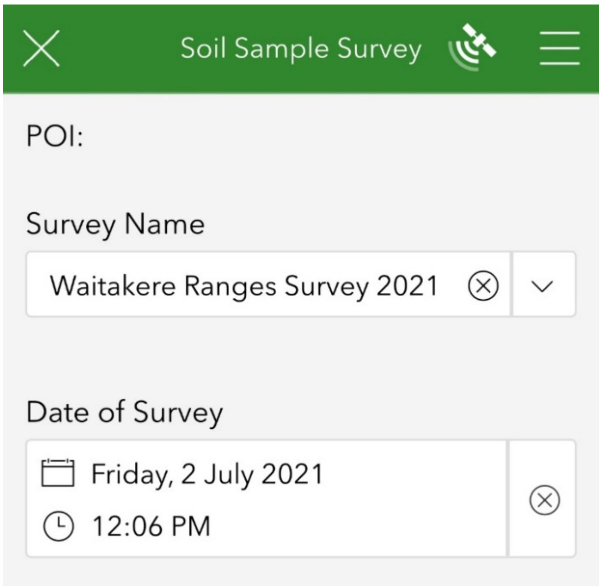
Question 1: Survey name

Question 2: Date and time of survey

Prevalence study; Risk factors study

This survey was recorded as 'Waitākere Ranges Survey 2021'. The date and time variable sets the date component of 'time and place' for future comparison of sampled trees. In addition, we were interested to understand if a pattern could be detected in some variables over the five-month survey period (e.g., if canopy colour, new flush foliage and female cones changed over the survey period of 8 March 2021 to 8 July 2021 and also if there was a difference in foliage and colour detection at different times of the day).

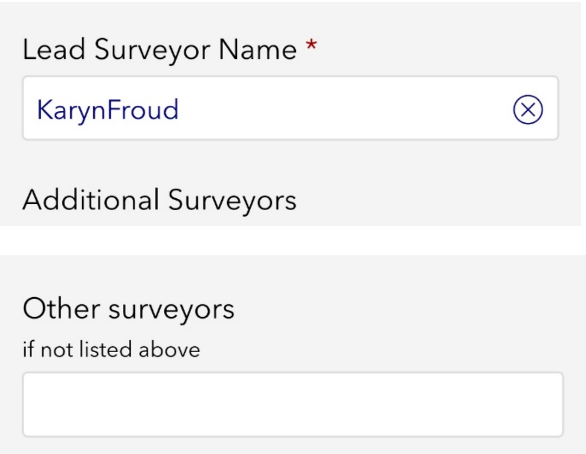
The 'Survey Name' box is a drop-down of all active surveys that the team are undertaking (typically just a single survey, but some team members may be undertaking multiple surveys in the same area). The date and time should auto-populate when a new POI is selected. Note for future surveys, the date and time need to be checked prior to the survey to make sure they are correct and set to 24-hour time to avoid an AM/PM error (some records were 12 hours ahead of actual time and were later amended in the data cleaning process).



Question 3: Lead and support surveyors

Prevalence study; Risk factors study

To meet the case definition of kauri dieback, the symptomatic criteria need to be assessed by an ‘approved observer’. In this case all survey team members had been fully trained prior to becoming a ‘lead surveyor’ and in most cases an additional surveyor was also present when the tree was observed.



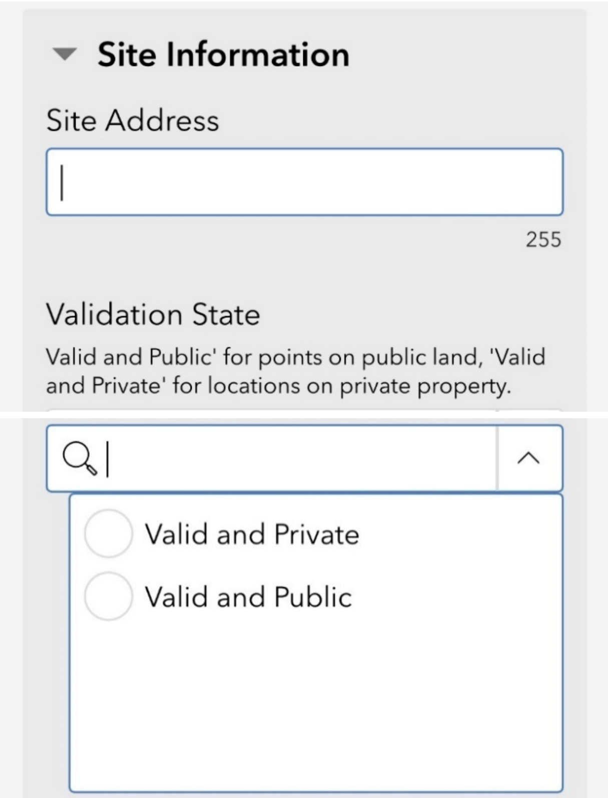
A3 Site information

Ngā pārongo mō te wāhi

Question 4: Site address

Question 5: Validation state

Site address is a placeholder for future surveys and is in line with historic data collection. Validation state has two options which determine whether the survey data can be entered into the publicly available dataset or not once analysis is completed and reported, as private land data may not be made publicly available. This variable was also designed for where iwi/hapū permission was granted for collection of data from sacred or tapu sites to be kept private.



A4 Sampled tree information

Ngā pārongo mō ngā rākau kua tīpakohia

Question 6: Tree/POI location

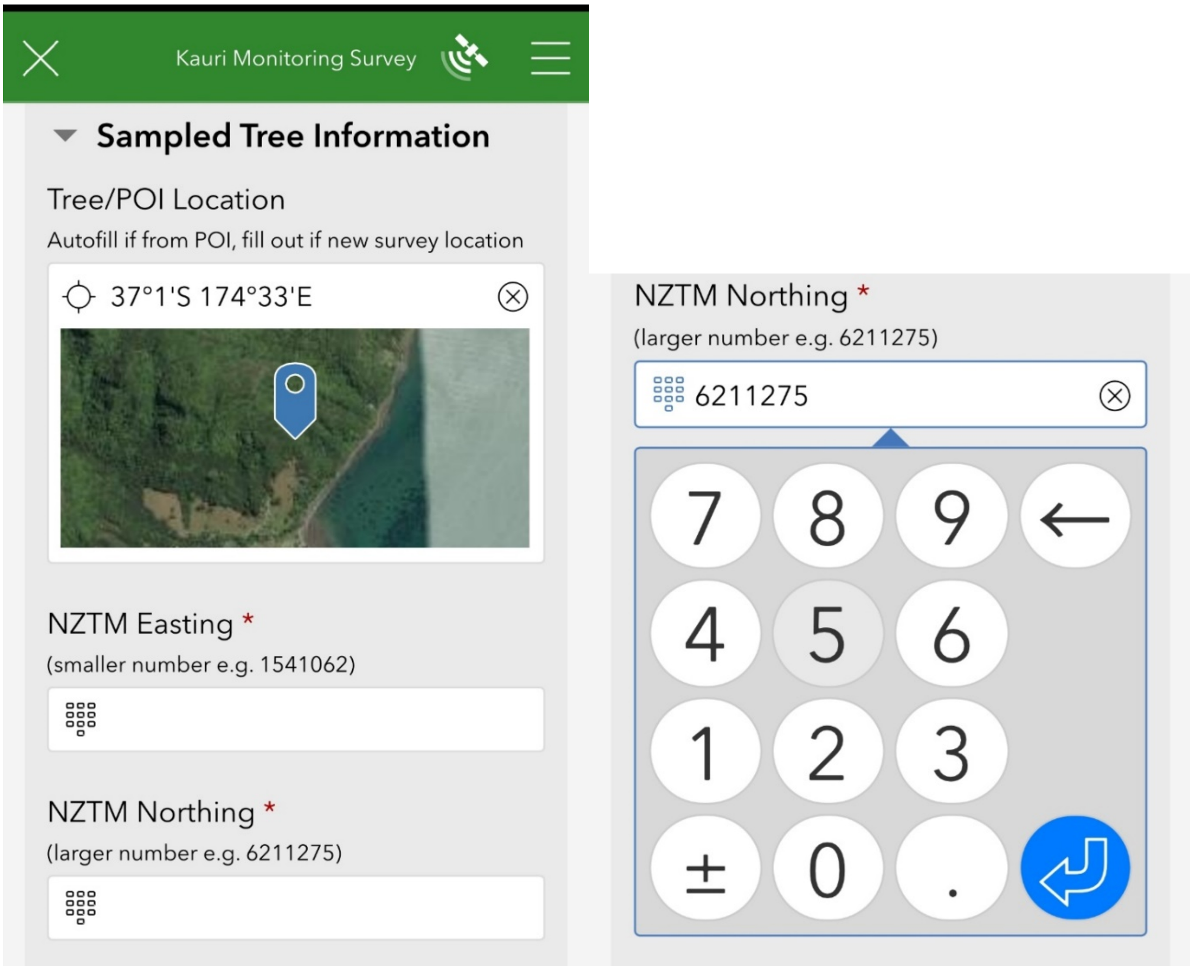
Question 7: New Zealand Transverse Mercator (NZTM) Easting

Question 8: NZTM Northing

Prevalence study; Risk factors study

If the kauri point was selected from the inbox, then this field auto-fills with the GPS coordinates of the tree (derived from the remote sensing LiDAR data on the highest point of the tree crown). Regardless, the handheld GPS coordinates were requested and entered to confirm position of the tree or to georeference the replacement tree.

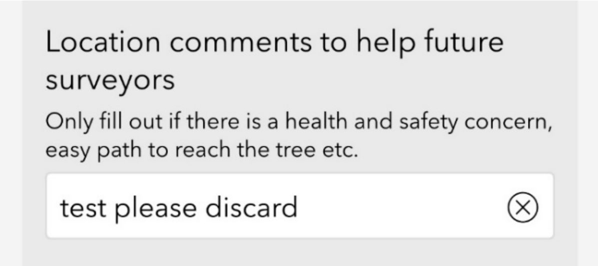
These spatial coordinates, along with GPX track files from each handheld GPS, were used to reconcile the exact GPS points for each monitored tree (validated by the Auckland Council Environmental Services BioInformation team) to assign GIS-related variables values to trees and used to develop prevalence maps.



For future reference, the decimal space should not be available on the keypad for this field, and it should have field protection of only 7 digits.

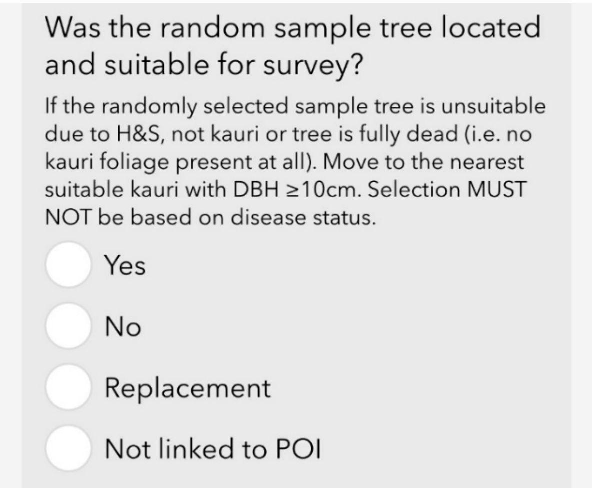
Question 9: Location comments

This field was to inform future survey efforts to locate the same tree. Surveyors were asked to comment if the tree was hard to find or if there was a health and safety concern. In the example below, the comment field has been used to indicate that this is a test which needs to be discarded from the dataset. We recommend a change to the hint text to include an example “e.g., during a return visit, go round slope rather than through gully”.



Question 10: Random sample tree located and suitable for survey?

The field teams used their handheld GPS units to navigate to the pre-loaded kauri points. If the selected tree was located, the survey continued. If the selected tree was fully dead, could not be located as the host species was misclassified by remote sensing, or it was not accessible due to health and safety concerns, a replacement tree was then selected. To avoid any selection bias, the surveyors were tasked to select the closest kauri tree with a DBH of ≥ 10 cm and selection COULD NOT be based on disease status. Note: if the tree was selected for soil sampling but was found to be dead, the soil sample was collected from the dead tree AND a replacement tree selected and soil sampled. For future reference, this section should come prior to the Q7, Q8, Q9 location coordinates and comments section.



If 'Yes' or 'Not linked to POI' was selected, then the survey continues to the next section. 'Not linked to POI' is for ad-hoc surveys on trees that are sampled outside a specific survey effort and are there for future passive surveillance use. It is recommended that this field is excluded or not visible for future surveys where all observations are on pre-selected trees.

If 'No' is selected, then additional questions are asked regarding host and dead status.

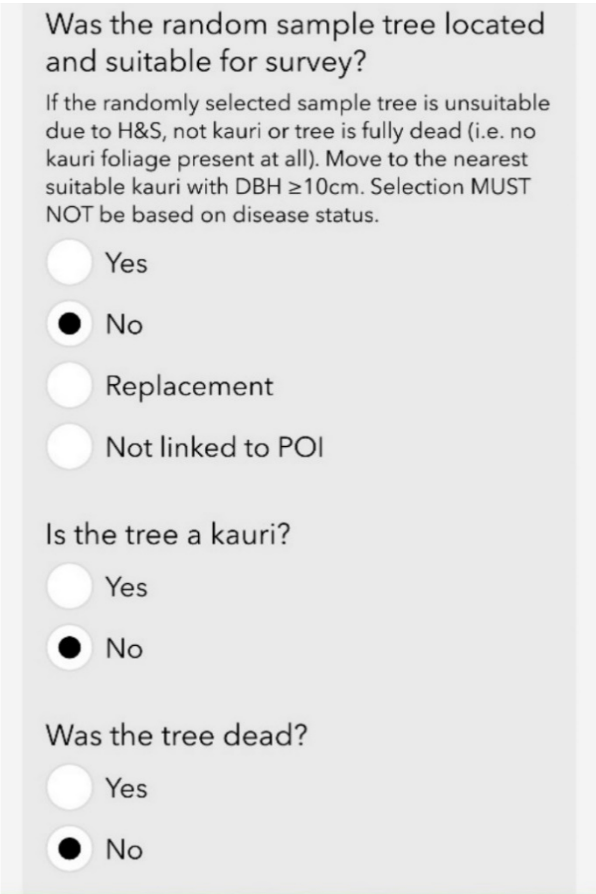
Question 10a: Is the tree a kauri?

Question 10b: Was the tree dead?

If the POI tree was not suitable for survey, the surveyor is asked if it was a kauri or not, and whether the tree was dead or not.

These results inform validation and future improvement of the methods used to undertake remote sensing detection of host species.

These fields were added during the 24 April upgrade to the two survey forms.


Was the random sample tree located and suitable for survey?

If the randomly selected sample tree is unsuitable due to H&S, not kauri or tree is fully dead (i.e. no kauri foliage present at all). Move to the nearest suitable kauri with DBH ≥10cm. Selection MUST NOT be based on disease status.

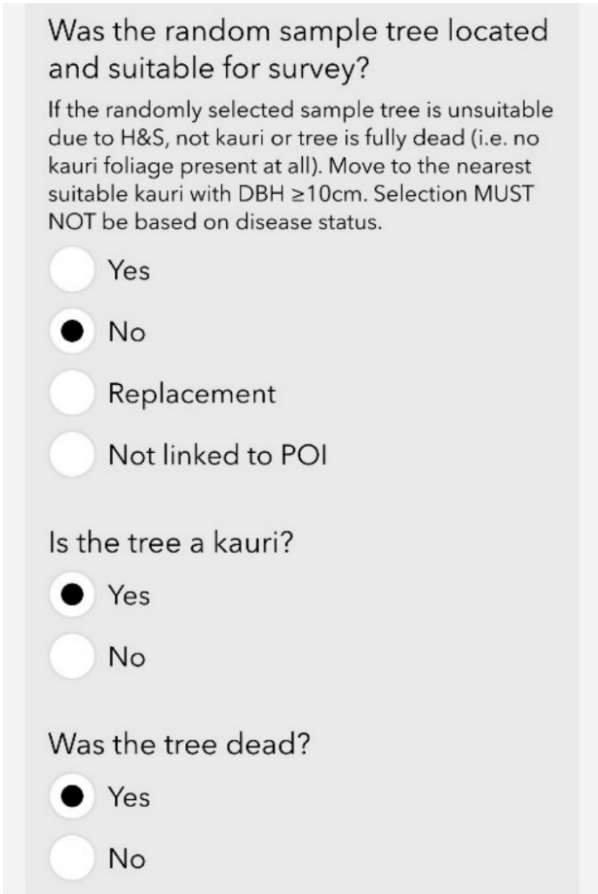
- ○ Yes
- ● No
- ○ Replacement
- ○ Not linked to POI

Is the tree a kauri?

- ○ Yes
- ● No

Was the tree dead?

- ○ Yes
- ● No


Was the random sample tree located and suitable for survey?

If the randomly selected sample tree is unsuitable due to H&S, not kauri or tree is fully dead (i.e. no kauri foliage present at all). Move to the nearest suitable kauri with DBH ≥10cm. Selection MUST NOT be based on disease status.

- ○ Yes
- ● No
- ○ Replacement
- ○ Not linked to POI

Is the tree a kauri?

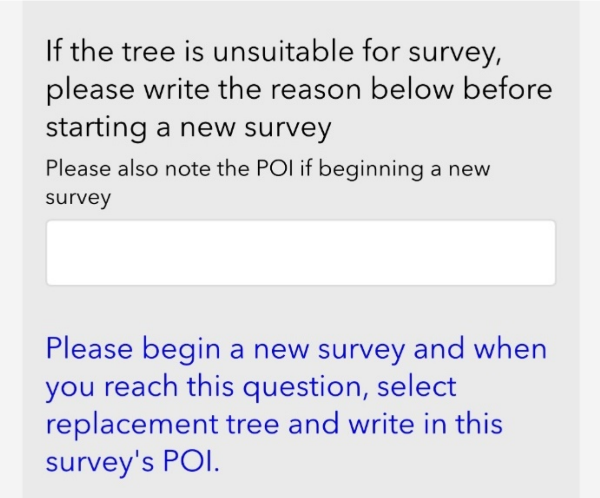
- ● Yes
- ○ No

Was the tree dead?

- ● Yes
- ○ No

Question 10c: If the tree is unsuitable for survey, please write the reason below before starting a new survey

The surveyor was then asked to provide a reason for the tree being unsuitable. Following this, further instructions were provided regarding recording replacement trees. For future reference, the comment field for ‘Not a kauri’ should be compulsory, such that the true tree species is able to be identified and therefore provide information for host detection validation. In some instances, where a whole stand has been mis-classified, e.g., a large stand of pine trees, the surveyors reported back directly to Auckland Council to have these POIs recorded as ‘Not a kauri’ and ‘Pine’ to save time in the field.


If the tree is unsuitable for survey, please write the reason below before starting a new survey

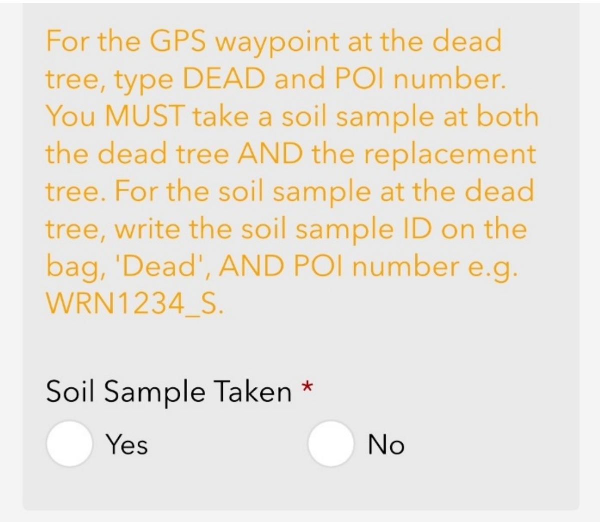
Please also note the POI if beginning a new survey

Please begin a new survey and when you reach this question, select replacement tree and write in this survey's POI.

Question 10d: Soil sample taken

For trees that had been selected for soil sampling, the surveyors would select 'Yes' and label the soil sample bag with the code that appears on the screen, for use in cross-referencing laboratory results.

For trees selected for soil sampling that were kauri but were found to be dead, instructions were provided in the form to collect a soil sample for both the dead tree and the replacement tree.


For the GPS waypoint at the dead tree, type DEAD and POI number. You MUST take a soil sample at both the dead tree AND the replacement tree. For the soil sample at the dead tree, write the soil sample ID on the bag, 'Dead', AND POI number e.g. WRN1234_S.

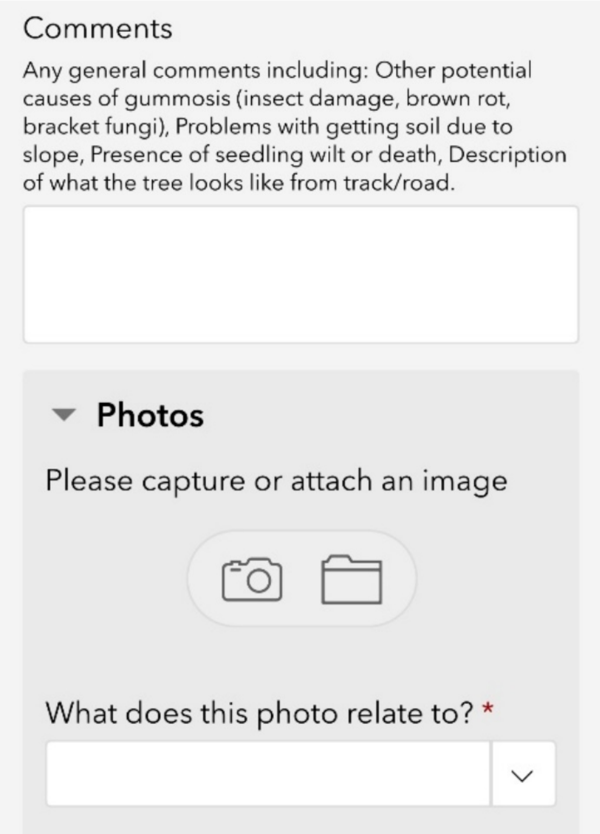
Soil Sample Taken *

Yes No

Question 10e: Comments

Question 10f: Photos

Finally, a comments section was provided to enter any other relevant information. Surveyors were also tasked with taking photos of the canopy, basal bleeds, tree tag ID and clearly labelled soil sample bag.



A5 Replacement tree information

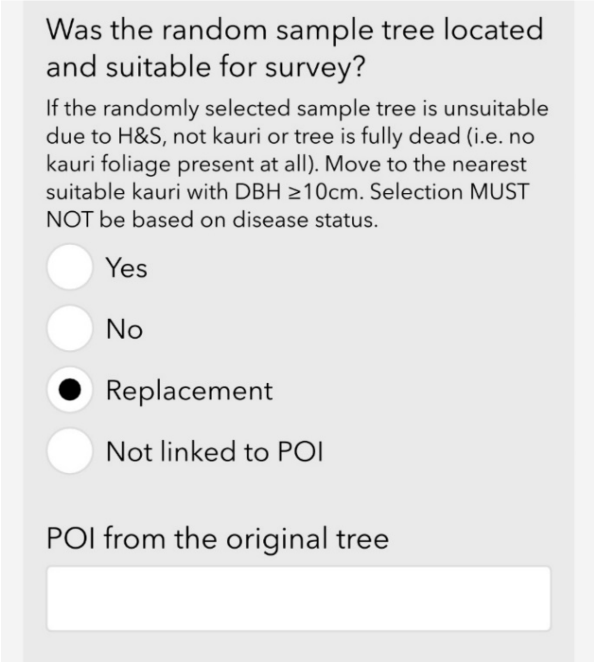
Ngā pārongo mō ngā rākau whakakapi

Question 1-9: Repeat for replacement trees

Question 10: Was the random sample tree located and suitable for survey?

If the original kauri POI was unsuitable for survey (i.e., due to it not being a kauri or already dead), another nearby kauri was then selected for survey as a replacement tree. The surveyor would then return to the initial Survey123 screen, selecting the ‘Collect’ function rather than the ‘Inbox’, and proceed to fill in Questions 1-9 as per original instructions.

At Question 10 “Was the random sample tree located and suitable for survey?”, ‘Replacement’ is then selected. An additional question would then appear for input of the POI code of the original tree. From this point on, the survey continued as per normal.


Was the random sample tree located and suitable for survey?

If the randomly selected sample tree is unsuitable due to H&S, not kauri or tree is fully dead (i.e. no kauri foliage present at all). Move to the nearest suitable kauri with DBH ≥10cm. Selection MUST NOT be based on disease status.

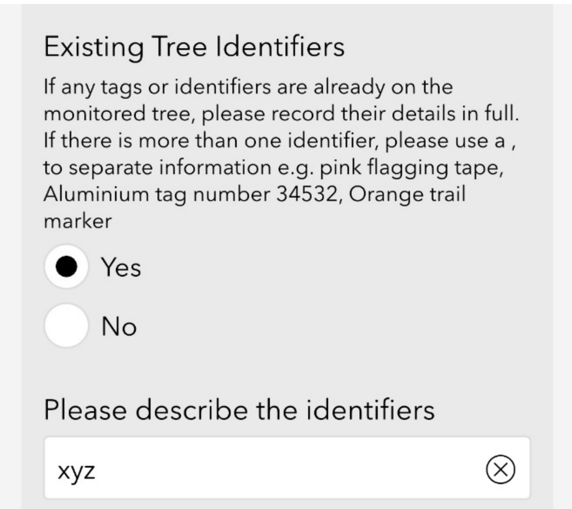
- Yes
- No
- Replacement
- Not linked to POI

POI from the original tree

Question 11: Existing tree identifiers

Many trees in the Waitākere Ranges have been labelled in the past. They may indicate a bait line trail, phosphite injection trees or other research labels. To identify the tree and any prior history that may be relevant, the surveyor was requested to describe any existing identifiers.

It is recommended that future forms have an extra field with a specific question asking if there is evidence that the tree has been phosphite treated (tagged or drill holes) with the options of Yes/No/Unsure.


Existing Tree Identifiers

If any tags or identifiers are already on the monitored tree, please record their details in full. If there is more than one identifier, please use a , to separate information e.g. pink flagging tape, Aluminium tag number 34532, Orange trail marker

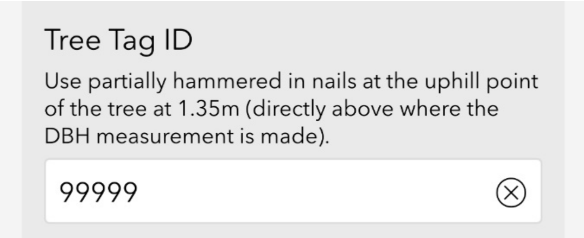
- Yes
- No

Please describe the identifiers

xyz

Question 12: Tree Tag ID

The tree tag ID was one of the unique data identifiers. Every kauri in the survey was given a tree tag ID that had a unique code imprinted on aluminium. The tree tag was attached by a nail partially hammered in at the DBH height (1.35 m) at the uphill point of the tree. The tree tag ID was then recorded on the sample form.

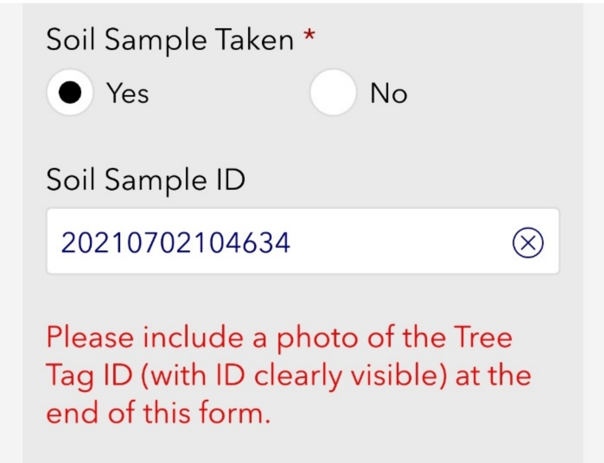

Tree Tag ID
Use partially hammered in nails at the uphill point of the tree at 1.35m (directly above where the DBH measurement is made).
99999

Question 13: Soil sample taken?

Question 14: Soil sample ID
Prevalence study

The question of whether a soil sample is taken is provided on both survey forms to allow the option for the collection of additional soil samples for other purposes.

If 'Yes' was selected for 'Soil sample taken?', a soil sample ID was then generated. The soil sample ID was one of the unique data identifiers. The surveyor was tasked to record this ID on the sample bag and take a photo of this for ease of data cleaning.

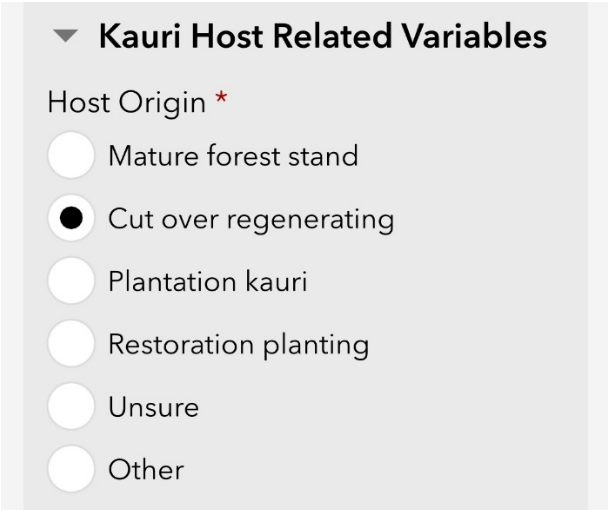

Soil Sample Taken *
Yes No
Soil Sample ID
20210702104634
Please include a photo of the Tree Tag ID (with ID clearly visible) at the end of this form.

A6 Kauri host-related variables

Ngā taurangi ā-papa rauropi kauri

Question 15: Host Origin
Prevalence study; Risk factors study

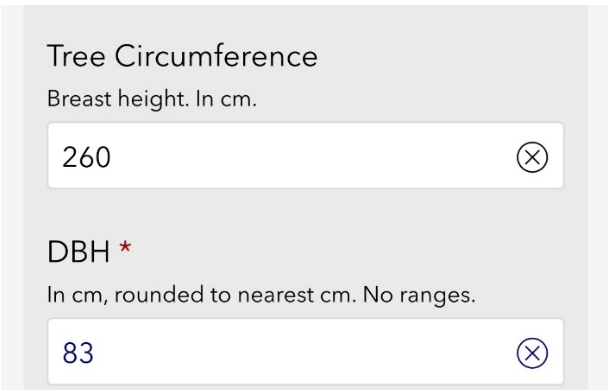
Host origin was consistently mentioned at all risk factor development hui. This factor will need to be carefully interpreted if it proves to have a significant association with cases of kauri dieback, as there are several hypotheses associated with host origin. Measurement of this factor requires some knowledge of the area and therefore may only be partially completed in the field; however mature forest stand can be implied by the presence of very large mature trees. Cut-over regenerating areas have evidence of old tree stumps that were cut decades earlier and are dominated by smaller size classes or regenerating trees. Plantation kauri may need to be identified using historic records of the NZ Forestry Service, which would require digitising archived map records identified by Beachman (2017). Information on restoration planting may be reconciled using other GIS layers.



Question 16: Tree circumference

Question 17: Diameter at breast height (DBH)
Prevalence study; Risk factors study

The DBH was automatically calculated in the form following the formula of circumference divided by *pi*. The circumference of the tree was measured at breast height, starting at the uphill point of the tree where the tree tag was placed. In some instances, where the tree was very large and positioned on steep and unstable ground (common in the Waitākere Ranges), it was unsafe to measure the full circumference of the tree. In these cases, the circumference was estimated by measuring the accessible half of the tree and doubling the measurement.



Approximate size classes were calculated to be consistent with historical kauri data based on circumference measures of <150 cm = Ricker, 150-449 = Intermediate, 450 or greater = Mature.

Question 18: Active growth flush in canopy

Question 19: Epicormic growth

Question 20a: Are female cones visible on the tree?

Question 20b: Are there green female cone scales on the ground within the dripline of the monitored tree?
Prevalence study impact variables. Soil sampling trees only.

These host variables were aimed at assessing host health in addition to disease symptoms, as we were concerned that symptomatic trees might show epicormic growth, not have active growth or be reproductive (female cones).

Epicormic growth was assessed in the lower 3 m of the trunk and is a common indicator of ill-thrift in trees.

Active growth flush and female cones were measured to determine if the tree was actively growing and/or reproducing this season. New growth flush should be visible throughout the summer months, indicated by lighter green leaves and light green coloured twigs at the end of branches as per the photo included in the form.

We had several concerns with these two fields during the 2021 Waitākere Ranges Monitoring Survey. We planned to check several components of these variables. Firstly, whether these variables were able to be measured as we transitioned from summer into winter (i.e., is there a bias towards 'no' over time). In addition, how many observations might be lost due to the difficulty of obtaining this information, potentially because a good view of the canopy was hard to obtain from ground level especially on taller trees or, due to dense canopy and during different times of the day, the daylight contrast made it difficult to detect. It is also important to note that some monitored trees could be too young to be reproductive as small ricker trees are typically not reproductive until they are 25-40 years old (Steward and Beveridge, 2010). Careful assessment of this variable will be needed to address potential confounding of reproductive status with small DBH scores. Absence of active growth, female cones or presence of epicormic growth might be correlated with disease or be a symptom of tree stress. It is useful to understand any associations with symptomatic trees now and into the future as these may be early symptoms for detection and could guide proactive phosphite or other treatments. In addition, if these symptoms are common in the absence of disease, they could indicate that there are wider ecosystem changes that are putting kauri at risk of stress and ill-thrift.

Both active growth flush and female cones were found to be difficult to assess. This difficulty was tree-specific rather than season- or stand-specific, in that they were hard to measure on both densely growing rickers and on very tall mature trees. The field teams reported that these two variables were extremely unreliable to assess, and most female cones were gone after March. It is not recommended that they are used for analysis due to unreliability, and recommend that Q18, 20a and 20b be removed from future survey forms.

Active growth flush in canopy *

Are there signs of new growth flush (i.e. green twigs).

- (•) Yes
- ( ) No
- ( ) Unable to see

Epicormic growth *

Are there leafy twigs coming directly from the main trunk of the tree (i.e not in canopy) within the lower 3m of the trunk?

- ( ) Yes
- (•) No

Are female cones visible on the tree? *

Select not able to see if the canopy is obscured enough that you can't tell (e.g. sun angle, under-canopy density).

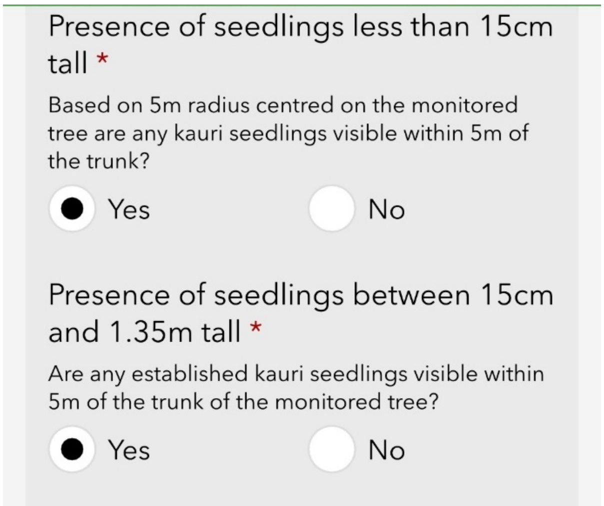
- ( ) Yes
- (•) No
- ( ) Unable to see

In order to address the potential issue of female cones falling over late summer to early winter, we included an option to observe green female cone scales on the forest floor, which indicated the current season's cones. However, an issue with the electronic form was noted at the end of data collection, in that the question of green female cone scales only appeared after the surveyor selected 'Yes' to 'Are female cones visible on the tree?'. Therefore, the data for this variable need to be assessed carefully. We recommend that 20b is removed from future forms.

Question 21: Presence of seedlings less than 15 cm tall

Question 22: Presence of seedlings between 15 cm and 1.35 m tall
Prevalence study impact variables. Soil sampling trees only

These seedling-related questions aimed to understand if any recruitment was occurring under symptomatic trees, and if there is an association between *P. agathidicida* detection and seedling presence. It is related to the previous group of questions in that disease may be reducing reproduction even if tree death does not occur. In addition, *P. agathidicida* is thought to be particularly lethal to seedlings, so these measurements might provide evidence for this. A consideration in interpretation of this measurement is the potentially confounding effect that there may not be any seedlings near the host parent plant due to the Janzen-Connell hypothesis which in brief implies that seedling survival is greatest further from the parent; however, how well this is supported in temperate species has been questioned (Hyatt et al., 2003).



Presence of seedlings less than 15cm tall *

Based on 5m radius centred on the monitored tree are any kauri seedlings visible within 5m of the trunk?

Yes No

Presence of seedlings between 15cm and 1.35m tall *

Are any established kauri seedlings visible within 5m of the trunk of the monitored tree?

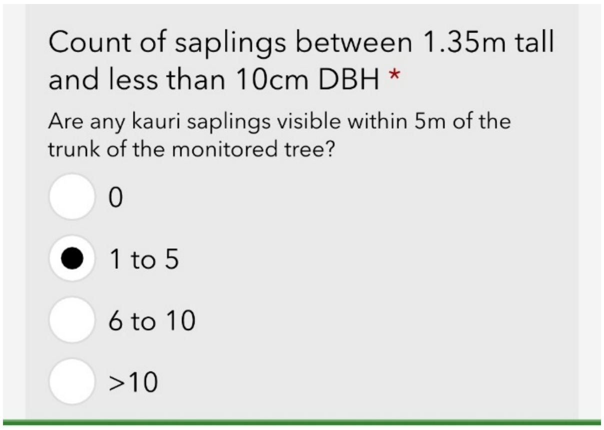
Yes No

Question 22: Count of saplings between 1.35 m tall and less than 10 cm DBH

Prevalence study impact variables. Soil sampling trees only

As with seedling presence or absence, this is a measure of kauri reproductive activity. Note that Bruce Burns has cautioned against its use as a measure of kauri sapling density as this could be confounded according to the Janzen-Connell hypothesis, with kauri saplings probably less likely to occur close to adult trees than away from them. In addition, for medium-large trees, the 5 m radius circle would all be under the kauri canopy, which should also be considered as a confounder.

If seedlings and saplings are surviving under trees with *P. agathidicida* in the soil, then these trees could represent a source of genetic resistance to the pathogen and will inform sites for future protection, monitoring and research.



Count of saplings between 1.35m tall and less than 10cm DBH *

Are any kauri saplings visible within 5m of the trunk of the monitored tree?

0

1 to 5

6 to 10

>10

A7 Disease-related variables

Ngā taurangi ā-mate

Prevalence study outcome variables; Risk factors study outcome variables; Diagnostic test evaluation test results

The disease-related variables provide the outcome variables for all three studies. It is important to note that all symptoms could be caused by other biotic or abiotic factors, and therefore the opinion of a trained observer is required to determine if the recorded symptoms are consistent with kauri dieback. This is particularly important where basal and lateral root bleeds can be caused by physical damage to the tree. To meet the symptomatic criteria of the case definition, both symptoms and field status were assessed as described below.

Symptomatic criteria for the case definition

The symptomatic criteria for kauri dieback on a kauri tree are met if a National Programme (Tiakina Kauri Partners) approved trained observer detects one or more of the following symptoms <u>that are consistent with kauri dieback</u>: bleeding lesions on the basal trunk, lesions on roots, the presence of canopy thinning, yellowing of the foliage, tree death.

For these studies, the symptomatic criteria were met if:

Basal bleed = 'Yes' *or* 'Unsure'

OR

Lateral root bleed = 'Yes' *or* 'Unsure'

OR

Canopy score ≥3

OR

Canopy colour = 'Yellow-Green' *or* 'Copper Brown'

AND

Kauri dieback field status (approved observer considers symptoms are consistent with kauri dieback) = 'Kauri with possible kauri dieback symptoms' *or* 'Kauri with severe kauri dieback symptoms'

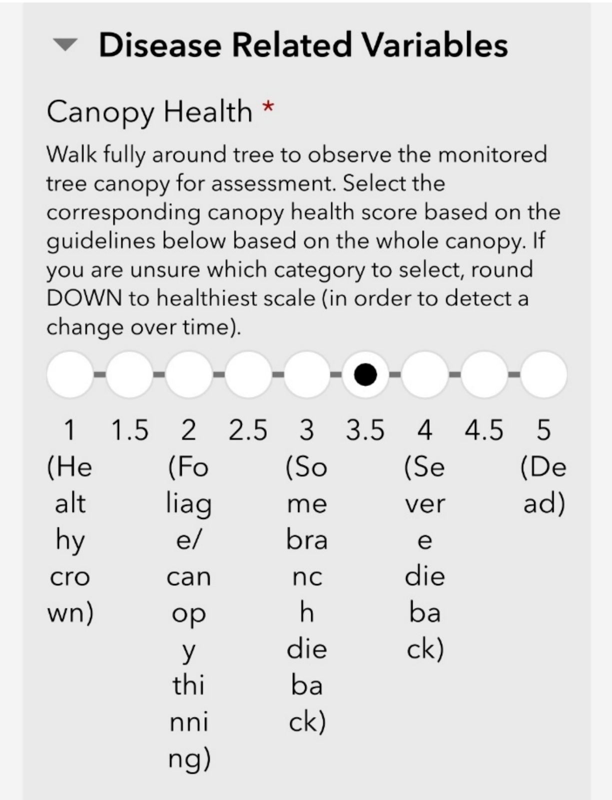
NOTE: Dead trees (canopy score = 5 or canopy colour = dead) are excluded as a tree cannot be considered diseased after death.

Question 23: Canopy Health

Prevalence study outcome variables; Risk factors study outcome variables; Diagnostic test evaluation test results

Canopy health is one of the listed symptomatic criteria for the case definition of kauri dieback. This variable is included in the formula for classifying symptomatic trees. The level of canopy health score required to be included in the case definition has tentatively been set to a canopy score of 3 or higher after discussion with the field team and I. Horner (Plant and Food Research, pers. comm.). This is consistent with being considered symptomatic by Bellgard et al. (2013). Scores from 1-2.5 relate to healthy canopy or some foliage or canopy thinning, whereas scores from 3-5 show signs of branch dieback through to canopy loss and death of the tree. For the purposes of calculating prevalence of disease, trees that scored 5 and were considered dead were excluded as a tree cannot be considered diseased after death. Dead trees are reported separately from prevalence.

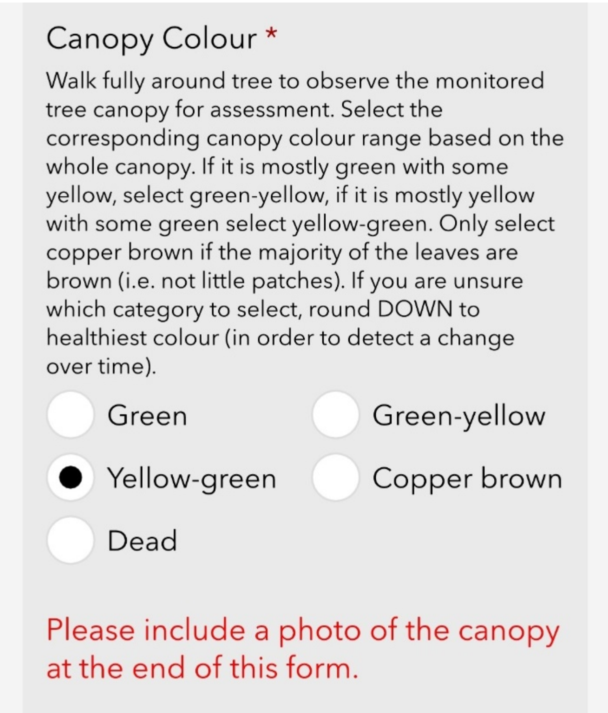
The baseline **severity** of disease is quantified based on the Dick and Bellgard (2012) 5-scale canopy health score. However, under guidance from experts, it was adjusted to include half-points to provide more differentiation, particularly between 2-3 and 3-4 canopy scores (I. Horner and N. Williams, Plant and Food Research, pers. comm.).



Question 24: Canopy Colour

Prevalence study outcome variables; Risk factors study outcome variables; Diagnostic test evaluation test results

Canopy yellowing is one of the listed symptomatic criteria for the case definition of kauri dieback. Canopy colour is included in the symptomatic criteria formula to classify cases. The canopy colour score required to be included in the case definition has tentatively been set to a canopy colour that is more yellow than green and includes 'Yellow-green', 'Copper brown' and 'Dead'. Dead trees are reported separately from prevalence.


Canopy Colour *

Walk fully around tree to observe the monitored tree canopy for assessment. Select the corresponding canopy colour range based on the whole canopy. If it is mostly green with some yellow, select green-yellow, if it is mostly yellow with some green select yellow-green. Only select copper brown if the majority of the leaves are brown (i.e. not little patches). If you are unsure which category to select, round DOWN to healthiest colour (in order to detect a change over time).

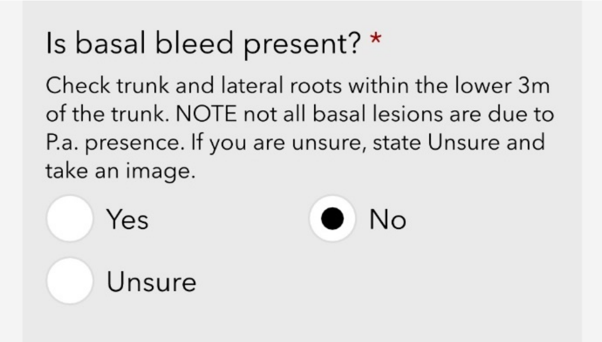
- Green
- Green-yellow
- Yellow-green (selected)
- Copper brown
- Dead

Please include a photo of the canopy at the end of this form.

Question 25: Is basal bleed present?

Prevalence study outcome variables; Risk factors study outcome variables; Diagnostic test evaluation test results

Basal bleeds (bleeding lesions on the lower 3 m of the trunk) are one of the listed symptomatic criteria for the case definition of kauri dieback. The surveyors were trained in the variety of basal lesion presentations that have been associated with kauri dieback caused by *P. agathidicida*, and only selected 'Yes' if the bleed presented as such. Further, they were instructed to select 'Unsure' when they could not rule out a basal bleed due to kauri dieback but probably due to other causes (e.g., physical damage). Both 'Yes' and 'Unsure' were included in the symptomatic criteria formula to classify cases. Images of basal bleeds were taken for future assessment and development of training guides.


Is basal bleed present? *

Check trunk and lateral roots within the lower 3m of the trunk. NOTE not all basal lesions are due to P.a. presence. If you are unsure, state Unsure and take an image.

Yes

No

Unsure

If ‘No’ was selected, then the surveyor moves to the next question. If ‘Yes’ or ‘Unsure’ were selected, then a further series of questions about the basal bleed appear.

Question 25a: Basal bleed age

Prevalence study outcome variables

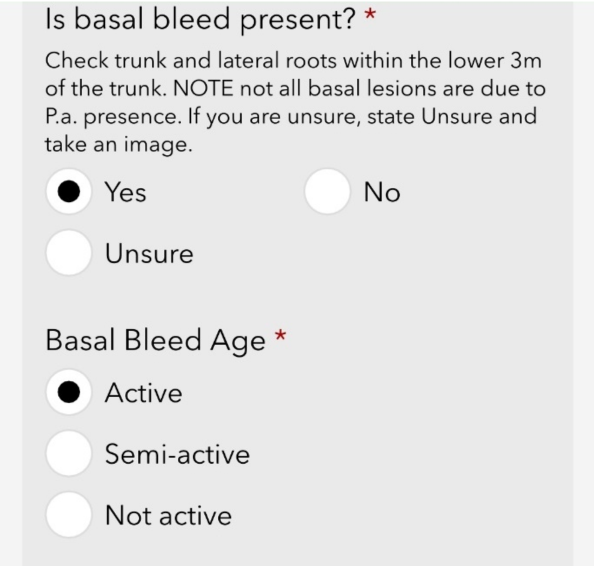
The basal bleed age indicates how active a bleed is. This will be useful to indicate if bleeds heal over time with or without interventions. Dick and Bellgard (2010) described a binary resin category to identify basal lesion activity, to classify between fresh resin bleeds and old resin (that is, pus-like, soft and squishy versus hard to the touch), under guidance from several experts it was adjusted to state ‘Active’, ‘Semi-active’ or ‘Not active’ (I. Horner and N. Williams, Plant and Food Research, pers. comm.). For comparison with older surveillance data, ‘Active’ and ‘Semi-active’ correspond to fresh bleeds and ‘Not active’ correspond to old bleeds. This classification follows the Horner methodology of whether the gum is sticky (active), soft but not sticky (semi-active) or hard (not-active) and relates to whether the tree is still exuding gum. Where more than one category of bleed is present on the trunk, the most active one is selected.

The assessment guide is:

Active = Bleed soft and sticky

Semi-active = Not sticky, but slightly soft and can be dented with fingernail

Not active = Hard and dry and cannot be dented with fingernail.



Is basal bleed present? *

Check trunk and lateral roots within the lower 3m of the trunk. NOTE not all basal lesions are due to P.a. presence. If you are unsure, state Unsure and take an image.

- (•) Yes
- ( ) No
- ( ) Unsure

Basal Bleed Age *

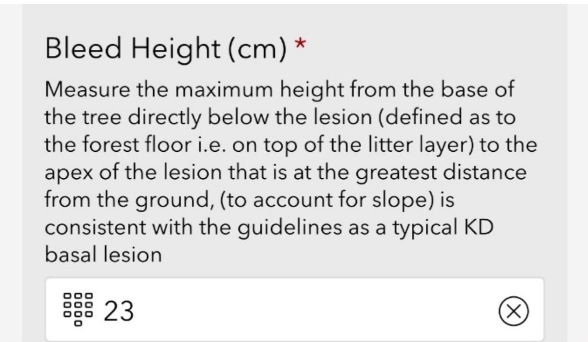
- (•) Active
- ( ) Semi-active
- ( ) Not active

Photos are requested for all basal bleeds.

Question 25b: Bleed height (cm)
Prevalence study outcome variables

The bleed height is a measure of severity in that it indicates how long a tree may have been infected, as the pathogen infects via the roots and then travels up the trunk over time, remaining at the leading edge (outer/upper edge) of the lesion. This will form a comparison for ongoing monitoring to determine how fast lesions develop over time and if there is an association between canopy score and lesion height.

Where more than one bleed is present on the trunk, then the highest one is assessed.



Bleed Height (cm) *

Measure the maximum height from the base of the tree directly below the lesion (defined as to the forest floor i.e. on top of the litter layer) to the apex of the lesion that is at the greatest distance from the ground, (to account for slope) is consistent with the guidelines as a typical KD basal lesion

23

Question 25c: Percentage of basal bleeds
Prevalence study outcome variables

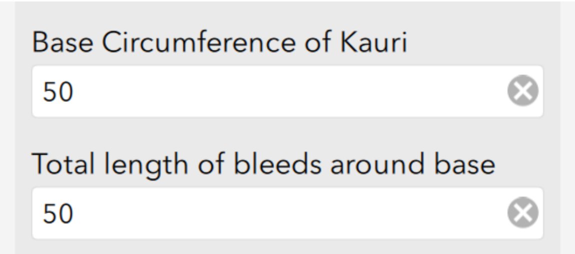
This question was changed during the April form update as the original question was too difficult and time-consuming to measure accurately. Initially the question stated:

Base circumference of kauri (cm): Measure the circumference around the base of the tree.

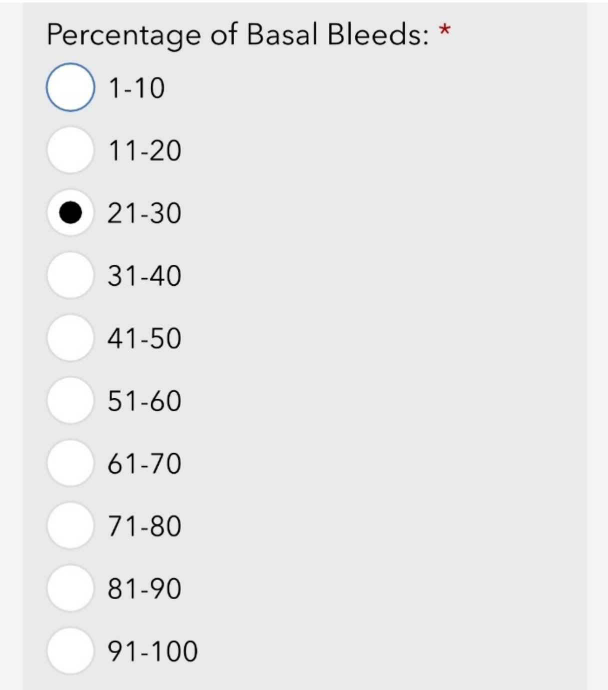
Total length of bleeds around base (cm): Measure the horizontal length (width) of the bleed around the base.

If there are multiple basal bleeds, add the lengths up to one number.

Basal bleed percentage is automatically calculated from the above two numbers and showed like this on screen:



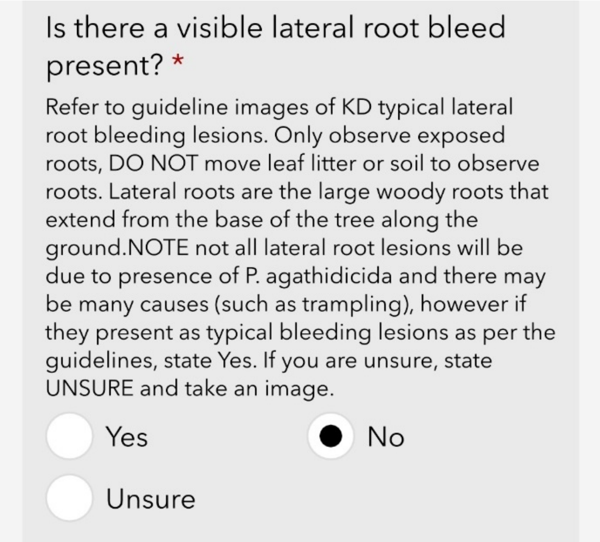
However, it was changed in April to ‘Percentage of basal bleeds’ as an estimate (in deciles) of the base of the trunk that was affected by the basal bleed. This is a measurement of severity and gives a crude indication of the diameter of girdling that has occurred through pathogen infection.



Question 26: Is there a visible lateral root bleed present?

Prevalence study outcome variables; Risk factors study outcome variables; Diagnostic test evaluation test results

Visible lateral root bleeds (bleeding lesions on the exposed (above ground) large lateral roots) are one of the listed symptomatic criteria for the case definition of kauri dieback. It was important not to disturb the kauri roots during this measurement and the surveyors were provided with guideline images. Further, they were instructed to select ‘Unsure’ when they could not rule out a lateral root bleed due to other causes (obvious physical damage). Lateral root bleed = ‘Yes’ or ‘Unsure’ are included in the symptomatic criteria formula to classify cases.



Is there a visible lateral root bleed present? *

Refer to guideline images of KD typical lateral root bleeding lesions. Only observe exposed roots, DO NOT move leaf litter or soil to observe roots. Lateral roots are the large woody roots that extend from the base of the tree along the ground.NOTE not all lateral root lesions will be due to presence of P. agathidicida and there may be many causes (such as trampling), however if they present as typical bleeding lesions as per the guidelines, state Yes. If you are unsure, state UNSURE and take an image.

Yes
No
Unsure

If ‘No’ is selected, then the surveyor moves to the next question. If they select ‘Yes’ or ‘Unsure’, then a bleed activity question was asked.

Question 26a: Lateral root bleed age

Prevalence study outcome variables

Lateral root bleed age uses the same method as basal bleed age.

Lateral Root Bleed Age *

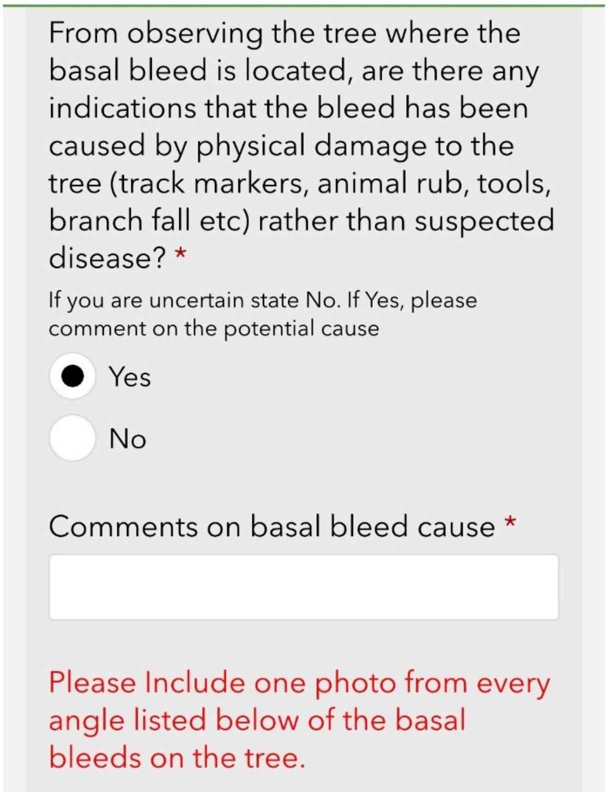
Active
Semi-active
Not active

Question 25d: Basal bleed cause

Question 25e: Basal bleed cause comment

Prevalence study outcome variables

This question allows the surveyor to list any observations that indicate that a basal bleed is caused by abiotic factors rather than indicating kauri dieback disease. These reasons will allow us to build up a group of common causes of abiotic basal bleeds which can be included in a dropdown menu in future versions of the monitoring form.


From observing the tree where the basal bleed is located, are there any indications that the bleed has been caused by physical damage to the tree (track markers, animal rub, tools, branch fall etc) rather than suspected disease? *

If you are uncertain state No. If Yes, please comment on the potential cause

Yes

No

Comments on basal bleed cause *

Please Include one photo from every angle listed below of the basal bleeds on the tree.

Question 27: Kauri dieback field status

Prevalence study outcome variables; Risk factors study outcome variables; Diagnostic test evaluation test results

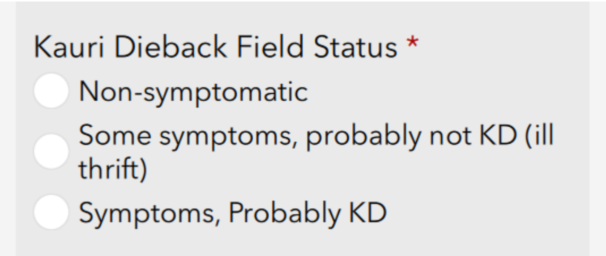
The trained observer assesses all observed symptoms, the surroundings of the tree and any other potential causes of symptoms and makes a field diagnosis, i.e., the 'kauri dieback field status'.

After feedback from the field teams that an additional category was useful for the kauri dieback symptomatic category to differentiate between the possible/probable and obvious kauri dieback observations, we revised this from a 3-point scale to an improved 4-point scale to differentiate between possible kauri dieback and severe kauri dieback described in the monitoring field guide as shown in **Table A-2**. All 'Symptoms, probably kauri dieback' scores were converted to 'Kauri with possible kauri dieback symptoms' after the review as this did not affect classification to the case definition.

Table A-2. Kauri dieback field status wording compared between the first 6 weeks of monitoring and the remaining 10 weeks of monitoring.

Initial field status categories	Post-review field status categories
Non-symptomatic kauri	Non-symptomatic kauri

Some symptoms, probably not kauri dieback	Kauri with ill-thrift (probably not kauri dieback)
Symptoms, probably kauri dieback	Kauri with possible kauri dieback symptoms
	Kauri with severe kauri dieback symptoms


Kauri Dieback Field Status *
Non-symptomatic
Some symptoms, probably not KD (ill thrift)
Symptoms, Probably KD

Changes from the original form to an improved wording with a 4-point scale to differentiate between possible kauri dieback and severe kauri dieback as below.


Kauri Dieback Field Status *
Non-symptomatic kauri
Kauri with ill thrift (probably not KD)
Kauri with possible kauri dieback symptoms
Kauri with severe kauri dieback symptoms

A8 Disturbance-related variables

Ngā taurangi ā-whakararu

Question 28a: Was there evidence of disturbance?

Question 28b: Evidence of disturbance – details

Prevalence study; Risk factors study

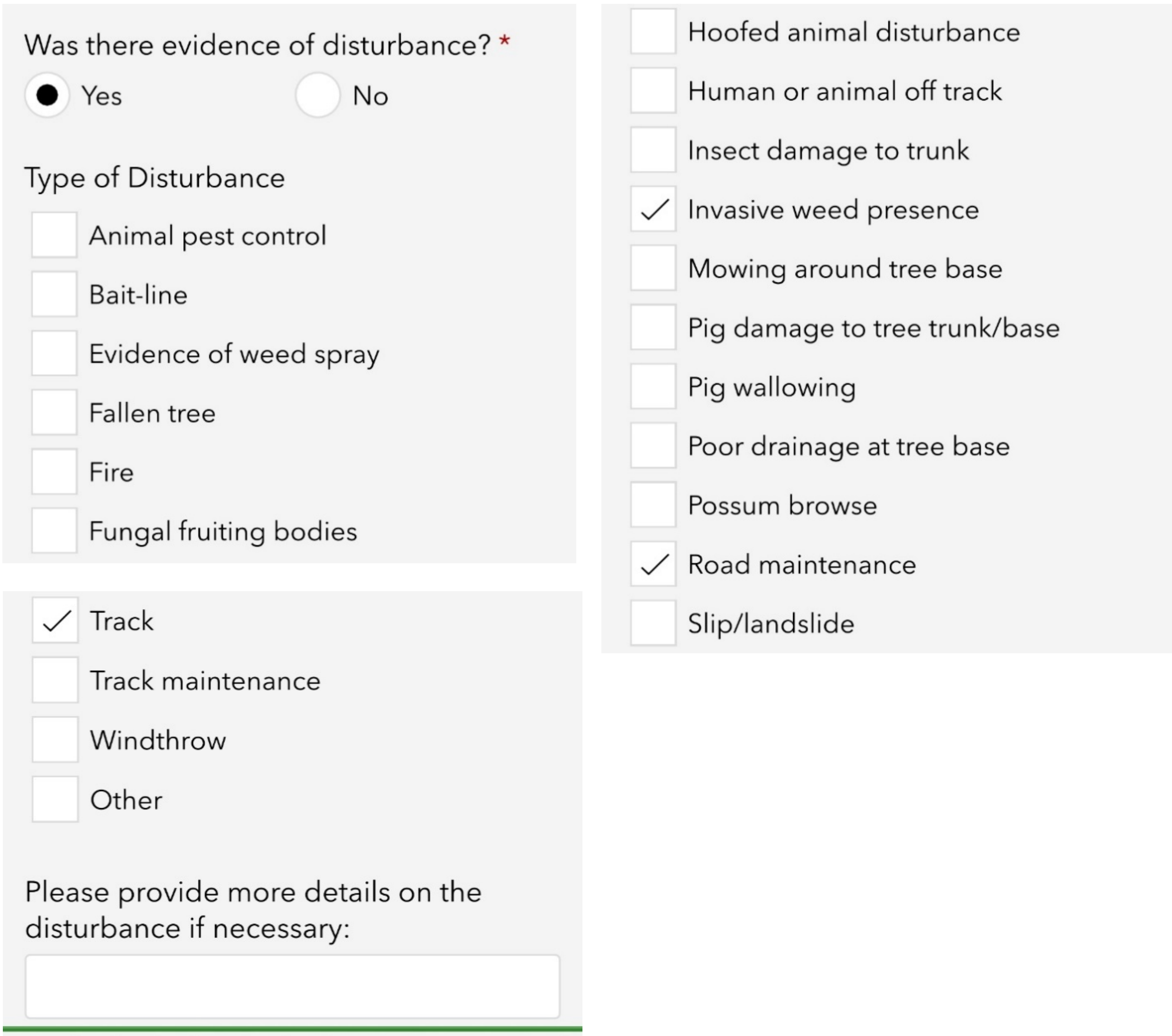
This environmental variable was included to assess if there were external factors that could explain ill-thrift in the hosts and contribute to disease development. If there was no evidence of disturbance, the surveyor selected 'No' and moved to the next question. If they ticked 'Yes', a checklist of options was displayed to select from including common expected disturbances, with the option of selecting 'Other'. They were also asked to provide more details on the disturbance if necessary. In a future form format, a comment describing ‘Other’ should be enforced when Other is selected.

While this is a single question, each of the options for disturbance need to be split into individual columns with binary Present/Absent values (1,0) for analysis.

Several disturbance options that are not fully independent need to be managed carefully when modelled and only one included at a time, e.g., animal pest control, bait-line, human or animal off-track, possum browse, pig damage, pig wallowing.

‘Pest control’ indicates that pest control is active (e.g., rat bait stations) and ‘Bait-lines’ indicate that off-track activities occur within the rootzone of the trees, which are directly related to pest control. Likewise, human off-track and bait-lines are related, as are animal off-track, pig damage and wallowing, and track and track maintenance. In addition, possum browse and animal pest control; and Invasive weed presence and weed spray may be the inverse of each other.

In the future, it is recommended that phosphite injections and soil erosion are added to the list as this was common in the ‘Other’ disturbance comments.



Was there evidence of disturbance? *

- [x] Yes
- [ ] No

Type of Disturbance

- [ ] Animal pest control
- [ ] Bait-line
- [ ] Evidence of weed spray
- [ ] Fallen tree
- [ ] Fire
- [ ] Fungal fruiting bodies
- [ ] Hoofed animal disturbance
- [ ] Human or animal off track
- [ ] Insect damage to trunk
- [x] Invasive weed presence
- [ ] Mowing around tree base
- [ ] Pig damage to tree trunk/base
- [ ] Pig wallowing
- [ ] Poor drainage at tree base
- [ ] Possum browse
- [x] Road maintenance
- [ ] Slip/landslide
- [x] Track
- [ ] Track maintenance
- [ ] Windthrow
- [ ] Other

Please provide more details on the disturbance if necessary:

Question 29: Is the site fenced off from stock?

Prevalence study; Risk factors study

We asked surveyors to assess if the site was fenced off from stock. This is mostly a placeholder for future surveys and not very applicable to the Waitākere Ranges Regional Park, where we expect almost all values to be 'NA' with a few 'Yes' entries on trees close to the Park boundary. This has limited value depending on the location of survey; however, in areas where stock fencing may be available to protect kauri, it is useful to have this information.

> Is the site fenced off from stock?
>
> Only answer Yes or No if you are aware that the whole site has stock excluded by fencing, if you are in a large forest and do not know what the boundaries are like, answer NA
>
> ○ Yes ○ No
>
> ○ NA

Question 30: Please include photos of any disturbance

Prevalence study; Risk factors study

Finally in this section, surveyors were reminded to take photos of any evidence of disturbance if they required confirmation, an identification of disturbance type, or if they selected 'Other'.

> Please include photos of any evidence of disturbance at the end of this form if they require confirmation/ID or if not in the above list.

A9 Ecological variables

Ngā taurangi ā-hauropi

Question 31a: Forest floor layer (depth) left (cm)

Question 31b: Forest floor measure to tree distance left (m)

Question 31c: Forest floor measure orientation left

Question 31d: Forest floor layer (depth) right (cm)

Question 31e: Forest floor measure to tree distance right (m)

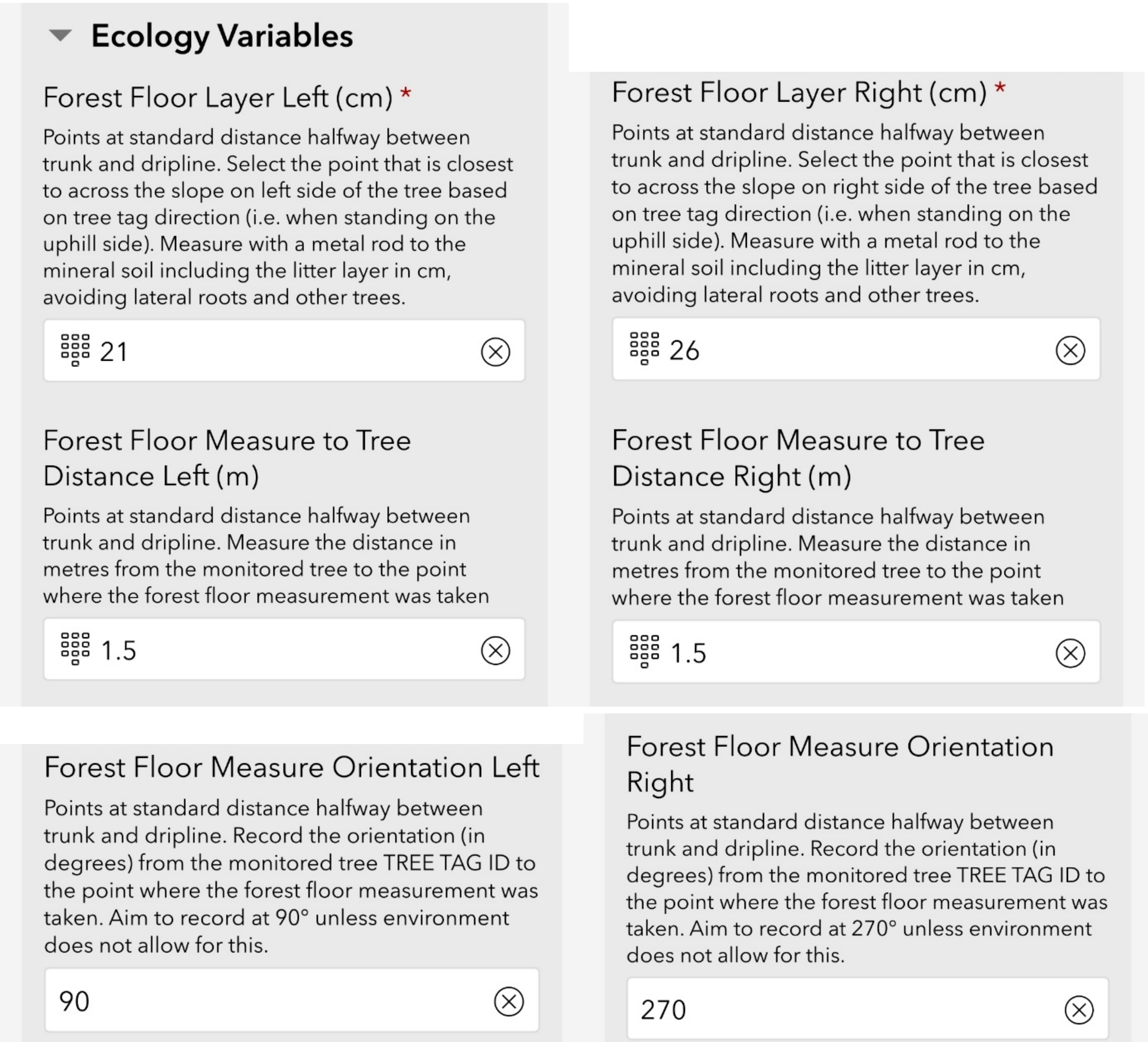
Question 31f: Forest floor measure orientation right

Prevalence study impact variables. Soil sampling trees only

The forest floor measurement gives a baseline indication of potential changes in ecosystem functions (e.g., forest productivity, nutrient cycle) and needs to be remeasured over time.

The ‘forest floor measure to tree distance’ was measured in metres halfway between trunk and dripline. The method measures the depth of the soil organic layer, which includes the partially decomposed leaf litter and soft organic layer that makes up the forest floor above the mineral soil (Silvester and Orchard, 1999). Surveyors were asked to measure the layer at 90° and 270° from the tree tag (i.e., the left and right across-slope points from the uphill tree tag point), and halfway between the trunk and the dripline at these points. The organic layer was measured in cm using the rigid Perspex rod which was disinfected after each tree.

The coordinates were recorded to enable return visits to the tree and consistent measurements at approximately the same point for future impact studies.



Ecology Variables

Forest Floor Layer Left (cm) *

Points at standard distance halfway between trunk and dripline. Select the point that is closest to across the slope on left side of the tree based on tree tag direction (i.e. when standing on the uphill side). Measure with a metal rod to the mineral soil including the litter layer in cm, avoiding lateral roots and other trees.

21

Forest Floor Layer Right (cm) *

Points at standard distance halfway between trunk and dripline. Select the point that is closest to across the slope on right side of the tree based on tree tag direction (i.e. when standing on the uphill side). Measure with a metal rod to the mineral soil including the litter layer in cm, avoiding lateral roots and other trees.

26

Forest Floor Measure to Tree Distance Left (m)

Points at standard distance halfway between trunk and dripline. Measure the distance in metres from the monitored tree to the point where the forest floor measurement was taken

1.5

Forest Floor Measure to Tree Distance Right (m)

Points at standard distance halfway between trunk and dripline. Measure the distance in metres from the monitored tree to the point where the forest floor measurement was taken

1.5

Forest Floor Measure Orientation Left

Points at standard distance halfway between trunk and dripline. Record the orientation (in degrees) from the monitored tree TREE TAG ID to the point where the forest floor measurement was taken. Aim to record at 90° unless environment does not allow for this.

90

Forest Floor Measure Orientation Right

Points at standard distance halfway between trunk and dripline. Record the orientation (in degrees) from the monitored tree TREE TAG ID to the point where the forest floor measurement was taken. Aim to record at 270° unless environment does not allow for this.

270

Question 32a: Distance to nearest neighbouring tree (m)

Question 32b: Circumference of closest neighbour (breast height in cm)

Question 32c: DBH of closest neighbouring tree (cm)

Question 32d: Closest neighbour species name

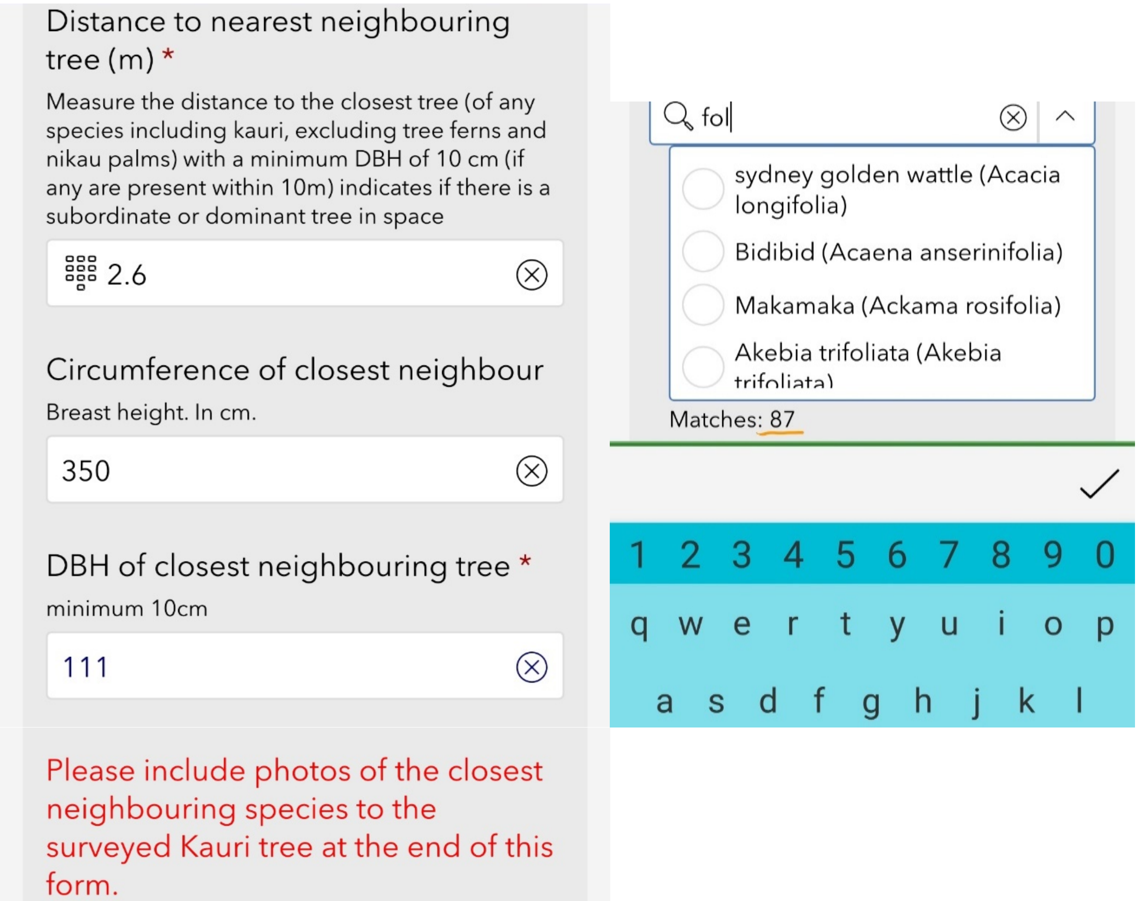
Question 32e: Closest neighbour photo

Prevalence study; Risk factors study

These variables were collected for all trees to indicate if there is a subordinate or dominant tree in the space. It provides a measure of competition intensity/stress that each tree is under within the subject-neighbour relationship, usually measured in terms of the distance, diameter and identity of the tree (see examples in Orso et al. (2020)).

The surveyors were asked to measure the distance to the closest tree (of any species including kauri, excluding tree ferns and nīkau palms) with a minimum DBH of 10 cm (if any were present within 10 m). The circumference of the nearest neighbouring tree was also measured and the DBH was auto calculated.

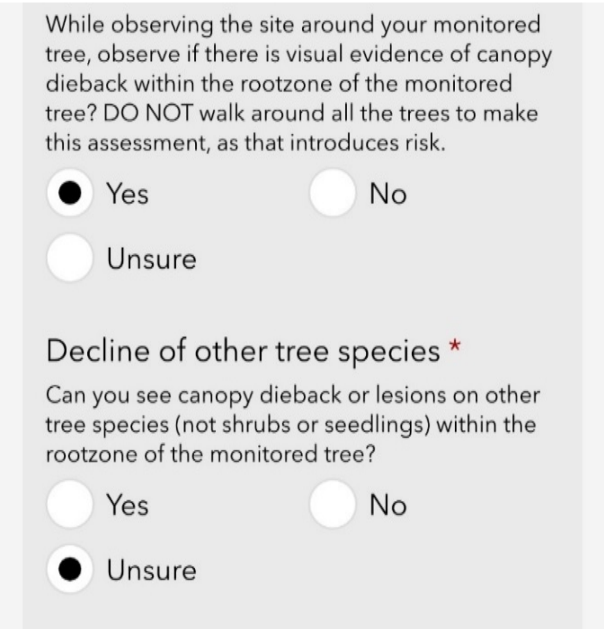
The surveyors were asked for the species of the closest neighbour, which was added using a search-based look-up of either the common or scientific name using an in-house list of flora in the Auckland region, as illustrated in the example image below.



Question 33: Suspected kauri dieback on nearby kauri – canopy

Prevalence study impact variables. Soil sampling trees only

This variable was introduced to determine if there was evidence of widespread disease in some areas around our selected trees. Surveyors were asked to look for canopy dieback on nearby kauri trees. This can be used to indicate if the observed tree is largely alone or within a group of trees expressing canopy dieback symptoms. For future form development, we need to also ask if there are any kauri within the rootzone of the kauri before asking if any are showing canopy dieback. We deliberately excluded a similar observation of basal bleeds after the 28 April 2022 form update as we felt that these were not easily observed without walking around the tree plot, increasing the risk of root damage and reducing hygiene efficacy.



Question 34: Decline of other tree species

Question 34b: Select all species showing decline

Question 34c: Are any other species declining?

Prevalence study impact variables. Soil sampling trees only

This variable was to understand if there was evidence of other tree species within the rootzone of kauri trees showing signs of decline including canopy dieback or lesions. This information may inform future studies for sites to investigate alternate hosts.

We found this very difficult to assess in the field and was of questionable value. We recommend removing this question.

Where the surveyor selected ‘Yes’ for observed decline in other species, they were prompted to record all of the tree species affected from a short list of likely species of interest and had the ability to write in any additional species as needed.

Decline of other tree species *

Can you see canopy dieback or lesions on other tree species (not shrubs or seedlings) within the rootzone of the monitored tree?

- ( ) Yes
- (●) No
- ( ) Unsure

Decline of other tree species *

Can you see canopy dieback or lesions on other tree species (not shrubs or seedlings) within the rootzone of the monitored tree?

- (●) Yes
- ( ) No
- ( ) Unsure

Select all species showing decline

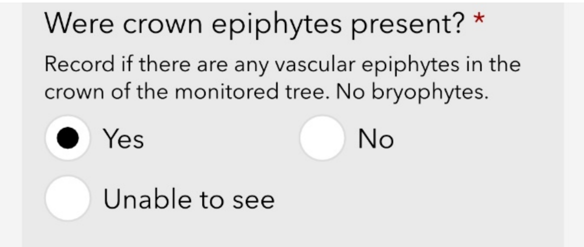
- [ ] Astelia trinervia – kauri grass
- [ ] Brachyglottis kirkii – Kirk's tree daisy
- [ ] Coprosma arborea - mamangi
- [ ] Coprosma lucida – shining karamu
- [ ] Dacrydium cupressinum – rimu
- [ ] Knightia excelsa – rewarewa
- [ ] Kunzea robusta – kanuka
- [ ] Leucopogon fasciculatus – mingimingi
- [ ] Melicytus macrophyllus – large-leaved mahoe
- [ ] Myrsine australis – mapou
- [ ] Nestegis lanceolata – white maire
- [ ] Olearia rani – heketara
- [x] Pectinopitys ferruginea – miro
- [ ] Phyllocladus trichomanoides – tanekaha
- [ ] Pseudopanax crassifolius – lancewood
- [x] Toronia toru - toru
- [ ] None

Any other species declining?

Question 35: Were crown epiphytes present?

Prevalence study impact variables. Soil sampling trees only

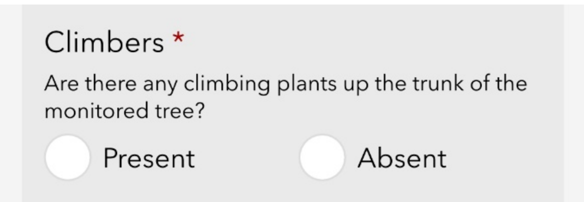
This question focused on the presence of vascular epiphytes in the crown of the target kauri. This will be correlated with DBH as epiphytes are typically in larger mature trees. It may also be of use in the tracking of host decline using remote sensing. Trees may appear to be recovering but this may be due to the loss of foliage exposing crown epiphytes rather than true recovery.


Were crown epiphytes present? *
Record if there are any vascular epiphytes in the crown of the monitored tree. No bryophytes.
Yes
No
Unable to see

Question 36: Climbers?

Prevalence study impact variables. Soil sampling trees only

This question investigated the presence of climbing plants on the trunk of the target kauri. This was a presence-only question as the aim of this was to find out if there were any correlations between kauri health and presence/absence of climbers.


Climbers *
Are there any climbing plants up the trunk of the monitored tree?
Present
Absent

Question 37: Common plants

Prevalence study impact variables. Soil sampling trees only

This question was time-consuming and was only undertaken on trees selected for soil sampling.

Surveyors were asked to select all plants on the list of common plants present within 10 m of the tree (ignoring seedlings) and without walking around the area, to ensure roots were not disturbed more than necessary.

Common Plants:

Select all species from the list that are visually present within 10m of the tree. Ignore seedlings.

- [x] Astelia trinervia – kauri grass
- [ ] Brachyglottis kirkii – Kirk's tree daisy
- [ ] Coprosma arborea - mamangi
- [x] Coprosma lucida – shining karamu
- [ ] Dacrydium cupressinum – rimu
- [ ] Knightia excelsa – rewarewa
- [ ] Kunzea robusta – kanuka
- [ ] Leucopogon fasciculatus – mingimingi
- [x] Melicytus macrophyllus – large-leaved mahoe
- [ ] Myrsine australis – mapou
- [ ] Nestegis lanceolata – white maire
- [ ] Phyllocladus trichomanoides – tanekaha
- [ ] Pseudopanax crassifolius – lancewood
- [ ] Toronia toru - toru
- [ ] None

Question 38: Comments

At the end of the survey, surveyors were provided an opportunity to add any general comments about the tree or site.

Comments

Any general comments including: Other potential causes of gummosis (insect damage, brown rot, bracket fungi), Problems with getting soil due to slope, Presence of seedling wilt or death, Description of what the tree looks like from track/road.

A10 Photos

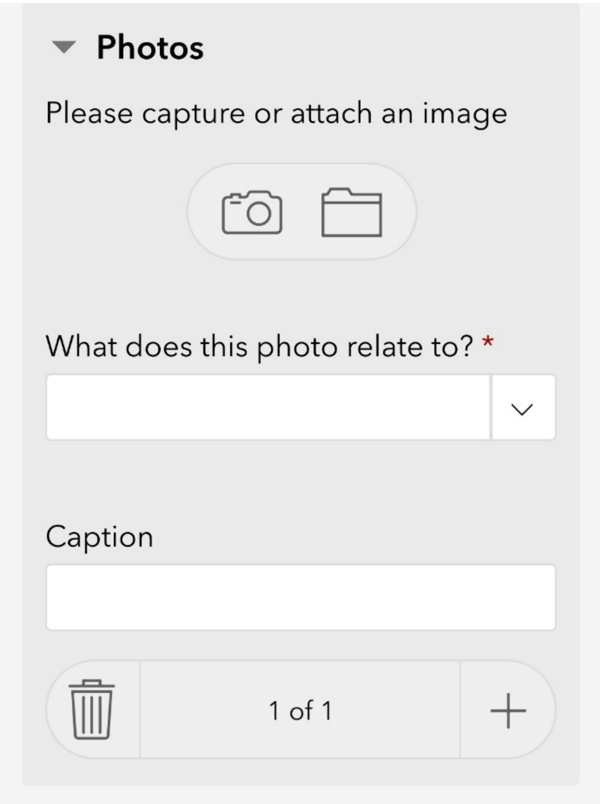
Ngā whakaahua

Question 39a: Please capture or attach an image

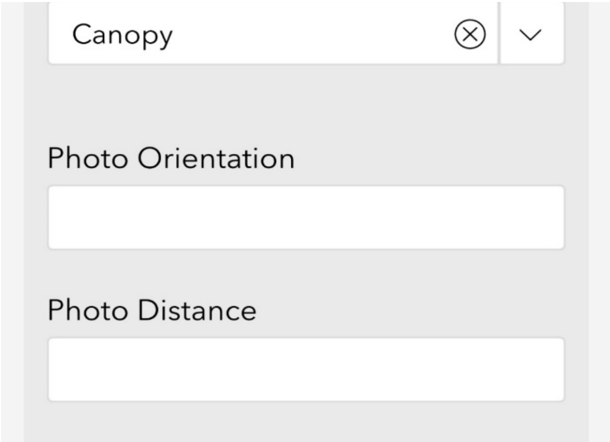
Question 39b: What does this photo relate to?

Question 39c: Caption

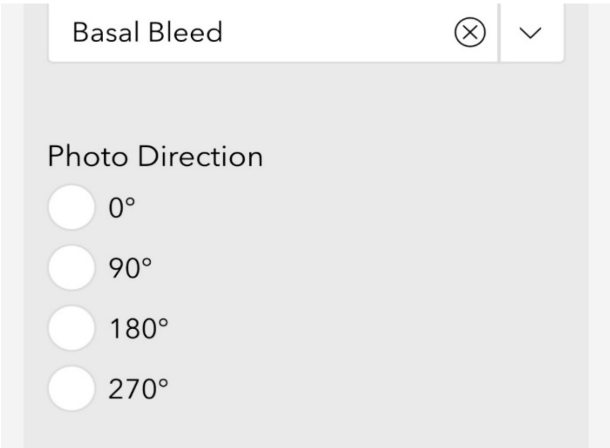
At the end of the survey, surveyors are tasked with taking images of canopy health, basal bleeds (if any), tree tag ID, soil sample ID (if required), neighbouring species (if required) and evidence of disturbance (if required).



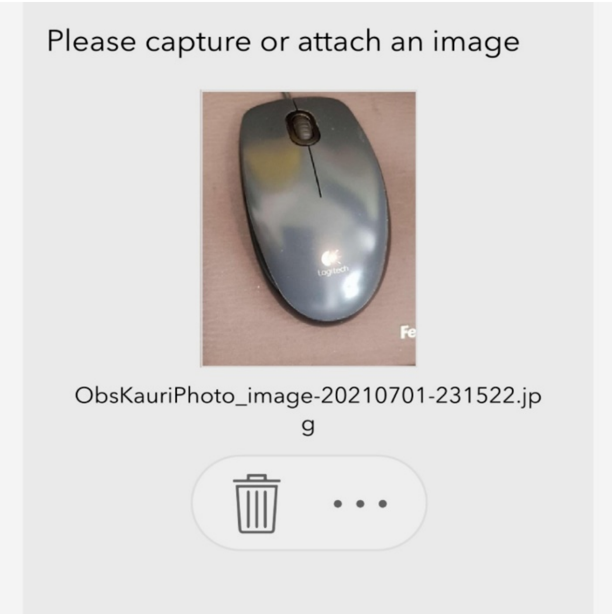
If Canopy is selected from the drop-down, then additional information is requested so that images can be compared in future surveys.

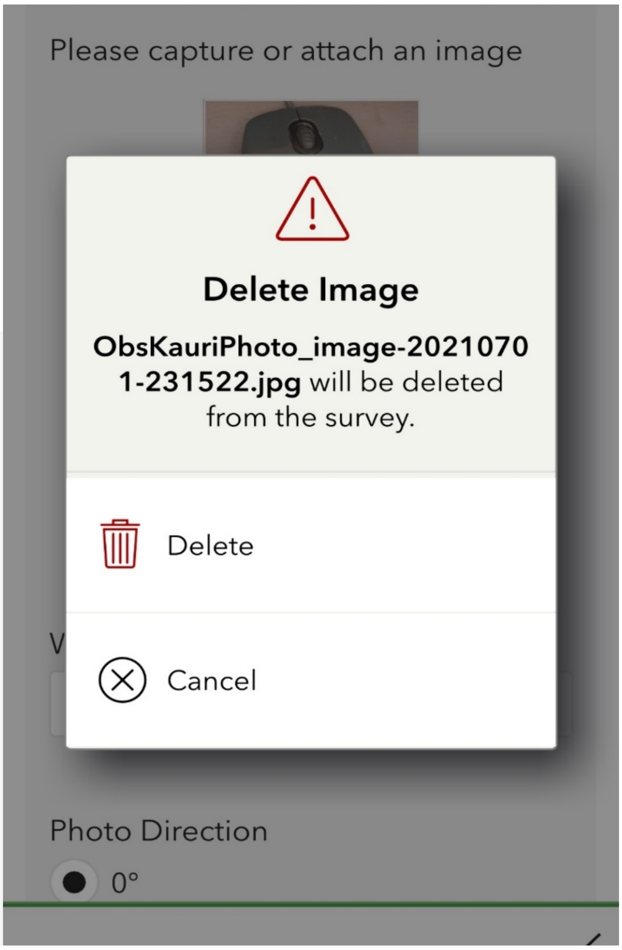


If Basal Bleed is selected from the drop-down, then additional information is requested so that images can be compared in future surveys.



Once the image is captured (example of a computer mouse below) then a filename is generated, and the image can be checked to make sure it is clear and then saved or deleted if a better image is required.





Once photos have been acquired, a ‘Survey completed’ message is generated. If more photos are required, then ‘Continue this survey’ is selected to add additional images.

Question 40: Survey completed

When the survey is completed, the surveyor can check if the device is online and send the survey to the database immediately or save the survey to the outbox.

A11 Variables calculated using existing data sources

Ngā taurangi kua tātaihia mā te whakamahi i ngā puna raraunga o te wā

A11.1 Host-related risk factors

Host factors included epicormic growth, if active growth flush or female reproductive cones were visible and if immature kauri growth stages were present within a 5 m radius around the monitored tree. Growth stages were split into small seedlings <15 cm tall, tall seedlings between 15 cm and 1.35 m (breast height) and saplings which were characterised as >1.35 cm tall and less than 10 cm DBH. Saplings were also counted into groups of 0, 1-5, 6-10 and >10 saplings present.

A11.2 Anthropogenic risk factors

There were several potential anthropogenic risk factors that were able to be calculated using existing GIS data both from the Auckland Council GIS layers and other geospatial data sources. The calculations of these GIS related variables are described in Table A-3.

All distance measures were from the point of interest which was the canopy central point to the centre of the feature if not otherwise described.

A11.3 Environmental risk factors

There were many potential environmental risk factors that could be calculated using existing GIS data both from the Auckland Council GIS layers and other geospatial data sources. The calculations of GIS related variables are described in Table A-3.

Table A-3. GIS derived variable names, units and a description of how they were derived.

Variable name	Unit	Description
Canopy height	metres	Tree height based on LiDAR
Distance to closest track	metres	Distance to closest track
Closest track name	text	Name of closest track
Uphill distance to track	metres	Distance from kauri tree and the closest uphill track point - based on two conditions: i) tree and track are in the same sub-catchment; ii) elevation of the track is higher than the elevation of the kauri tree
Natural sub-catchment	text	Name of the delineated natural drainage sub-catchment the tree is located within
Stream sub-catchment	text	Name of the smaller stream based sub-catchments within the natural drainage sub-catchments
Distance to closest road	metres	Distance from closest public road
Distance to ocean	metres	Distance from mean high-water mark from closest coastline including harbours and estuaries

Elevation	metres	Elevation in metres above sea level at location where tree is growing
Aspect	degrees	The geographical direction in degrees the slope is facing at the tree location
Slope	degrees	Slope at location where tree is growing
Depth to water index	Metres	Depth to water index (DTW) – a soil moisture index. The DTW output is a 32 bit 1x1 m surface raster. It was created using a multistep process; first, smoothing the high-resolution hydro conditioned 2016 DEM. Smoothing was used to blur DEMs to remove the changes in elevation that are too small to indicate features of interest (i.e., microtopographic noise), which are ubiquitous in high-resolution DEMs. The default Perona Malik smoothing method and 10 m smoothing width with 50 iterations were applied. This smoothed DEM is the primary input for the Depth to Water index tool (Archydro toolbox). The other is a surface water raster layer – this was generated from a combination of the water bodies in the 'Inland Water Bodies' feature from the Auckland Council Ecosystems layer and the permanent streams layer. These layers were rasterised for use in the DTW tool. This tool calculates the cartographic depth-to-water index (DTW). The DTW, developed by Murphy et al. (2007), is a soil moisture index based on the assumption that soils closer to surface water in terms of distance and elevation are more likely to be saturated.
Distance to closest overland flow path	Metres	Distance to overland flow path
Distance to park boundary	Metres	Distance to park boundary
Distance to historic timber sites	Metres	Distance to early European timber mills/saw pits
Landcover database types	Text	New Zealand Landcover database (LCDB) class from the LCDB v5.0 - Land Cover Database version 5.0, Mainland, New Zealand, Manaaki Whenua Landcare Research
Ecosystem types	Text	Habitat types e.g., wetlands vs shrubland, clearings, forest types (Native, Plantation, Restoration, Remnant, Riparian, Urban) based on Singers and Rogers (2014)
Within 500 m of archaeological features	Count	Number of archaeological features within 500 m

Closest confirmed *P. agathidicida* site	Text	Distance to closest confirmed *P. agathidicida* site from current and historic soil test results as defined in Stevenson and Froud (2020)

A12 Updated summary of the Stevenson and Froud (2020) draft kauri dieback case definition

Te whakarāpopoto hou i tā Stevenson rāua ko Froud (2020) whakamahuki i te hukihuki o te rangahau iti mō te puruheka patu kauri

Case definition	**Case classification**	**Soil test positive**	**Symptomatic criteria**	**Epidemiological criteria**	**Approved observer**
Symptomatic	Confirmed	Yes	Yes	Yes	Yes
Symptomatic	Probable	No	Yes	Yes	Yes
Symptomatic	Suspect	No	Yes	No	Yes
Non-symptomatic	Ill-thrift	Yes or no	No but ill-thrift	Yes or no	Yes
Non-symptomatic	Healthy	Yes or no	No	Yes or no	Yes or no

A13 Common species method development

Te huarahi whakawhanake mō ngā momo māori

A common kauri tree community species checklist was developed using the following methods:

The Auckland University Waitākere kauri plot data (unpublished data) were assessed, and the most common tree species were extracted from those plots. Based on both the number of plots they occurred in and the mean ranking of these species within plots, the top 15 species were identified as:

1. *Coprosma arborea* - māmāngi
2. *Cyathea dealbata* - ponga
3. *Pseudopanax crassifolius* – lancewood
4. *Myrsine australis* – māpou
5. *Dacrydium cupressinum* – rimu
6. *Knightia excelsa* – rewarewa
7. *Phyllocladus trichomanoides* – tanekaha
8. *Kunzea robusta* – kānuka
9. *Nestegis lanceolata* – white maire
10. *Leucopogon fasciculatus* – mingimingi
11. *Geniostoma ligustrifolium* – hangehange

12. *Coprosma lucida* – shining karamū
13. *Leptospermum scoparium* – mānuka
14. *Melicytus macrophyllus* – large-leaved māhoe
15. *Pittosporum ellipticum*

A potential criticism of this list is that it includes some species that occur equally commonly with and without kauri, e.g., *Cyathea dealbata, Geniostoma ligustrifolium, Leptospermum scoparium*

A second source of information was the research carried out by Wyse et al. (2014) which looked at the strength of association of species with kauri at Waipoua and Russell forests using large plot databases. The results from Wyse et al. (2014) were used to come up with a list of 15 tree species that had the highest mean association between kauri and each species, as follows:

1. *Phyllocladus trichomanoides* – tanekaha
2. *Leucopogon fasciculatus* – mingimingi
3. *Olearia rani* – heketara
4. *Brachyglottis kirkii* – Kirk's tree daisy
5. *Toronia toru* – toru
6. *Myrsine australis* – māpou
7. *Podocarpus laetus* – Hall's tōtara
8. *Pseudopanax crassifolius* – lancewood
9. *Dacrydium cupressinum* – rimu
10. *Coprosma lucida* – shining karamū
11. *Kunzea robusta* – kānuka
12. *Knightia excelsa* – rewarewa
13. *Nestegis lanceolata* – white maire
14. *Pectinopitys ferruginea* – miro
15. *Coprosma arborea* – māmāngi

These lists shared many species and a final list that combines them by removing the three species that are common with and without kauri in the Waitākere Ranges (*Cyathea dealbata, Geniostoma ligustrifolium, Leptospermum scoparium*), and excluding species that are rare in the Waitākere Ranges, e.g., *Podocarpus laetus, Pittosporum ellipticum*, was developed. The final list is as below:

1. *Coprosma arborea* – māmāngi
2. *Pseudopanax crassifolius* – lancewood
3. *Myrsine australis* – māpou
4. *Dacrydium cupressinum* – rimu
5. *Knightia excelsa* – rewarewa
6. *Phyllocladus trichomanoides* – tanekaha
7. *Kunzea robusta* – kānuka
8. *Nestegis lanceolata* – white maire
9. *Leucopogon fasciculatus* – mingimingi
10. *Coprosma lucida* – shining karamū
11. *Melicytus macrophyllus* – large-leaved māhoe
12. *Olearia rani* – heketara

13. *Brachyglottis kirkii* – Kirk's tree daisy
14. *Toronia toru* – toru
15. *Pectinopitys ferruginea* – miro

Appendix B

Supplementary results from the prevalence study – descriptive summary of host, environment and anthropogenic risk factors and ecological impact factors from Chapter 2

Ngā hua āpiti i tētahi mātai e tukupū ana

This appendix contains supplementary tables and descriptive summaries of some survey results, including host, environmental and anthropogenic risk factors.

B1 Host detection

Te kitenga o te papa rauropi

Table B-1. Tree species that were misclassified as kauri trees using remote sensing for host detection.

Misclassified trees common names (scientific name)	Number of tree sites	Percent of tree sites
Not recorded	132	5%
Rimu (*Dacrydium cupressinum*)	80	3%
Rātā (*Metrosideros robusta)*	35	1%
Rewarewa (*Knightia excelsa*)	32	1%
Kahikatea (*Dacrycarpus dacrydioides*)	24	1%
Pine (*Pinus radiata, P.* spp.)	24	1%
Tanekaha (*Phyllocladus trichomanoides*)	7	0.3%
Pūriri (*Vitex lucens*)	2	0.08%
Tawa (*Beilschmiedia tawa*)	2	0.08%
Matai (*Prumnopitys taxifolia*)	1	0.04%
Pōhutukawa (*Metrosideros excelsa*)	1	0.04%
Taraire (*Beilschmiedia tarairi*)	1	0.04%
Wattle (dead) (*Acacia* spp.)	1	0.04%
Total	**342**	**14%**

B2 Basal lesions

Ngā tūnga pukupuku ā-kiri

Field surveyors assessed that 16% of trees (338) had lesions that were consistent with possible or severe kauri dieback, and 6% of trees (125) had lesions that were not consistent with kauri dieback (assessed as non-symptomatic or ill-thrift) (Table B-2). There were surveyor comments for 14 of the basal bleed observations noting that bleeds were caused by physical damage. Where details were given about physical damage, the most common comments were that fallen branches and epiphytic climbers had dislodged and caused the bleed.

Table B-2. Numbers and proportion of monitored kauri trees (n=2140) with basal or lateral root bleeds present, stratified by kauri dieback field status.

Kauri dieback field status class	Disease lesions present	Disease lesions absent	Percent of trees with lesions present in each class
Non-symptomatic kauri	68	1145	6%
Kauri with ill thrift (probably not kauri dieback)	57	224	20%
Kauri with possible kauri dieback symptoms	301	304	50%
Kauri with severe kauri dieback symptoms	37	4	90%

The surveyors also added comments to 54 observations that had been scored as not having basal bleeds. These were typically referring to non-basal type bleeds that were higher up the tree and caused by physical damage (fallen branches, split trunks etc).

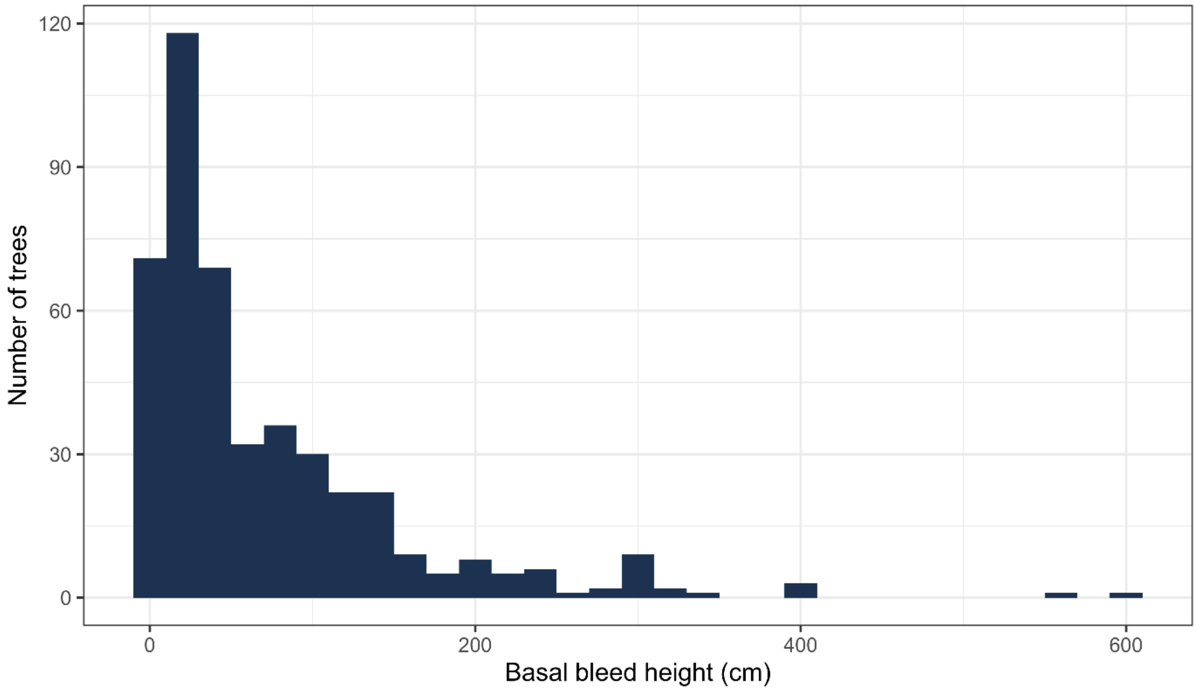


Figure B-1. Frequency histogram showing the number of trees in each 20 cm increment of basal bleed heights from 453 trees with basal bleeds present.

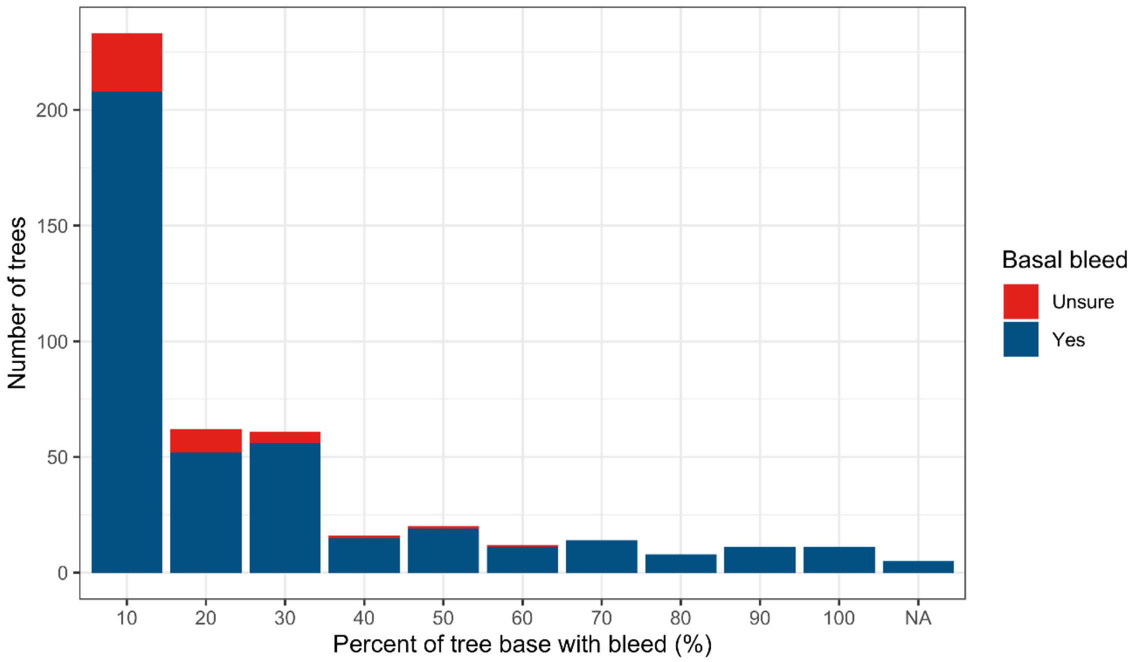


Figure B-2. Percent of the tree base affected by a basal lesion (bleed) from 453 monitored trees with basal lesions.

B3 Canopy health

Te hauora o ngā kāuru

Table B-3. Number and percent of monitored trees (n=2140) with different canopy health scores. Note that fully dead trees were reported separately.

Canopy score	Number of trees	Percent of trees
1 – Healthy crown	182	9%
1.5	845	39%
2 – Foliage/canopy thinning	652	30%
2.5	293	14%
3 – Some branch dieback	116	5%
3.5	40	2%
4 – Severe dieback	8	0.4%
4.5	4	0.2%
5 – Dead	NA	NA

B4 Approved observer kauri dieback field status

Te āhua o te puruheka patu kauri o te wā e ai ki te kaimātai kua whakaaetia

As part of the symptomatic criteria calculation, the surveyors assessed the field status of trees based on all observed symptoms of the individual tree and drawing on their experience in assessing kauri dieback in the field. Surveyors were instructed not to take the health status of nearby kauri into account as we were interested in disease expression of kauri dieback in the monitored trees. Most trees were assessed as non-symptomatic (57%) or possible kauri dieback (28%) with few showing severe kauri dieback symptoms (2%) (Table B-4).

Table B-4. Number and percent of 2140 kauri trees assessed by surveyors to have different kauri dieback field status scores.

Kauri dieback field status	Number of trees	Percent of trees
Non-symptomatic kauri	1213	57%
Kauri with ill-thrift probably not kauri dieback	281	13%
Kauri with possible kauri dieback symptoms	605	28%
Kauri with severe kauri dieback symptoms	41	2%

Basal bleeds and poor canopy scores were jointly involved in classifying the kauri dieback field status by surveyors (Figure B-3; Figure B-4). Likewise, a small number of trees that were scored as non-symptomatic and ill-thrift had canopy health scores of 2.5 and 3 but were also assessed by the surveyor to not be consistent with kauri dieback (Figure B-4). Almost all trees scored as severe dieback had basal bleeds and the 4 that did not have basal bleeds had canopy scores of 3.5.

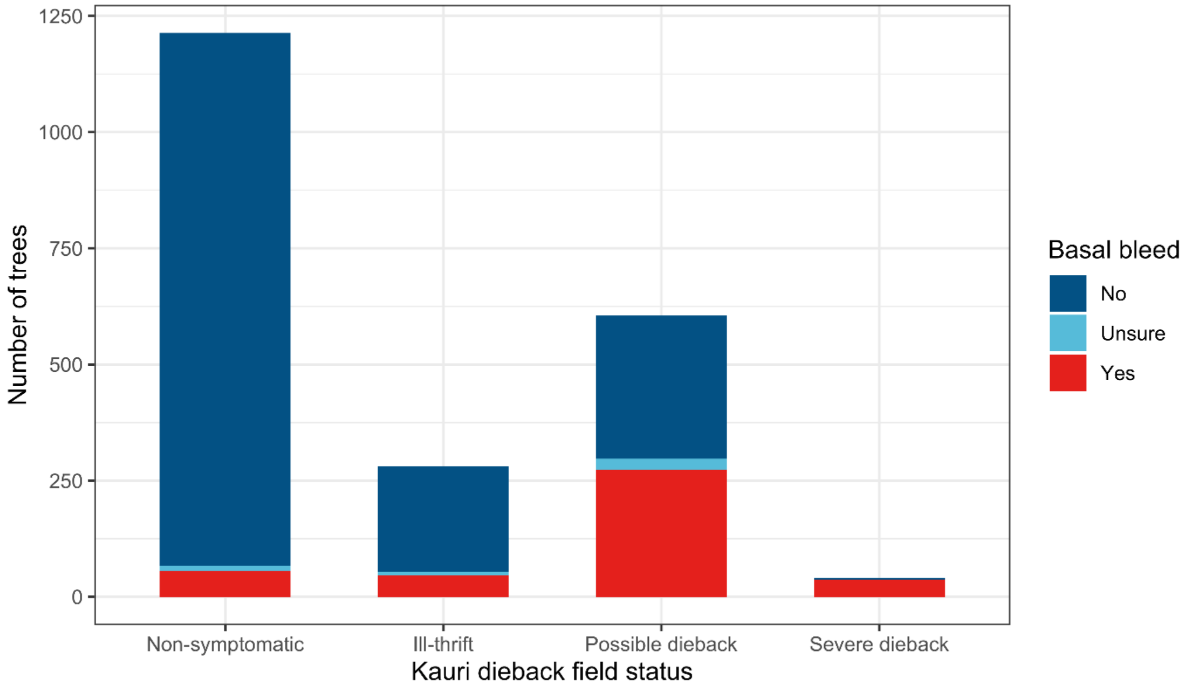


Figure B-3. Bar chart showing frequencies of kauri dieback field status assessment by presence or absence of basal bleeds.

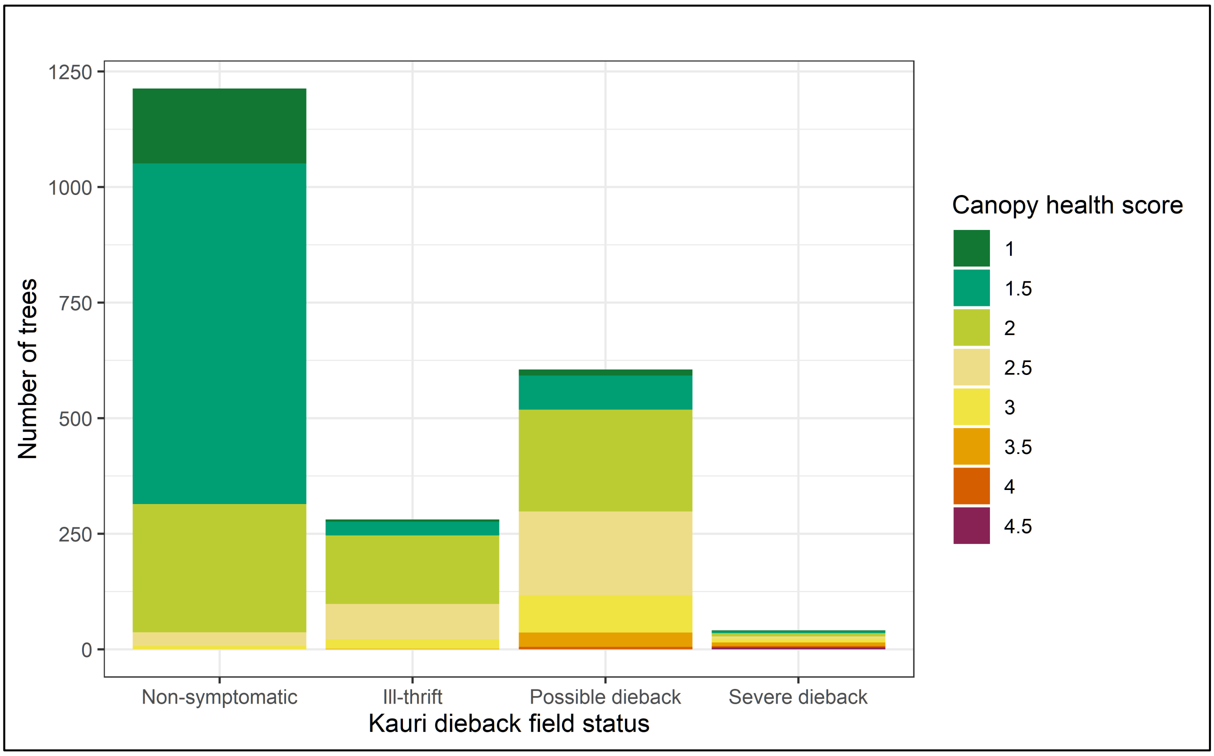


Figure B-4. Bar chart showing frequencies of kauri dieback field status assessment by canopy health scores.

B5 Host factors

Ngā āhuatanga ā-papa rauropi

B5.1 Age class

Figure B-5. Canopy images showing the range in size from one of the smallest trees in the study (DBH of 13 cm) and one of the largest trees with a DBH of 317 cm.

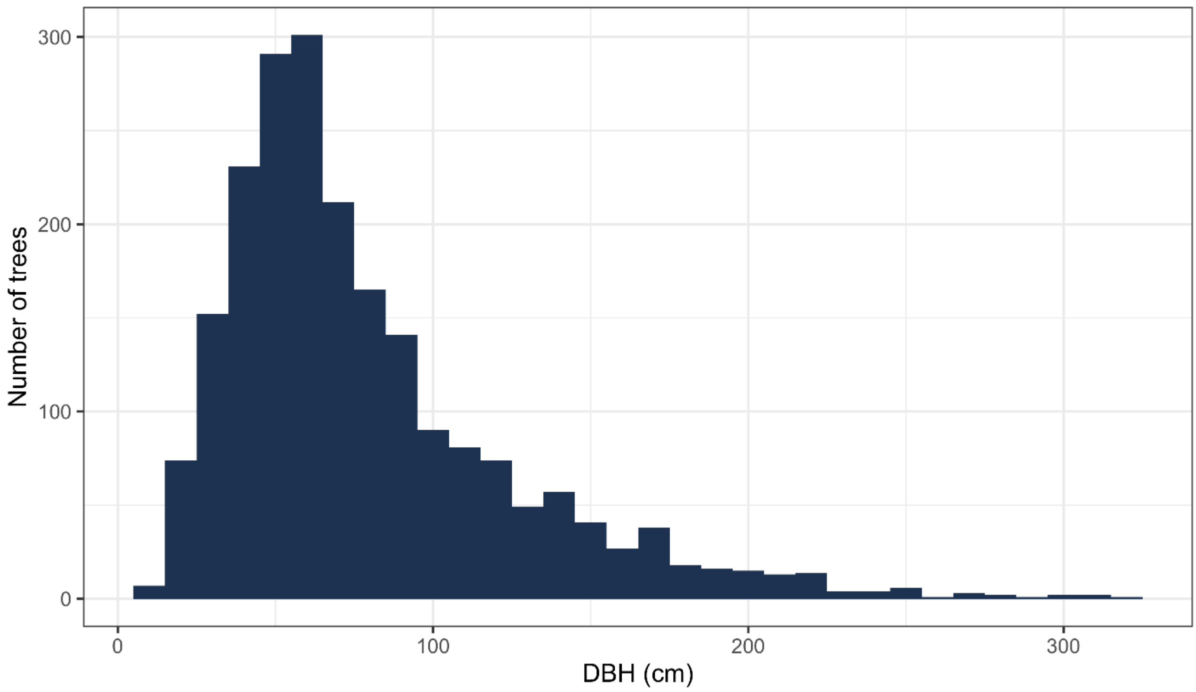


Figure B-6. Frequency histogram showing diameter at breast height (DBH) of monitored kauri trees (with a bin width of 10 cm).

Within the size classes that were eligible for monitoring (i.e., >15 m tall and >10 cm DBH) we found that the cut-over regenerating forest was dominated by intermediate size class trees with only 6% mature trees. In contrast the mature forest stand, while still dominated by intermediate trees, had a quarter of the trees in the mature size class (Table B-5).

Table B-5. Number and percent of monitored kauri trees in each size class (Ricker <150 cm; Intermediate 150-450 cm and mature >450 cm circumference), stratified by host origin forest type from 2133 observations.

Host origin	Ricker	Intermediate	Mature
Cut-over regenerating	448 (29%)	1035 (66%)	88 (6%)
Farmland	7 (39%)	11 (61%)	0 (0%)
Mature forest stand	63 (12%)	321 (62%)	130 (25%)
Other/Unsure	3 (21%)	11 (79%)	0 (0%)
Plantation kauri	3 (43%)	4 (57%)	0 (0%)
Restoration planting	3 (33%)	6 (67%)	0 (0%)
Total	527 (25%)	1388 (65%)	218 (10%)

Young seedlings were seen at 36% (524) of sites and established seedlings were seen at 24% (350) of sites. Saplings were seen at 36% of sites (525). The number of saplings present was typically between 1 and 5 when present (Table B-6).

Table B-6. Number of kauri tree monitoring sites where saplings were observed within 5 m of the trunk of the kauri tree, stratified by the range of counts of saplings per site from 1452 sites.

Range of sapling counts	Number of sites	Percent of sites
0	927	64%
1 to 5	400	28%
6 to 10	60	4%
>10	65	4%

B5.2 Epicormic growth

The presence of epicormic growth was assessed at 1453 sites and was observed at 11% of sites (153) and was widely distributed throughout the landscape (Figure B-7).

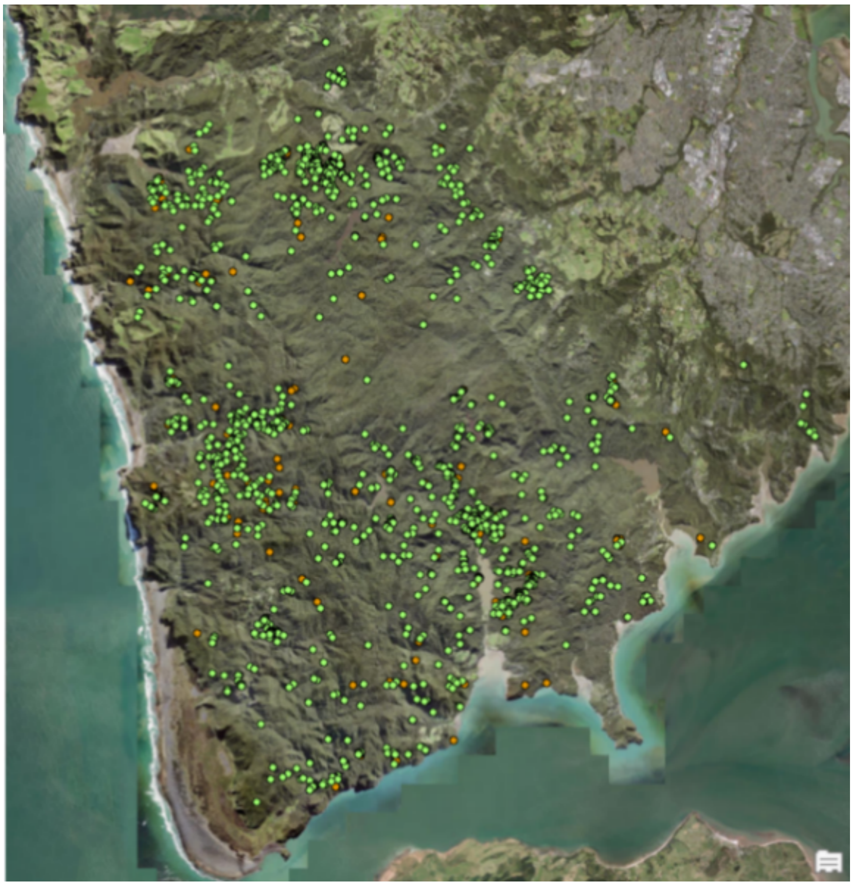


Figure B-7. Spatial distribution of monitored kauri trees in green with those showing epicormic growth in orange.

B5.3 Host phenology

A total of 1452 trees were assessed to see if they had active growth flush in the canopy. The surveyors gave feedback that it was difficult to observe growth flush in the canopy, especially if it was a dull day or if the sun was directly above the tree. Likewise female seed cones were difficult to observe. For 27% of observations (395 trees) growth flush was not able to be seen. For the remaining 1057 trees, a growth flush was observed in just under half of the trees (49%, n=522). This differed by month and was increasingly detected over time. There was a decrease in the 'not visible' category over time, possibly due to a seasonal difference in direct sunlight (Figure B-8).

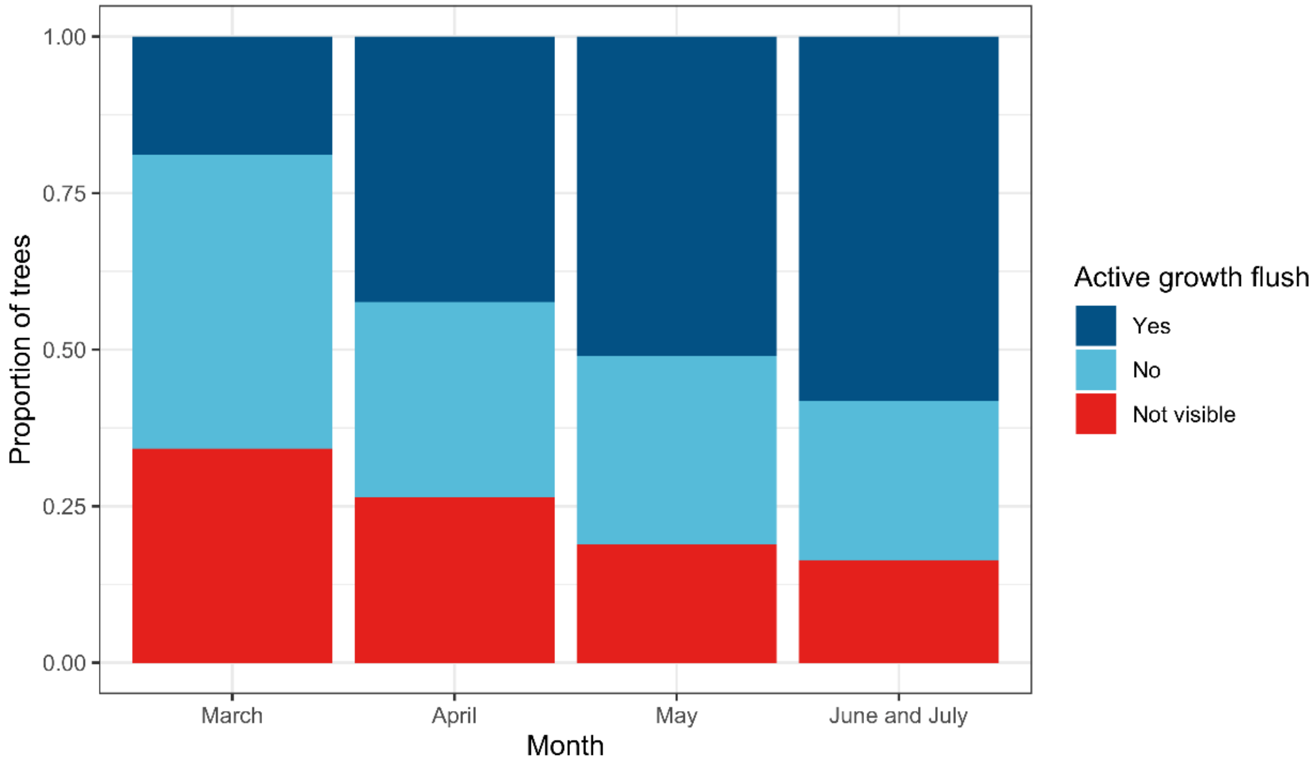


Figure B-8. Difference in the proportion of trees with active growth flush over time.

The presence of female cones was monitored on 1453 of the trees (including all soil sampled trees). They were observed on only 87 trees, were not present on 714 and were not visible for 652 of the trees. The detection of seed cones followed a seasonal pattern with 69% of cones seen in March with a drop-off over autumn (Figure B-9). Of the trees with seed cones present, 94% had visible cone scales on the forest floor from observations spanning from early-March to mid-May, indicating that the cones were mature and dropping during the survey. The 6% that did not have dropped scales spanned from late March to late June and may have included immature cones. Some monitored trees were too young to be reproductive as small ricker trees are typically not reproductive until they are 25-40 years old (Steward and Beveridge, 2010).

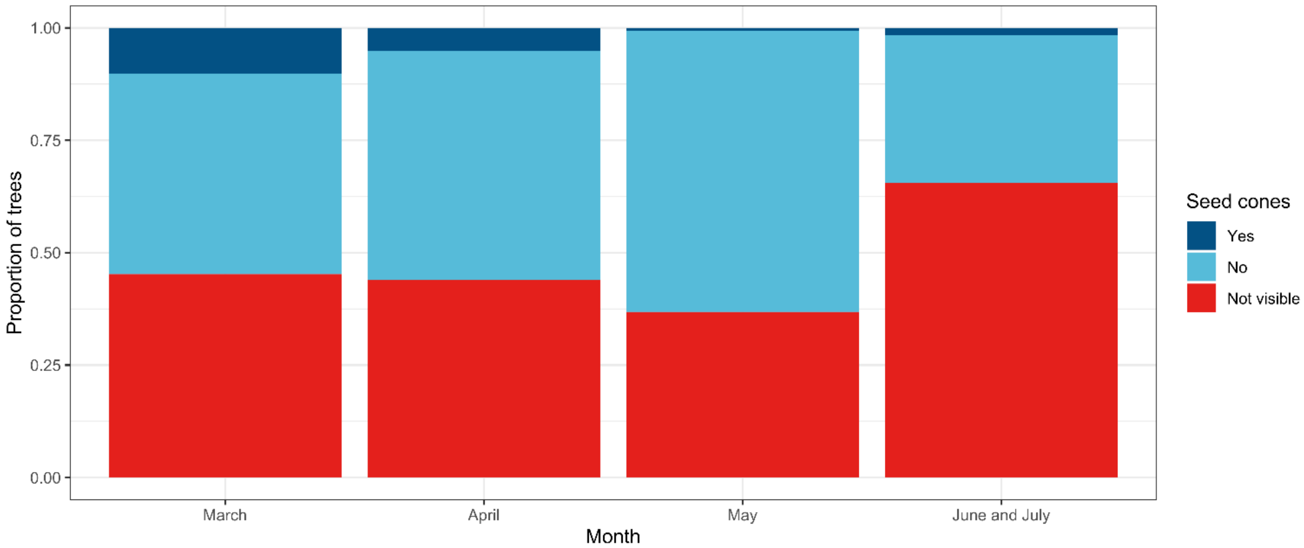


Figure B-9. Proportion of trees with female seed cones visible over time of monitoring (n=87).

B6 Environmental factors

Ngā āhuatanga ā-take taiao

B6.1 Nearby kauri with dieback

The canopy of nearby kauri showed evidence of canopy dieback in 28% of sites (597), no evidence at 41% of sites (876) and surveyors recorded that they were unsure at 5% of sites (116).

Kauri dieback basal bleeds on nearby kauri trees were difficult to observe from a distance and only bleeds visible from the monitored tree were counted. Of these, basal bleeds were observed on nearby trees of 7% of trees (145 in total, 77 near symptomatic kauri trees and 68 near non-symptomatic trees). A further 14% of trees (305) had suspected basal bleeds (where the surveyor was unsure) on nearby kauri trees. As absence was not reliably recorded, statistical significance was not calculated.

B6.2 Other species decline

Of the 1590 trees where ecological impact data were collected, there were 113 sites (7%) where other tree species were showing signs of decline and a further 86 (5%) sites where surveyors were unsure. Of the sites where decline was observed on other species, 89 had a description of the species that were showing decline, which were typically just one other species (n=71). There were 11 observations with 2 species showing decline, 6 of 3 species and 1 of 5 species. The most common species reported declining was kānuka followed by tanekaha (Table B-7).

Table B-7. Non-kauri plant species showing signs of decline at 89 kauri tree monitoring sites.

Common name	Species name	Number of sites
Kānuka	*Kunzea robusta*	48
Tanekaha	*Phyllocladus trichomanoides*	16

Māmāngi	*Coprosma arborea*	8
Lancewood	*Pseudopanax crassifolius*	8
Rewarewa	*Knightia excelsa*	7
Mingimingi	*Leucopogon fasciculatus*	5
Shining karamū	*Coprosma lucida*	4
Heketara	*Olearia rani*	4
Large-leaved māhoe	*Melicytus macrophyllus*	4
White maire	*Nestegis lanceolata*	3
Māpou	*Myrsine australis*	3
Kauri grass	*Astelia trinervia*	2
Miro	*Pectinopitys ferruginea*	2
Kirk's tree daisy	*Brachyglottis kirkii*	1
Rimu	*Dacrydium cupressinum*	1

B6.3 Distance to coastline or harbour

The distribution of trees in relation to distance to the high tide water mark of the ocean (including Manukau harbour) was bimodal in that trees were either quite close or far apart from the ocean or harbour (Figure B-10). The median distance was 3234 m (25th percentile 2021 m; 75th percentile 5944 m; min 4 m; max 8123 m).

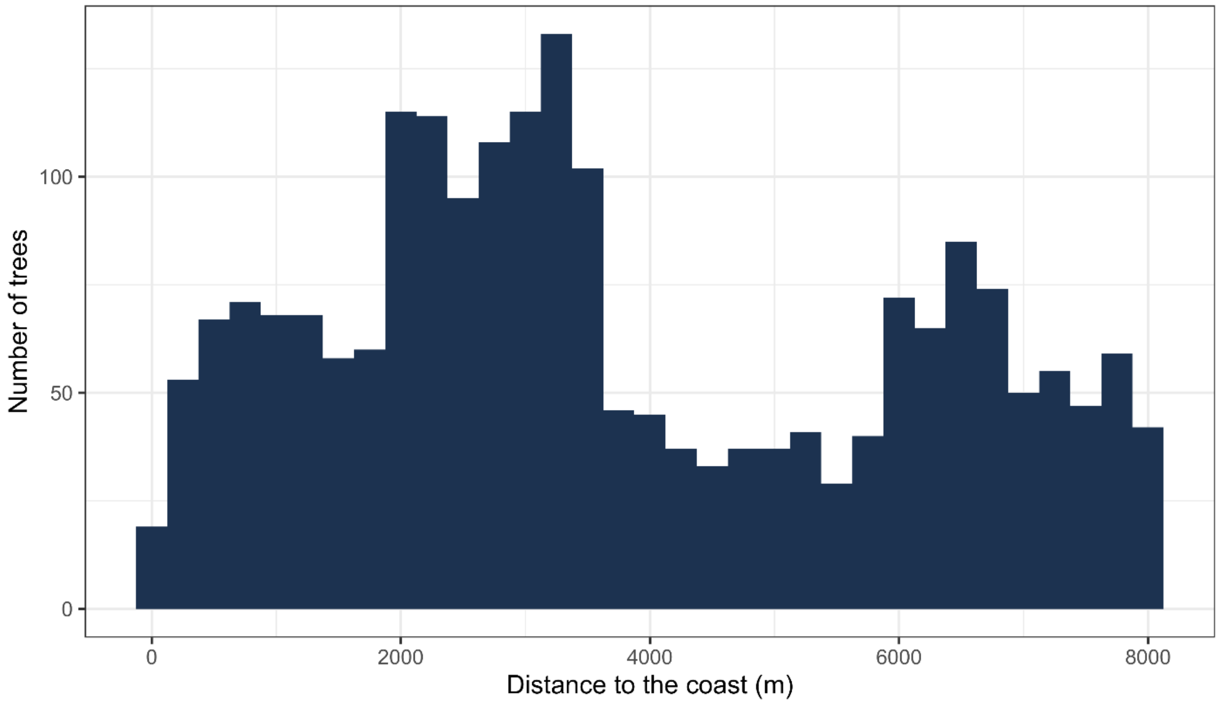


Figure B-10. Frequency histogram showing the number of trees at increasing distance (metres) from the high tide water mark of the coast (or harbour) of 2140 monitored kauri trees with a bin width of 250 m.

B6.4 Elevation

The range of elevation was slightly skewed to the left (Figure B-11) for the 2140 monitored trees with a median elevation of 182 m (25th percentile 134 m; 75th percentile 233 m; min 29 m; max 424 m). This was similar for the 761 soil sampled trees with a median of 184 m (25th percentile 135 m; 75th percentile 240 m; min 32 m; max 424 m).

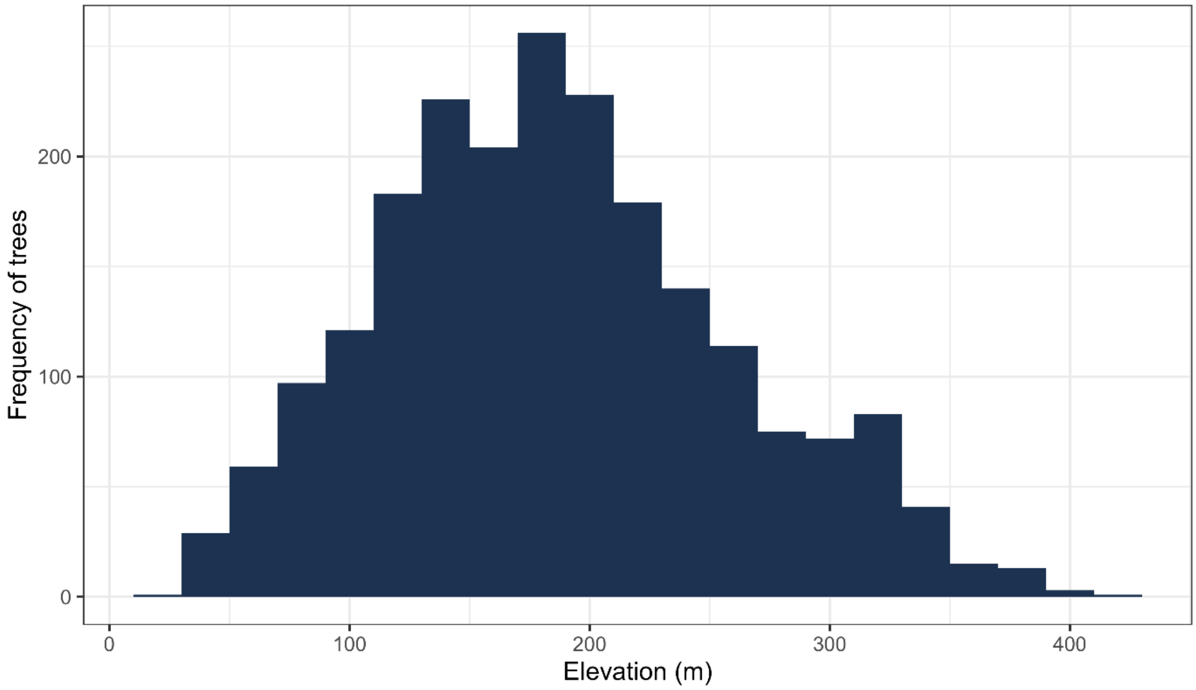


Figure B-11. Frequency histogram showing the elevation distribution in metres of 2140 kauri trees monitored in the Waitākere Ranges Regional Park.

B6.5 Aspect

The 2140 monitored trees were evenly distributed between aspects (Table B-8), with slightly more in the southwest.

Table B-8. Frequency of trees in each aspect group.

Aspect	Total in group	Percent in group
North	242	11%
Northeast	238	11%
East	274	13%
Southeast	285	13%
South	265	12%
Southwest	307	14%
West	288	13%
Northwest	241	11%

B6.6 Slope

The median slope of the 2140 trees was 25° (25th percentile 17°; 75th percentile 33°) with a maximum slope of 67°, which is extremely difficult terrain for ground surveillance teams (Figure B-12).

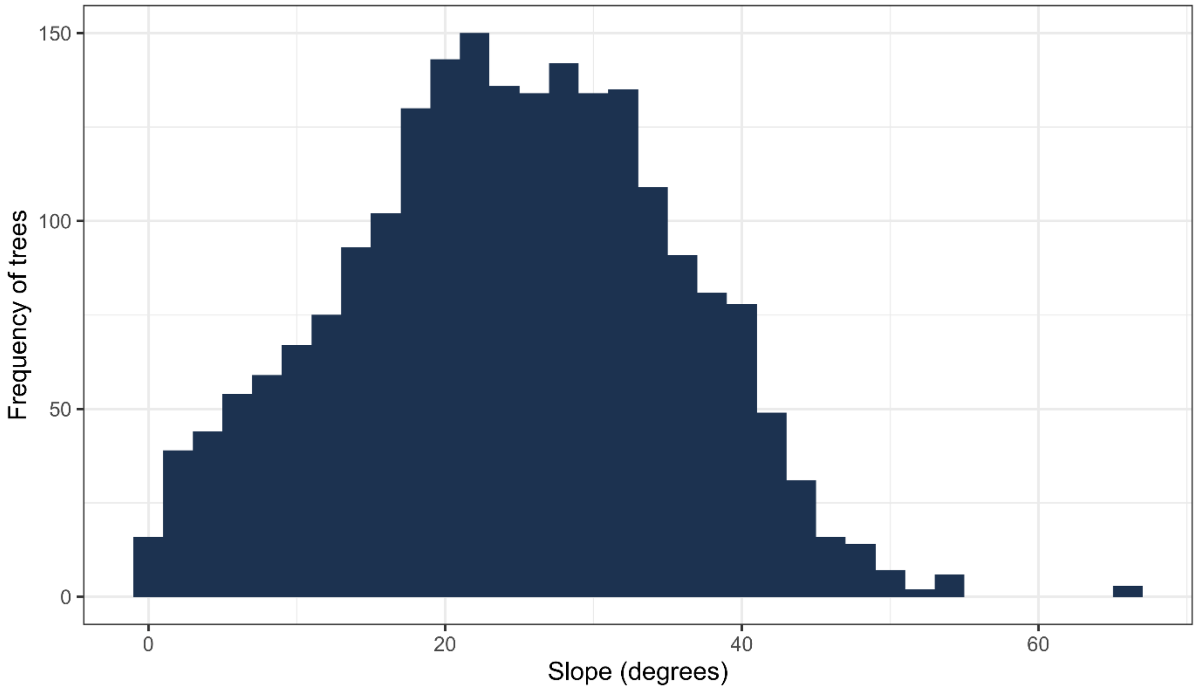


Figure B-12. Frequency histogram showing the distribution of slope in degrees of 2140 monitored kauri sites.

B6.7 Depth to water index

The cartographic depth-to-water index, which indicates how many vertical metres the base of the tree was above a saturated surface of water (overland flow path, stream, dam, wetland), was slightly left skewed with a median value for the 2140 monitored trees at 59 m above surface water (25th percentile 32 m; 75th percentile 81 m; min 0 m; max 227 m) (Figure B-13).

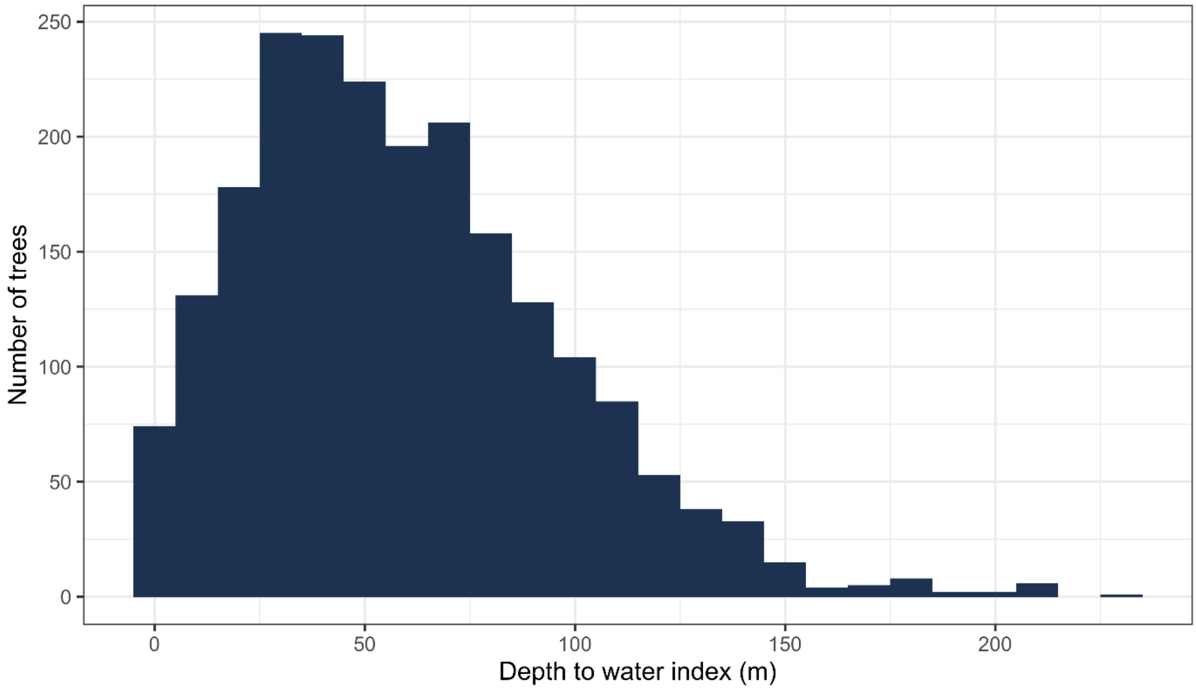


Figure B-13. Frequency histogram showing the number of trees at different depths to water using a depth to water index in metres with a bin width of 10 m.

B6.8 Distance to closest overland flow path

The distance to the closest overland flow path was left skewed with a median value for the 2140 monitored trees at 30 m (25th percentile 17 m; 75th percentile 45 m; min 0 m; max 107 m) (Figure B-14).

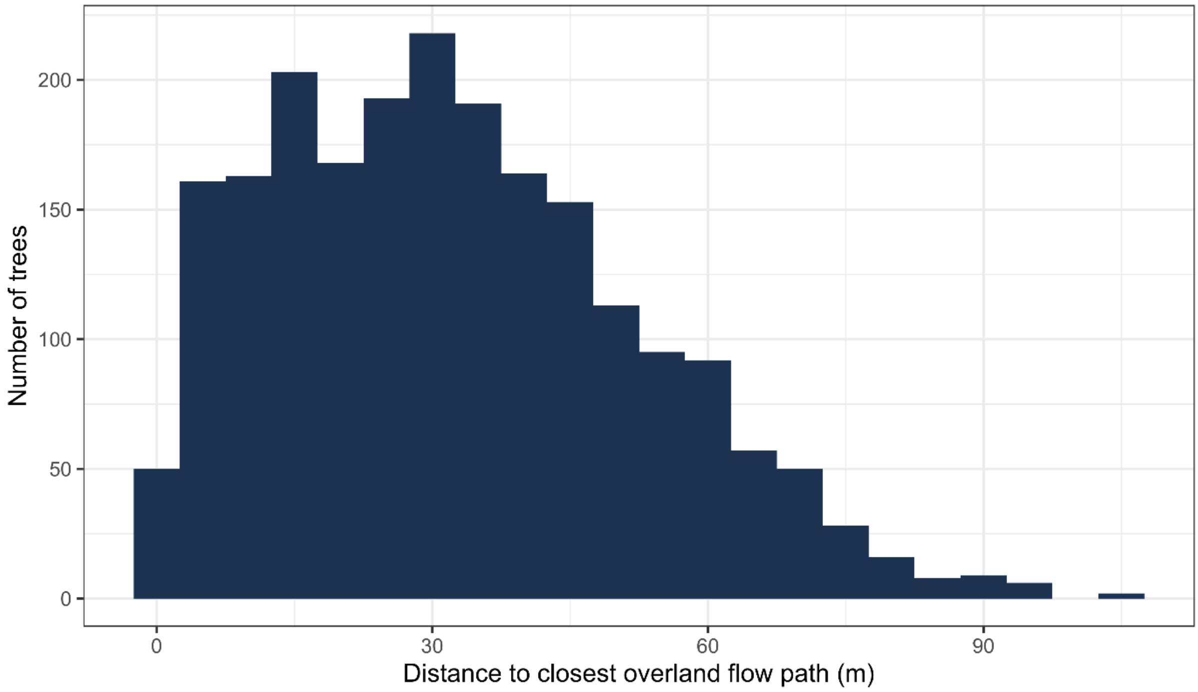


Figure B-14. Frequency histogram showing the number of trees at different distances to the closest overland flow path in metres with a bin width of 5 m.

B6.9 Distance to historic timber sites

The distance to the closest historic timber mill or sawpit sites was left skewed with a median value for the 2140 monitored trees at 1350 m (25th percentile 824 m; 75th percentile 2119 m; min 60 m; max 4605 m) (Figure B-15).

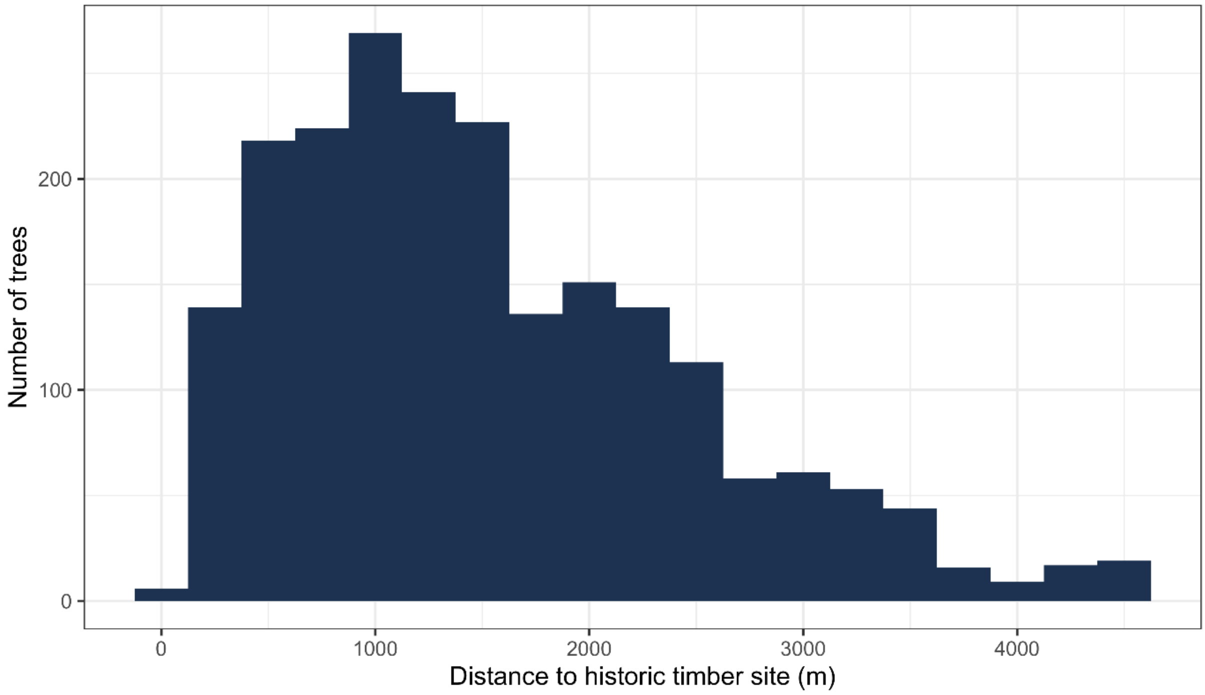


Figure B-15. Frequency histogram showing the number of trees at different distances to the closest historic timber mill in metres with a bin width of 250 m.

B6.10 Landcover database types

Of the 2140 monitored trees, 90% were within the indigenous forest class (n=1917), with only 7% in the mānuka or kānuka class (n=159), 3% in the broadleaved indigenous hardwoods class (n=63) and one tree in exotic grassland which was right on the edge of the forest adjacent to grass parkland.

B6.11 Ecosystem types

Ecosystem types are a finer classification than the landcover types (Singers and Rogers, 2014). The most common ecosystem type that the monitored trees were in was kauri podocarp broadleaved forest, followed by broadleaved scrub forest which is characterised as short forest. (Table B-9).

Table B-9. Total and proportion of trees by ecosystem type for 2140 monitored kauri trees.

Ecotype	Total	Proportion
Coastal broadleaved forest	16	1%
Kauri podocarp broadleaved forest	1320	62%

Kānuka scrub forest	166	8%
Broadleaved scrub forest	250	12%
Mānuka kānuka scrub	133	6%
Tawa kohekohe rewarewa hīnau podocarp forest	50	2%
Kauri forest	192	9%
Exotic forest	4	0%
Hebe wharariki flaxland rockland	1	0%

B7 Anthropogenic factors

Ngā āhuatanga ā-take tangata

Table B-10. Ecological origin of the kauri trees surveyed in the Waitakere Ranges, n=2140.

Host origin	Number of trees	Percent of trees
Cut-over regenerating	1576	65%
Mature forest stand	516	21%
Farmland	18	0.7%
Restoration planting	9	0.4%
Plantation kauri	7	0.3%
Unsure/other (not stated)	14	0.6%

B7.1 Evidence of disturbance

Evidence of disturbance was recorded at 23% of sites (490/2140 sites) and some sites had multiple disturbance types. Evidence of disturbance from being nearby a track was the most common (n=136), however surveyors were not asked to specify how the track was disturbing the tree. This was followed by human or animal off-track use which had 47 observations. Evidence of pest control or hoofed animals away from tracks also indicates off-track use by humans or animals and when those disturbances were added, this increased the human or animal off-track disturbance count to 281 trees. All other categories of disturbance were infrequent.

Table B-11. Number of trees with evidence of disturbance nearby.

Disturbance Type	Percent of trees	Number of trees
Animal pest control or bait-line	1.4%	29
Fallen tree or windthrow	1.6%	35
Fungal fruiting bodies	0.3%	6
Large, hooved animals (total)	2.1%	46
Hooved animals (excluding pigs)	1.0%	21
Pig damage to trunk	0.3%	7
Pig wallowing	0.8%	18

Human or animal off-track[a]	2.2%	47
Insect damage to trunk	0.4%	9
Invasive weed presence	0.3%	7
Phosphite use	0.4%	8
Poor drainage	0.0%	1
Possum browse	0.4%	9
Slip or landslide	0.6%	12
Track	6.4%	136
Track or road maintenance	0.9%	19
Other (all)[b]	3.0%	64
Other – road	0.4%	9
Other – stream	0.2%	4
Other – soil erosion	0.4%	8
Other – private land	0.2%	5
Other – tree damaged	0.3%	6
Other – neighbouring tree disturbance	0.3%	6

[a] While only 2.2% (47) of trees had human or animal off-track disturbance recorded, in total 13.1% (281) of trees that were not recorded as being near tracks had bait-lines, pest control, phosphite or research, pigs or hoofed animals recorded, which indicates additional off-track use.
[b] If other was recorded by the surveyor, they gave a description and the most common are presented.

B7.2 Closest roads

The distance to the closest road or track was highly left skewed with a median value for the 2140 monitored trees at 142 m (25th percentile 60 m; 75th percentile 274 m; min 0 m; max 981 m). All monitored trees were within 1 km of a road or foot track. The closest road or track class was dominated by foot tracks, followed by minor rural roads, which is expected with only a few main roads through the Waitākere Ranges Regional Park. There were no data on the road or track surface for most observations (94%). Access roads (urban or rural) are restricted service roads within the Ranges.

Table B-12. Prevalence of symptomatic kauri trees for different types of road classes closest to each of 2140 monitored kauri trees.

Road class	Symptomatic	Non-symptomatic	Total	Prevalence
Restricted access urban	5	7	12	42%
Minor urban	9	27	36	25%
Arterial rural	11	41	52	21%
Medium rural	5	19	24	21%
Minor rural	29	114	143	20%

Foot track	346	1452	1798	19%
Restricted access rural	6	48	54	11%
Arterial urban	2	16	18	11%
Foot path	0	1	1	0%
Medium urban	0	2	2	0%

B7.3 Closest tracks

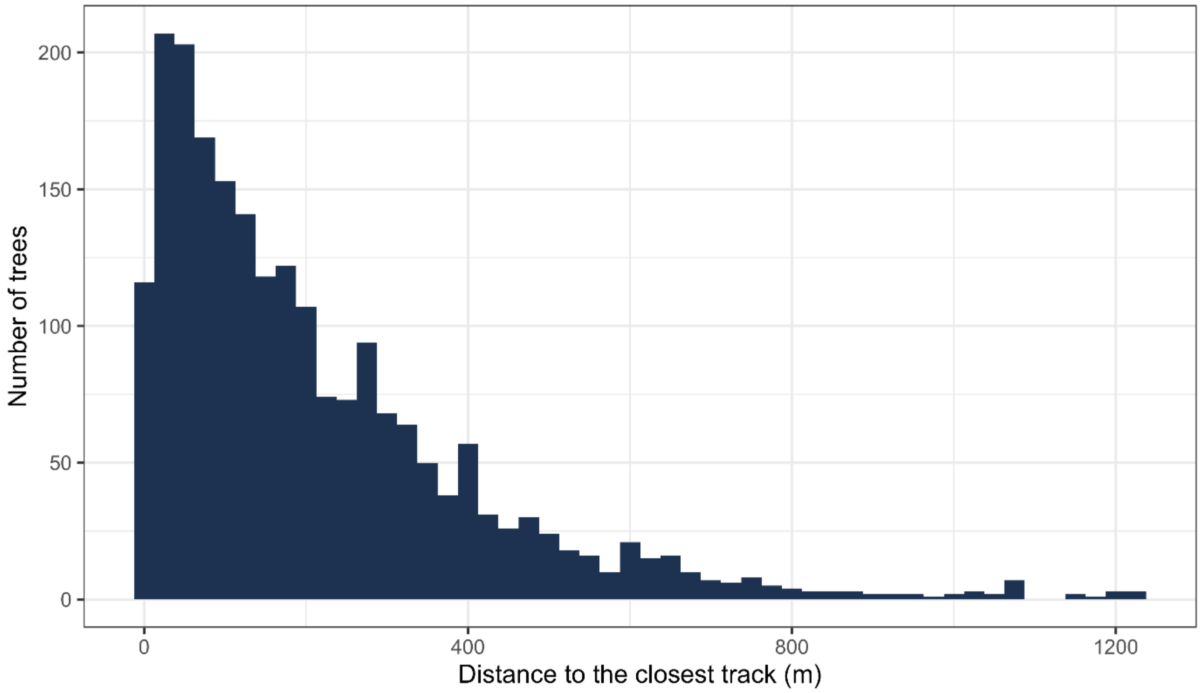


Figure B-16. Frequency histogram showing the distribution of distance to the closest track for 2140 monitored trees with a bin width set at 25 m.

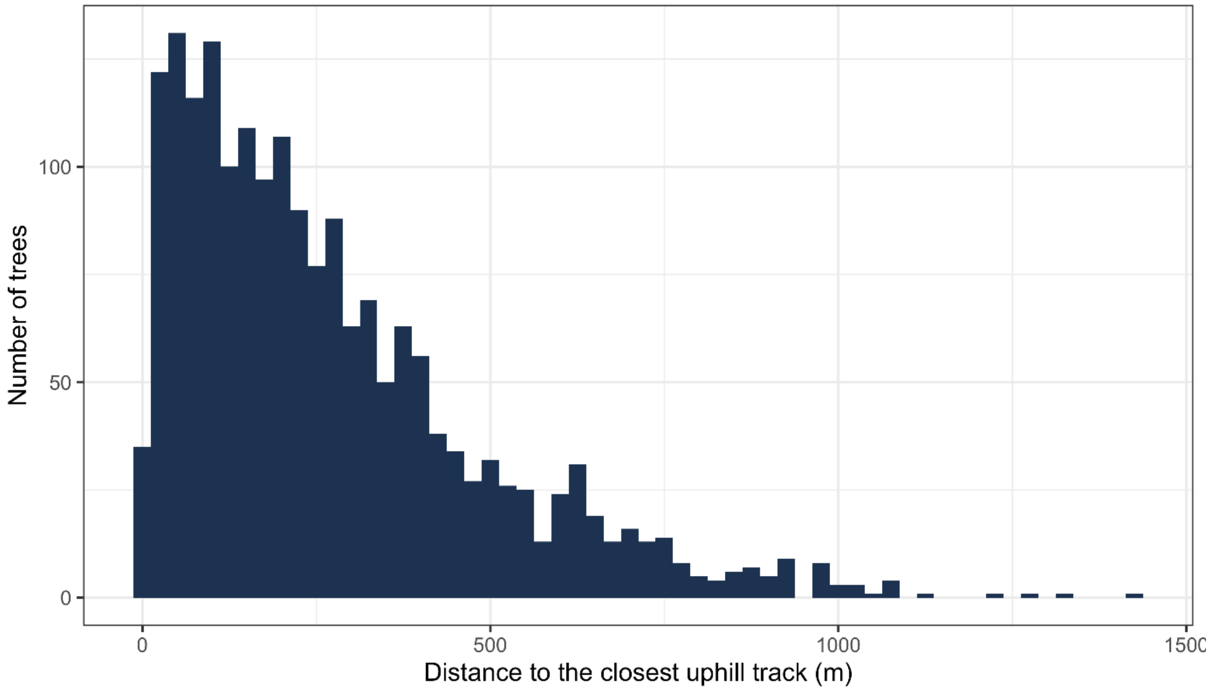


Figure B-17. Frequency histogram showing the distribution of the distance to the closest uphill track for 1895 monitored trees with a bin width set at 25 m.

B7.4 Distance to park boundary

The distance to the closest park boundary was left skewed with a median value for the 2140 monitored trees at 806 m (25th percentile 327 m; 75th percentile 1361 m; min 0.6 m; max 3191 m) (Figure B-18).

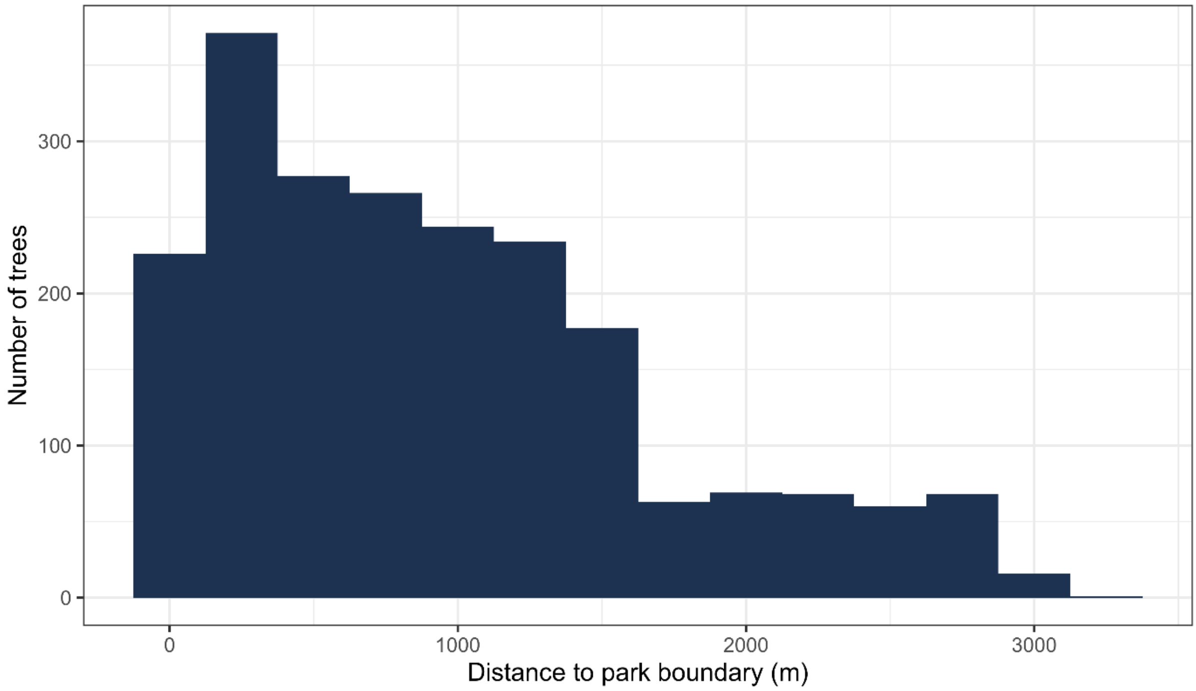


Figure B-18. Frequency histogram showing the number of trees at different distances to the closest Waitākere Ranges Regional Park boundary in metres with a bin width of 250 m.

B7.5 Within 500 m of archaeological features

Of the 2140 monitored trees, 77% (1643) were located within 500 m of one or more archaeological features. Of these, most were within 500 m of 1 or 2 archaeological features, with 2 trees being within 500 m of the maximum 35 archaeological features (Figure B-19**Figure B-19.** Bar plot of the number of archaeological features within 500 m of each of our 2140 monitored trees.

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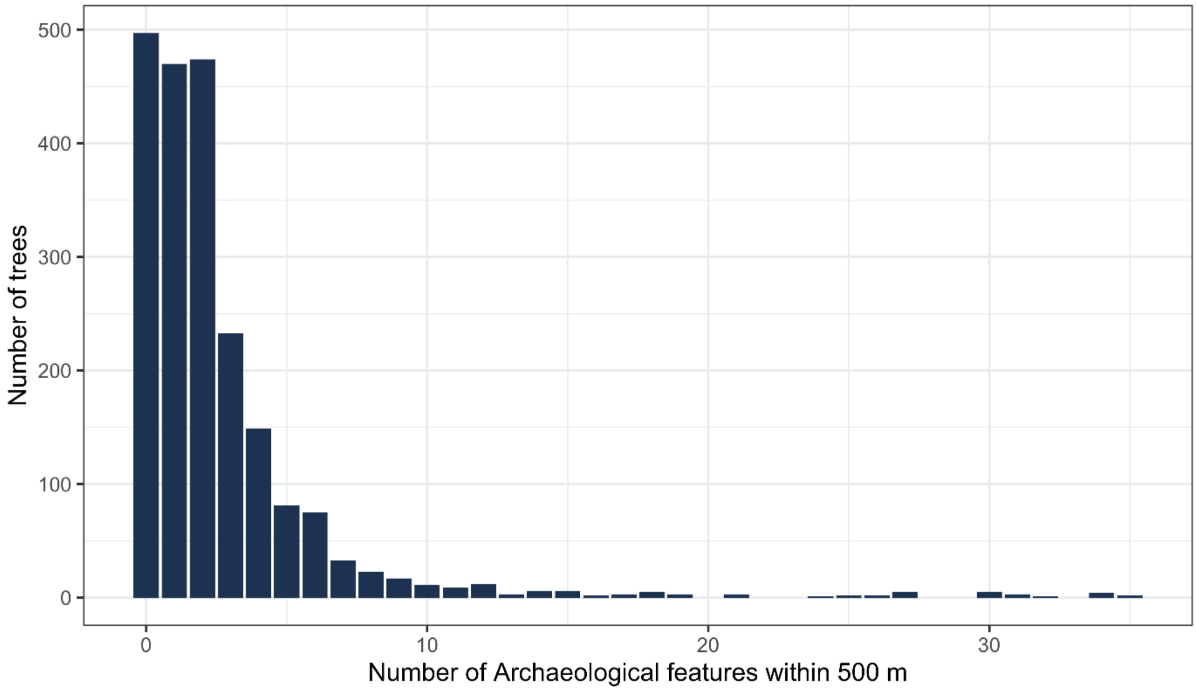


Figure B-19. Bar plot of the number of archaeological features within 500 m of each of our 2140 monitored trees.

B8 Ecological impact factors

Ngā āhuatanga nā ngā pānga ā-mātai hauropi

B8.1 Closest neighbour tree

The data for median distance to the closest neighbour had 31 scale of measurement errors (which may have been mm or cm rather than m) and these values were removed prior to analysis. Therefore, the distance to closest neighbour tree was analysed for 2109 trees. The median distance to the closest neighbour for dominant kauri trees was significantly further at 2 m (25th percentile 1 m and 75th percentile 3 m (min 0 m and max 8.5 m), compared to subdominant trees with a median distance of 1 m (25th percentile 1 m and 75th percentile 3 m (min 0 m and max 7 m), (p=0.02, Mann–Whitney test), (Figure B-20). This measurement needs to be collected in cm in the future.

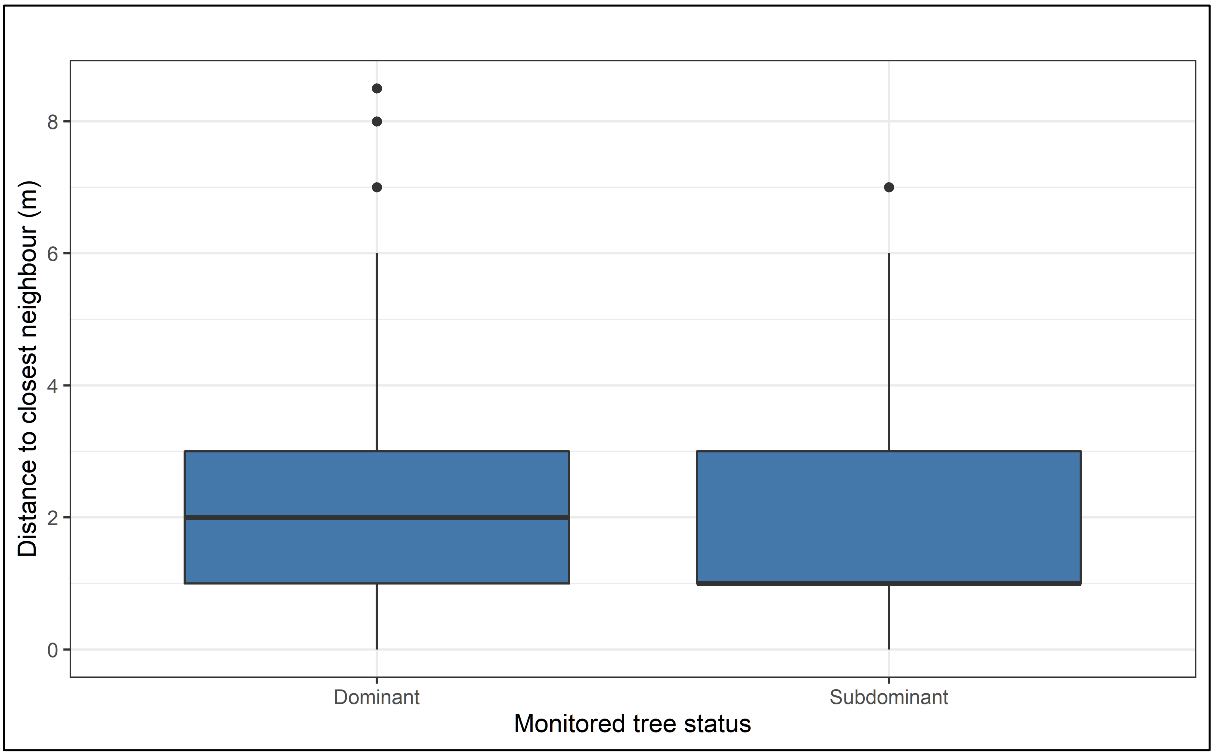


Figure B-20. Box and whisker plot showing the distance (m) between the monitored kauri tree and its closest neighbouring tree (>10 cm DBH) stratified by whether the kauri tree is the dominant or subordinate tree. Showing the median value (horizontal line), interquartile range (within box), maximum and minimum values (excluding outliers, vertical bars) and outliers (dots) for the population.

Across the closest neighbour trees, the median DBH was 18 cm (25th percentile 13 cm and 75th percentile 30 cm (min 5 cm and max 320 cm), in contrast to the median DBH of kauri of 66 cm (25th percentile 48 cm; 75th percentile 99 cm). The DBH values of the kauri trees that were dominant were significantly larger than the subdominant group ($p<0.001$ Mann–Whitney test). The median of the dominant group was 69 cm (25th percentile 51 cm and 75th percentile 103 cm (min 14 cm and max 317 cm), compared to subdominant trees with a median DBH of 39 cm (25th percentile 28 cm and 75th percentile 55 cm (min 11 cm and max 176 cm) (Figure B-21). Likewise, there was a significant difference ($p< 0.001$ Mann-Whitney test) between the DBH of neighbour species depending on whether they were the dominant or subordinate tree. Five out of the 6 closest neighbour trees with a DBH of >200 cm were neighbouring kauri trees.

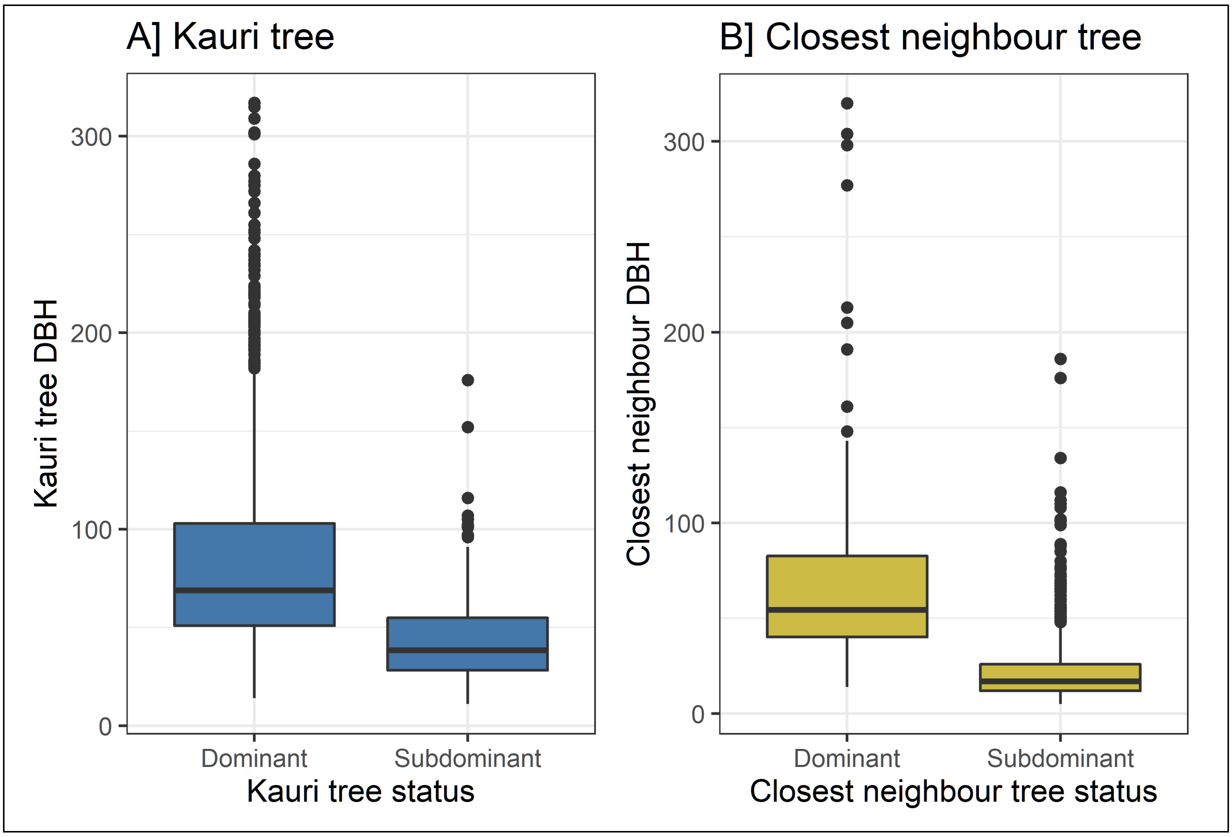


Figure B-21. Box and whisker plots showing diameter at breast height for A] monitored kauri trees where they were the dominant or subdominant tree and for B] the DBH of the closest neighbour tree where the monitored kauri tree was dominant vs subdominant. Showing the median value (horizontal line), interquartile range (within box), maximum and minimum values (excluding outliers, vertical bars) and outliers (dots) for the population.

After kauri, rewarewa and rimu were the next most common dominant species at 7% each (Table B-13). Rewarewa and tanekaha were the next most common subdominant species at 16% and 9% respectively (Table B-14).

Table B-13. Eight most common dominant closest neighbour species out of 117 sites where kauri were subdominant from 2080 monitored kauri tree sites where species was recorded.

Species	Common name	Count of sites	Percent of sites
Agathis australis	kauri	110	62%
Knightia excelsa	rewarewa	13	7%
Dacrydium cupressinum	rimu	12	7%
Kunzea robusta	kānuka	7	4%
Phyllocladus trichomanoides	tanekaha	7	4%
Dacrycarpus dacrydioides	kahikatea	4	2%
Coprosma arborea	māmāngi	4	2%
Metrosideros robusta	northern rātā	3	2%

Table B-14. Twelve most common subdominant closest neighbour species out of 1903 sites where kauri were subdominant from 2080 monitored kauri tree sites where species was recorded.

Species	Common name	Count of sites	Percent of sites
Agathis australis	kauri	334	18%
Knightia excelsa	rewarewa	295	16%
Phyllocladus trichomanoides	tanekaha	163	9%
Pseudopanax crassifolius	lancewood	124	7%
Dacrydium cupressinum	rimu	114	6%
Coprosma arborea	māmāngi	113	6%
Kunzea robusta	kānuka	103	5%
Pseudopanax ferox	fierce lancewood	86	5%
Nestegis lanceolata	white maire	80	4%
Prumnopitys ferruginea	miro	78	4%
Myrsine australis	red māpou	63	3%
Olearia rani var. *rani*	heketara	54	3%

B8.2 Common species

The most commonly observed plant was rewarewa (*Knightia excelsa*) at 86% of the sites. The least common of our common plants was toru (*Toronia toru*), seen at only 6% of sites. The other species ranged between 20% and 76% (Table B-15). There were no sites where no common plants were recorded by surveyors. There were 49 sites that had other ecological variables collected, where the common plants were not recorded; it is uncertain if they were not assessed or if the data were lost during upload.

Table B-15. Number and percent of kauri tree monitoring sites out of 1406 sites surveyed, where each of 16 common plants were observed.

Common Name	Scientific Name	Count	Percent
Rewarewa	*Knightia excelsa*	1187	84%
Lancewood	*Pseudopanax crassifolius*	1066	76%
Māpou	*Myrsine australis*	1042	74%
Kauri grass	*Astelia trinervia*	1028	73%
Shining karamū	*Coprosma lucida*	1011	72%
Rimu	*Dacrydium cupressinum*	846	60%
Māmāngi	*Coprosma arborea*	825	59%
Kānuka	*Kunzea robusta*	754	54%
Tall mingimingi	*Leucopogon fasciculatus*	732	52%
Tanekaha	*Phyllocladus trichomanoides*	691	49%
White maire	*Nestegis lanceolata*	647	46%

Heketara	*Olearia rani*	591	42%
Miro	*Pectinopitys ferruginea*	406	29%
Large-leaved māhoe	*Melicytus macrophyllus*	339	24%
Kirk's tree daisy	*Brachyglottis kirkii*	280	20%
Toru	*Toronia toru*	84	6%
None seen	–	0	0%

B8.3 Forest floor depth

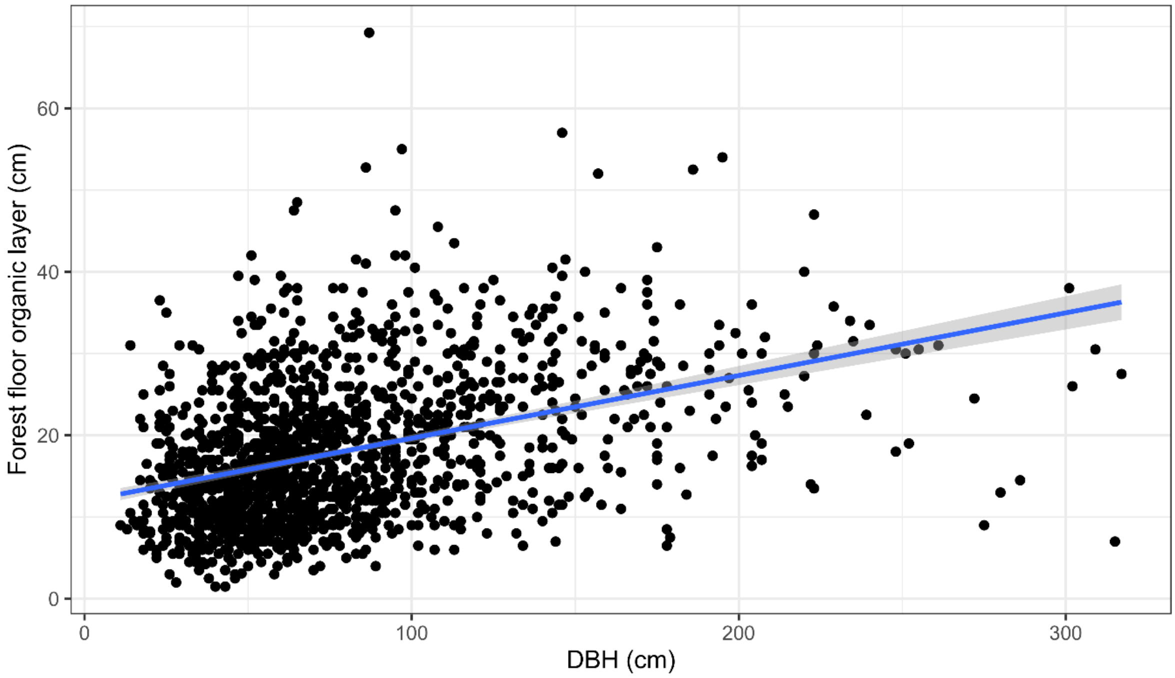


Figure B-22. Scatter plot showing average forest floor depth (cm) per tree as a function of tree size measured as DBH (cm). Superimposed on this plot is a loess smoothed linear regression line (blue) with 95% confidence intervals (grey shading).

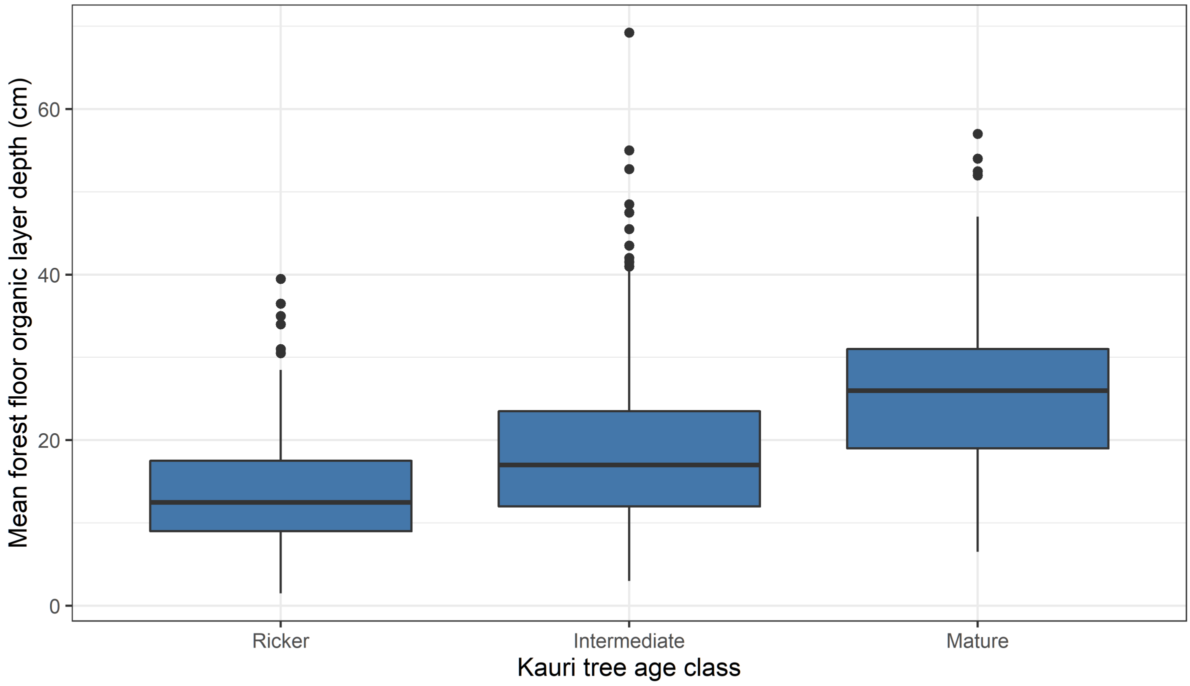


Figure B-23. Box and whisker plots showing the mean forest floor depth (cm) per tree, stratified by kauri tree size class from 2127 monitored trees where the size class value was recorded. Showing the median value (horizontal line), interquartile range (within box), maximum and minimum values (excluding outliers, vertical bars) and outliers (dots) for the population.

B8.4 Crown epiphytes

Crown epiphytes were assessed on 1452 trees, however 12% (180) of trees were unable to be assessed as the crown was not clearly visible. Climbers were assessed on 1452 trees and 63% of trees had climbing plants growing up the trunks (914).

Of the 1272 trees where the crown was visible, epiphytes were observed on 21% of trees (263). Epiphytes were more common on larger trees with a median of 136 cm DBH (inter-quartile range of 99-174 cm) than smaller trees with a median of 59 cm DBH (inter-quartile range 44-78 cm) (Figure B-24).

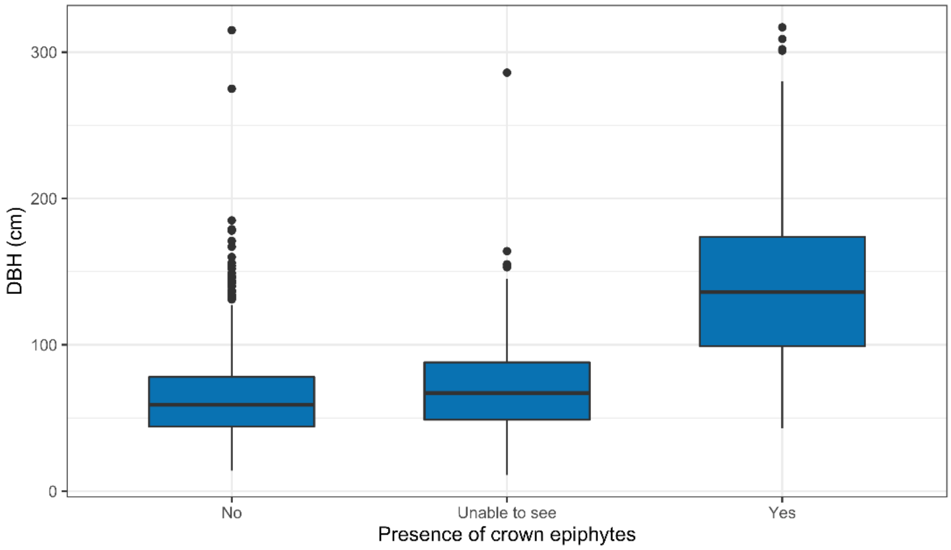


Figure B-24. Boxplot showing the median diameter (cm) at breast height (DBH) of kauri trees with crown epiphytes present, absent and where they were not visible from the ground. Showing the median value (horizontal line), interquartile range (within box), maximum and minimum values (excluding outliers, vertical bars) and outliers (dots) for the population.

B8.5 Climbing epiphytes

Climbers were assessed on 1452 trees and 63% of trees had climbing plants growing up the trunks (914). The median DBH of trees with climbers was higher at 76 cm DBH (25th percentile 54 cm; 75th percentile 113 cm) than those without climbers at 55 cm (25th percentile 41 cm; 75th percentile 72 cm) (Figure B-25).

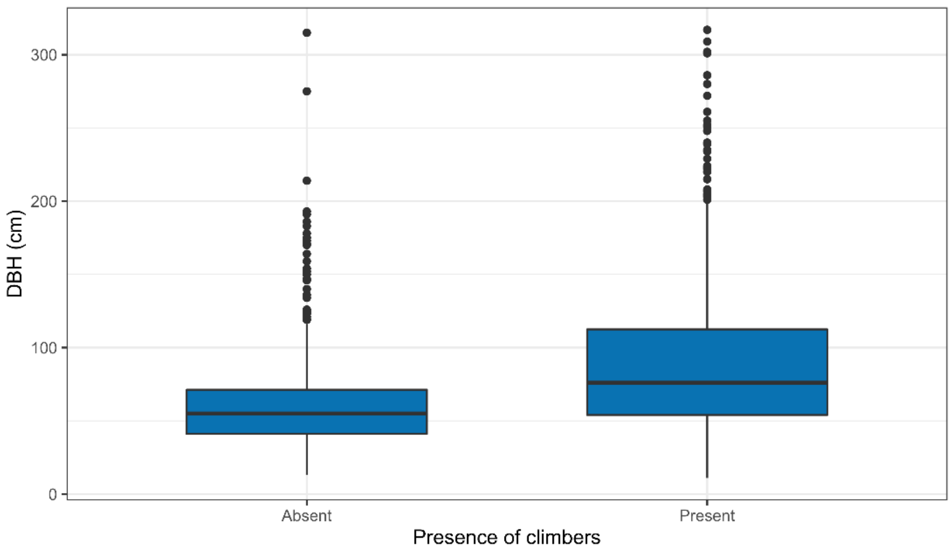


Figure B-25. Box and whisker plots of kauri tree diameter at breast height (DBH) differences between trees with climbing plants present or absent. Showing the median value (horizontal line), interquartile range (within box), maximum and minimum values (excluding outliers, vertical bars) and outliers (dots) for the population.

Appendix C
Results of univariable screening tests from Chapter 3

Ngā hua o ngā whakamātautau tauanga-rau i te Wāhanga 3

Result of univariable screening test presence of symptomatic kauri

Variable	N	Coefficient	SE	P-value
Size	2133			< 0.01
Ricker		Reference		
Intermediate		0.232	0.137	
Mature		0.671	0.193	
Diameter at breast height (10 cm)	2133	0.040	0.011	< 0.001
Canopy height (m)	2140	0.018	0.008	< 0.05
Canopy estimate (m)	1413	0.049	0.016	< 0.01
Host origin (= local tree stand)	2140			0.15
Cut over regenerating		Reference		
Farmland		0.517	0.530	
Mature forest stand		0.190	0.125	
Other/Unsure		-1.092	1.040	
Plantation kauri		-13.093	333.646	
Restoration planting		-0.607	1.063	
Ecotype (= forest type)	2132			< 0.05
Broadleaved forest		Reference		
Kauri forest		0.376	0.187	
Others		0.116	0.225	
DBH of closest neighbouring tree (cm)	2132	0.004	0.002	0.07
Distance to the closest neighbouring tree (m)	2109	-0.077	0.042	0.07
Slope	2140	-0.010	0.005	0.05
Elevation (100 m)	2140	-0.251	0.077	< 0.01
Drainage in km^2 (= size of sub-catchment area)	2140	0.017	0.011	0.12
Distance to the closest coast (100 m)	2140	-0.004	0.003	0.08

Distance to the closest *P. agathidicida* site (100 m)	2140	-0.054	0.007	< 0.0001
Distance to the closest *P. cinnamomi* site (100 m)	2140	-0.011	0.003	< 0.01
Presence of immature Kauri nearby	1452	-0.176	0.131	0.18
Presence of sapling nearby	1452	-0.219	0.139	0.11
Suspected kauri dieback nearby	1589			< 0.0001
No		Reference		
Unsure		0.600	0.276	
Yes		1.627	0.143	
Presence of *Coprosma arborea* nearby	1406	0.179	0.136	0.19
Presence of *Kunzea robusta* nearby	1406	-0.244	0.133	0.07
Presence of *Leucopogon fasciculatus* nearby	1406	-0.218	0.133	0.10
Presence of *Nestegis lanceolata* nearby	1406	-0.217	0.134	0.11
Presence of *Olearia rani* nearby	1406	-0.290	0.137	< 0.05
Presence of *Pseudopanax crassifolius* nearby	1406	-0.211	0.150	0.16
Decline of *Coprosma arborea* nearby	90	2.180	0.790	< 0.01
Decline of *Myrsine australis* nearby	90	2.180	1.256	0.08
Distance to the closest timber site (100 m)	2140	-0.048	0.007	< 0.0001
Type of the closest timber site	2135			< 0.001
Saw pit		Reference		
Timber mill		0.494	0.135	
Source of the closest timber site location	2140			< 0.05
Auckland museum map		Reference		
CHI		0.438	0.205	
Number of archaeological sites nearby	2140	0.018	0.012	0.14
Distance to the closest track (100 m)	2140	-0.073	0.030	< 0.05
Distance to the closest road (100 m)	2140	-0.105	0.037	< 0.01
Distance to the closest uphill track (100 m)	1895	-0.085	0.029	< 0.01
Angle of the closest uphill track	1895	-0.001	0.001	0.12
Evidence of disturbance	2140			< 0.001
No		Reference		
Yes		0.407	0.123	
Disturbance by track nearby	2140	0.600	0.200	< 0.01
Disturbance by possum browse nearby	2140	1.21	0.67	0.07
Disturbance by pig or hoofed animals nearby	2140	-0.69	0.48	0.15

Disturbance by pest control and bait-line nearby	2140	0.80	0.39	< 0.05
Disturbance by other cause nearby	2140	0.59	0.30	< 0.05

Result of univariable screening test presence of *Phytophthora agathidicida*

Variable	N	Coefficient	SE	P-value
Size	759			< 0.05
Ricker		Reference		
Intermediate		-0.733	0.264	
Mature		-0.708	0.423	
Diameter at breast height (10 cm)	759	-0.066	0.029	< 0.05
Canopy height	761	-0.037	0.020	0.06
Canopy estimate	743	-0.082	0.038	< 0.05
Crown epiphytes	761			< 0.01
No		Reference		
Unable to see		-0.211	0.397	
Yes		-1.303	0.437	
Distance to the closest neighbouring tree (m)	748	-0.329	0.107	< 0.01
Elevation (100 m)	761	-1.284	0.207	< 0.0001
Distance to the closest coast (100 m)	761	-0.025	0.007	< 0.001
Distance to the closest *P. cinnamomi* site (100 m)	761	-0.024	0.010	< 0.05
Presence of immature kauri nearby	761	0.319	0.250	0.20
Suspected kauri dieback nearby	761			< 0.0001
No		Reference		
Unsure		1.313	0.484	
Yes		2.156	0.312	
Presence of *Coprosma arborea* nearby	744	0.929	0.288	< 0.01
Presence of *Dacrydium cupressinum* nearby	744	-0.454	0.249	0.07
Presence of *Kunzea robusta* nearby	744	0.392	0.254	0.12
Presence of *Leucopogon fasciculatus* nearby	744	-0.429	0.250	0.09
Presence of *Olearia rani* nearby	744	-0.571	0.264	< 0.05
Presence of *Pectinopitys ferruginea* nearby	744	-0.553	0.279	< 0.05
Presence of *Phyllocladus trichomanoides* nearby	744	1.187	0.278	< 0.0001

Presence of *Pseudopanax crassifolius* nearby	744	-0.747	0.263	< 0.01
Distance to the closest timber site (100 m)	761	-0.143	0.022	< 0.0001
Type of the closest timber site	761			< 0.001
Saw pit		Reference		
Timber mill		1.739	0.470	
Source of the closest timber site location	761			0.05
Auckland museum map		Reference		
CHI		1.169	0.601	
Number of archaeological sites nearby	761	0.103	0.025	< 0.0001
Distance to the closest track (100 m)	761	-0.238	0.078	< 0.01
Distance to the closest road (100 m)	761	-0.233	0.085	< 0.01
Distance to the closest uphill track (100 m)	671	-0.100	0.059	0.09
Distance to the closest park boundary (100 m)	761	-0.025	0.007	< 0.001
Evidence of disturbance	761			0.14
No		Reference		
Yes		-0.486	0.327	
Evidence of climbers	761			< 0.01
Absent		Reference		
Present		-0.725	0.244	

Univariable screening test variables with p-values >0.2 for both outcomes

Variable	N (Symptomatic)	N (*P. agathidicida*)
Aspect	2140	761
Dieback of other nearby tree species	1588	759
Distance to closest overland flow path	2140	761
Disturbance by fallen tree/ windthrow nearby	2140	761
Disturbance by fungal fruiting bodies on trunk	2140	761
Disturbance by insect damage on trunk	2140	761
Disturbance by invasive weeds nearby	2140	761
Disturbance by poor drainage nearby	2140	761
Disturbance by track or road maintenance nearby	2140	761
Disturbance by slip or landslide nearby	2140	761
Disturbance by phosphite injections nearby	2140	761
Depth to water index	2140	761
Ecotypes	2132	757
Epicormic growth on trunk	1453	761

Host origin (farmland, mature forest stand, plantation, restoration, other)	2140	761
Kauri tree dominant or subdominant to closest neighbouring tree (based on DBH comparison)	2127	755
Landcare database class (40, 52, 54, 69)	2140	761
P. cinnamomi present	761	761
P. sp. present	761	761
Presence of *Astelia trinervia* nearby	1406	744
Presence of *Brachyglottis kirkii* nearby	1406	744
Presence of *Coprosma lucida* nearby	1406	744
Presence of *Knightia excelsa* nearby	1406	744
Presence of *Melicytus macrophyllus* nearby	1406	744
Presence of *Myrsine australis* nearby	1406	744
Presence of *Toronia toru* nearby	1406	744

Appendix D

Results of multivariable screening tests from Chapter 3

Ngā hua o ngā whakamātautau āta tirotiro i ngā taurangi tahi i te Wāhanga 3

Result of non-spatial multivariable models for presence of symptomatic kauri

Variables	Coefficient	SE	P-value
Intercept	-0.553	0.196	< 0.01
Diameter at breast height (10 cm)	0.072	0.013	< 0.0001
Distance to the closest neighbouring tree (m)	-0.082	0.048	0.081
Distance to the closest *P. agathidicida* site (100 m)	-0.055	0.009	< 0.0001
Distance to the closest coast (100 m)	-0.006	0.003	0.05
Distance to the closest timber site (100 m)	-0.031	0.008	< 0.0001
Distance to the closest uphill track (100 m)	-0.070	0.031	< 0.05

Key: SE, standard error of coefficient.

Result of non-spatial multivariable models for presence of *P. agathidicida*

Variables	Coefficient	SE	P-value
Intercept	1.374	0.603	< 0.05
Diameter at breast height (10 cm)	0.018	0.036	0.61
Distance to the closest neighbouring tree (m)	-0.338	0.129	< 0.01
Elevation (100 m)	-0.752	0.240	< 0.01

Presence of *P. trichomanoides* (tanekaha)	0.696	0.321	< 0.05
Distance to the closest coast (100 m)	-0.011	0.007	0.12
Distance to the closest timber site (100 m)	-0.114	0.023	< 0.0001
Distance to the closest track (100 m)	-0.210	0.092	< 0.05
Distance to the closest *P. cinnamomi* site (100 m)	-0.023	0.011	< 0.05

Key: SE, standard error of coefficient.

Appendix E

OpenBUGS code for the BLCA model from Chapter 4

Te tohu OpenBUGS mō te tauira BLCA i te Wāhanga 4

```
model{

#Multinomial Model for the Data

 #x1 is the test results in high prevalence population, the 4 combinations follow a multinomial
#distribution

x1[1:2,1:2] ~ dmulti(p1[1:2,1:2], n1)

x2[1:2,1:2] ~ dmulti(p2[1:2,1:2], n2)  #Observed prevalence

 p1[1,1] <- pi1*Se1*Se2+(1-pi1)*(1-Sp1)*(1-Sp2) #both tests are positive

 p1[1,2] <- pi1*Se1*(1-Se2)+(1-pi1)*(1-Sp1)*Sp2 #visual assessment positive, soil culture negative

 p1[2,1] <- pi1*(1-Se1)*Se2+(1-pi1)*Sp1*(1-Sp2) #visual assessment negative, soil culture positive

 p1[2,2] <- pi1*(1-Se1)*(1-Se2)+(1-pi1)*Sp1*Sp2 #both tests are negative

 p2[1,1] <- pi2*Se1*Se2+(1-pi2)*(1-Sp1)*(1-Sp2)

p2[1,2] <- pi2*Se1*(1-Se2)+(1-pi2)*(1-Sp1)*Sp2

p2[2,1] <- pi2*(1-Se1)*Se2+(1-pi2)*Sp1*(1-Sp2)

p2[2,2] <- pi2*(1-Se1)*(1-Se2)+(1-pi2)*Sp1*Sp2

 # Priors

pi1 ~ dbeta(14.59, 14.59)        # High, "40-50, some at 80" 95% sure >35% and most likely at 50%

pi2 ~ dbeta(53.88, 1270.24)    # low less than 5%, most likely set at 4%

Se1 ~ dbeta(4.53, 5.32)                    #for aerial inspection min=26, most likely = 45, max=66

Sp1 ~ dbeta(91.80, 7.83)         #min = 89, most likely = 93, max = 97
```

```
Se2 ~ dbeta(23.12, 9.18)        # soil culture min = 65, most likely = 73, max = 89
Sp2 ~ dbeta(60.04, 6.13)        # min = 86, most likely = 92, max = 95
 }


#Data
list(n1=189, n2=572)
#n1 is for high prevalence
 # test 1 (visual) in rows, test 2 (soil culture) in columns
 x1[,1] x1[,2] x2[,1] x2[,2]
 22      26      8       73
 35     106     11      480
 END
 #Initial values for the 3 chains
list(Se1=0.8, Sp1=0.2, Se2=0.2, Sp2=0.2, pi1=0.1, pi2=0.8)
list(Se1=0.45, Sp1=0.93, Se2=0.73, Sp2=0.92, pi1=0.61, pi2=0.17)
list(Se1=0.2, Sp1=0.98, Se2=0.9, Sp2=0.99, pi1=0.9, pi2=0.05)
```

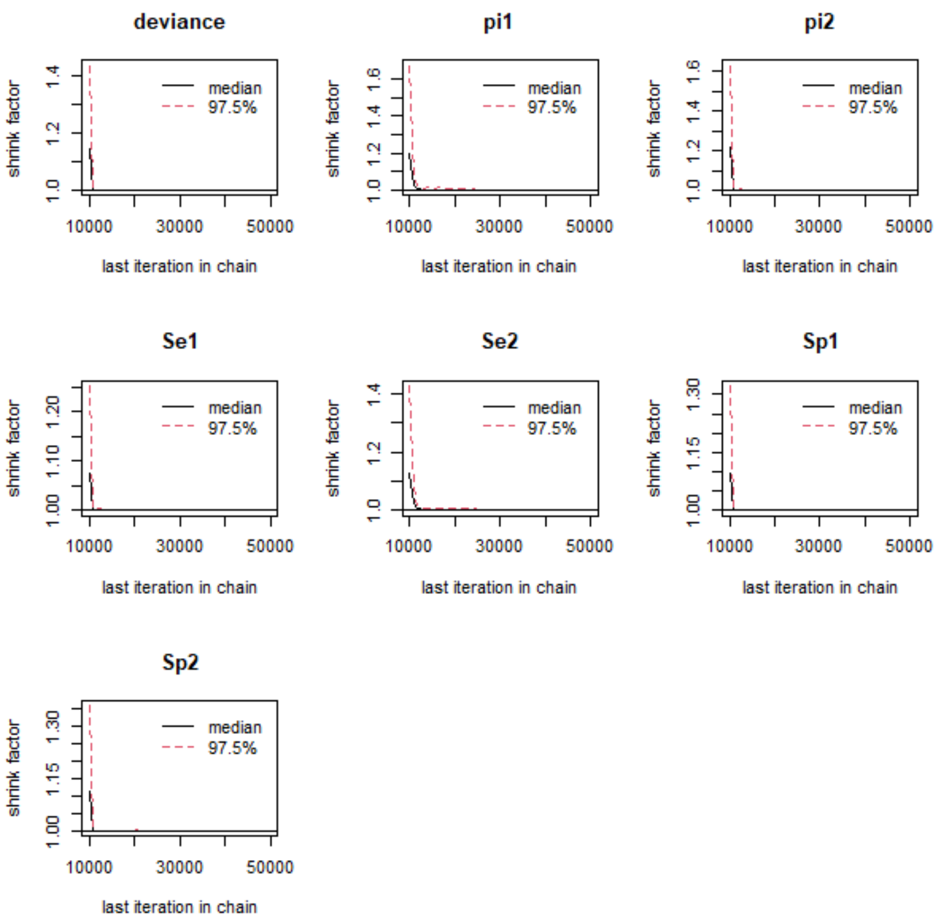
Appendix F

Supplementary information from Chapter 4

Ngā pārongo āpiti i te Wāhanga 4

F1 Gelman-Rubin-Brooks plot

Te kauwhata a Gelman-Rubin-Brooks



F2 Gelman and Rubin's potential scale reduction factor where a result of 1 means no issues were encountered

Tā Gelman rāua ko Rubin tauiti ā-whakatau tata e tohua ai e te 1 te korenga i tūpono ki ētahi raruraru

Parameter	**Point estimate**	**Upper confidence interval**
SeVA	1	1
SeSB	1	1
SpVA	1	1
SpSB	1	1
pi1	1	1
pi2	1	1

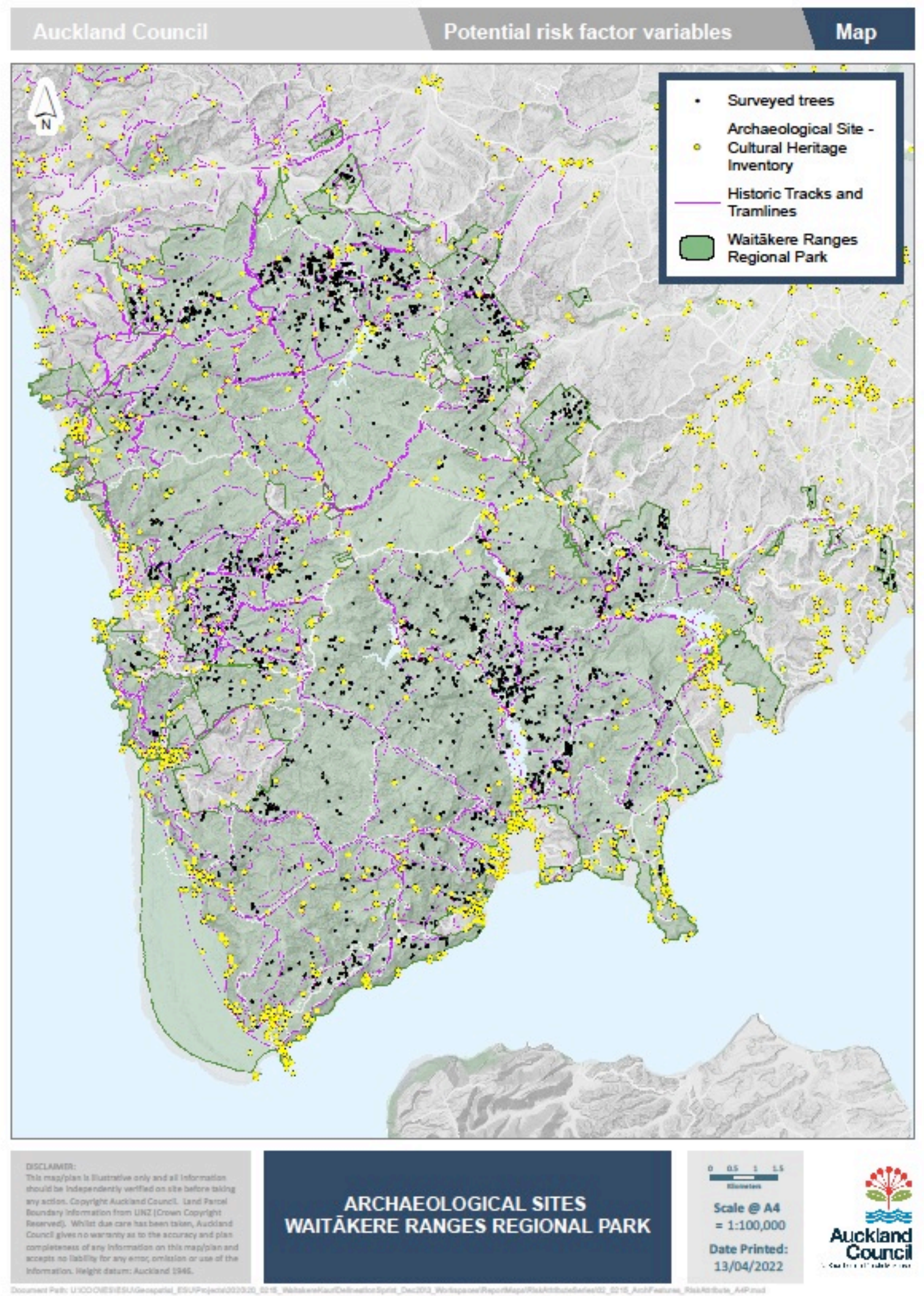
Appendix G

Supplementary information risk maps from GIS derived variables

Ngā mahere ā-tūraru āpiti mai i ngā taurangi i ahu mai i te GIS

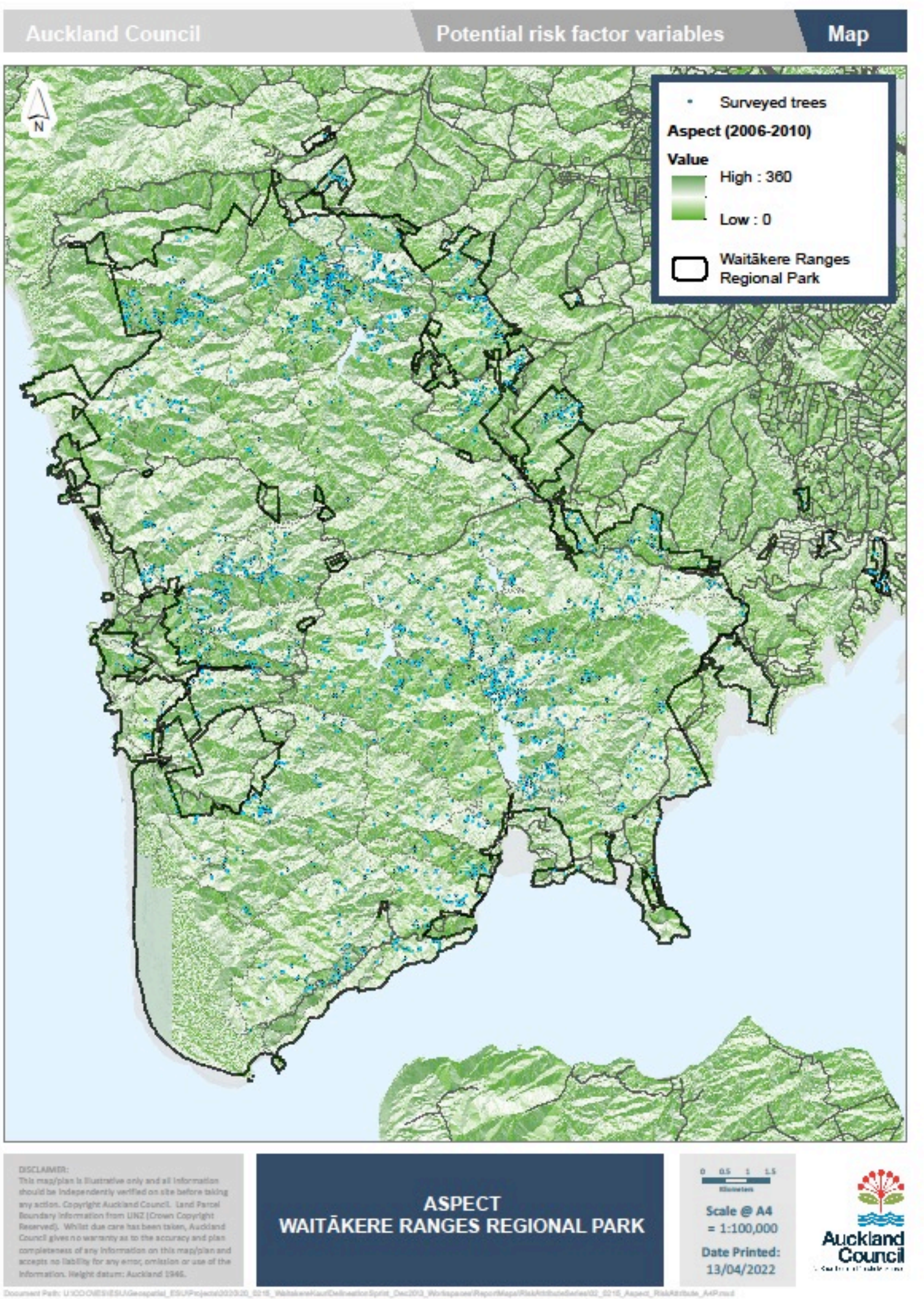
G1 Archaeological features risk map

Te mahere ā-tūraru mō ngā āhuatanga ā-mātai whaipara tangata



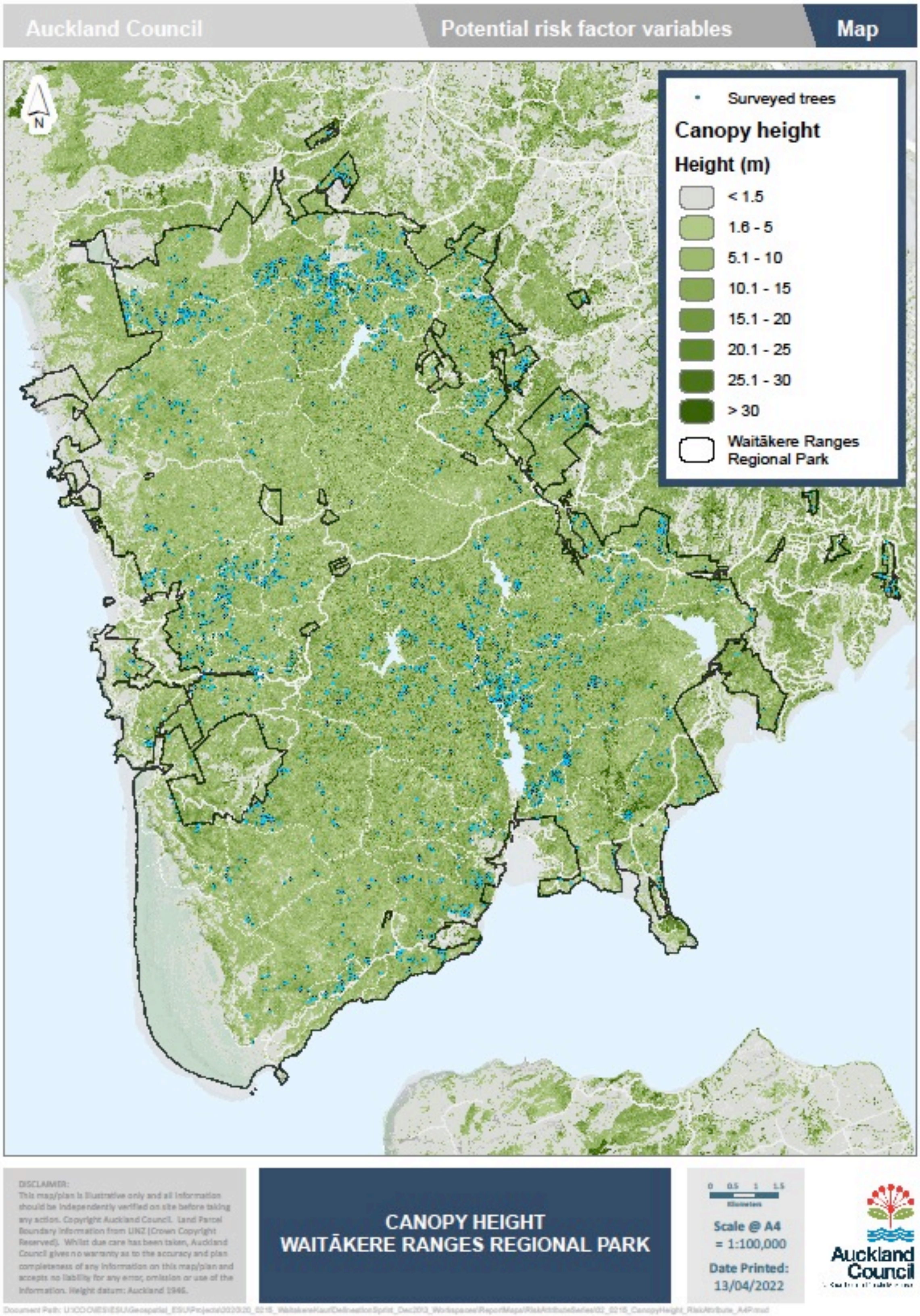
G2 Aspect risk map

Te mahere ā-tūraru mō te aronga



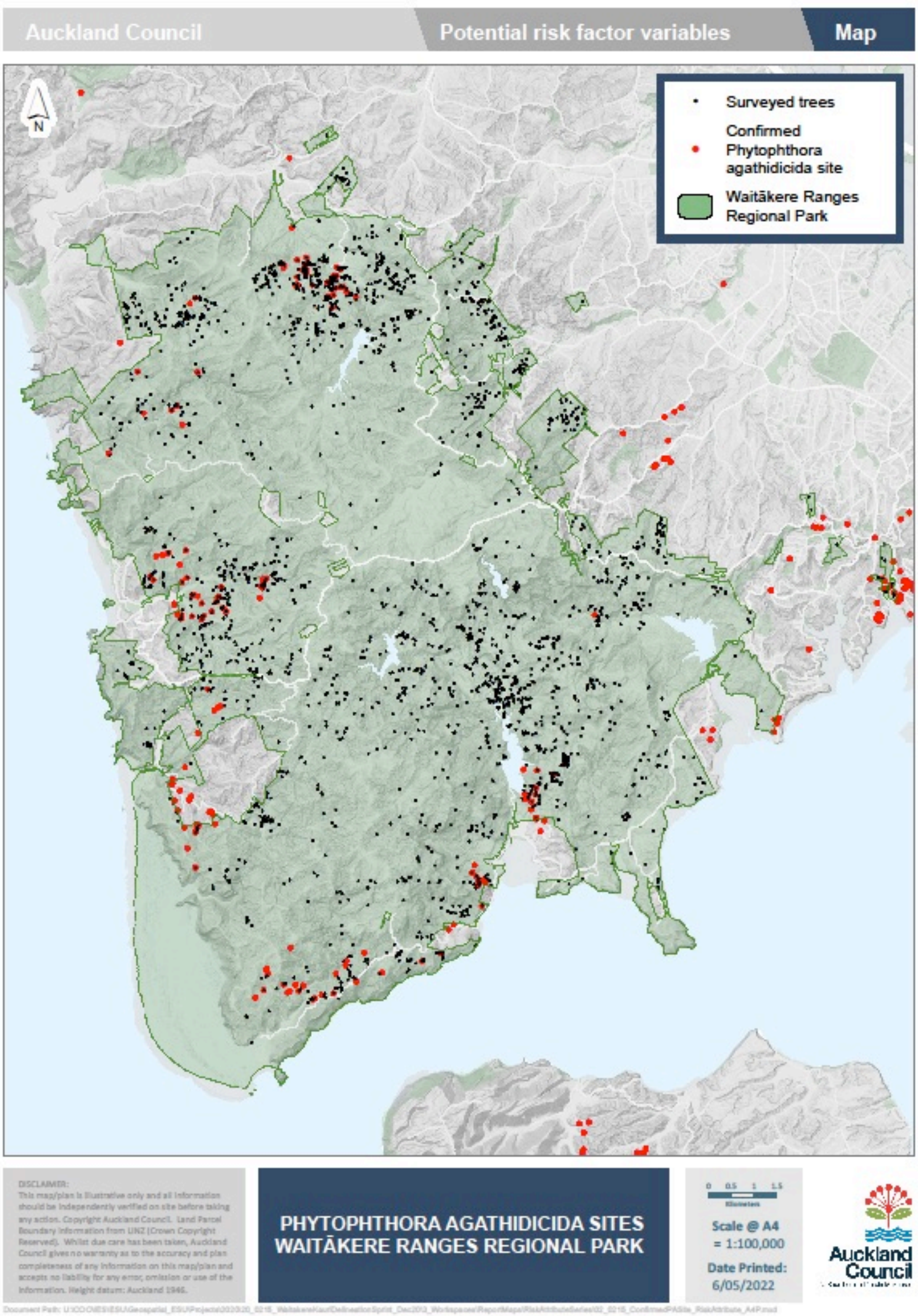
G3 Canopy height risk map

Te mahere ā-tūraru mō te teitei o ngā kāuru



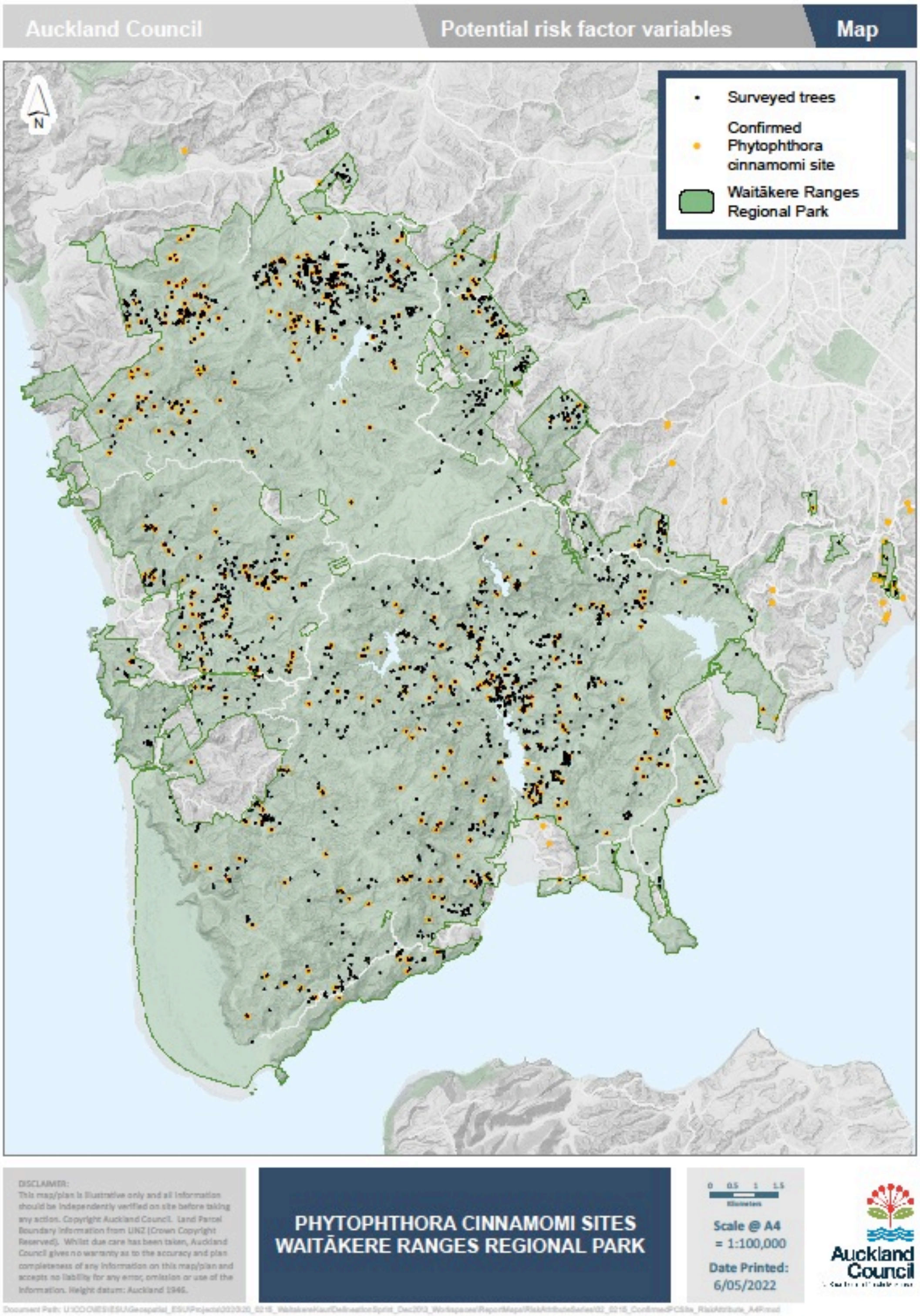
G4 Confirmed all *P. agathidicida* sites risk map (including historical detections)

Te mahere ā-tūraru mō ngā wāhi katoa i whakatauria rā te kitea o te puruheka patu kauri (tae noa ki ngā kitenga o mua)



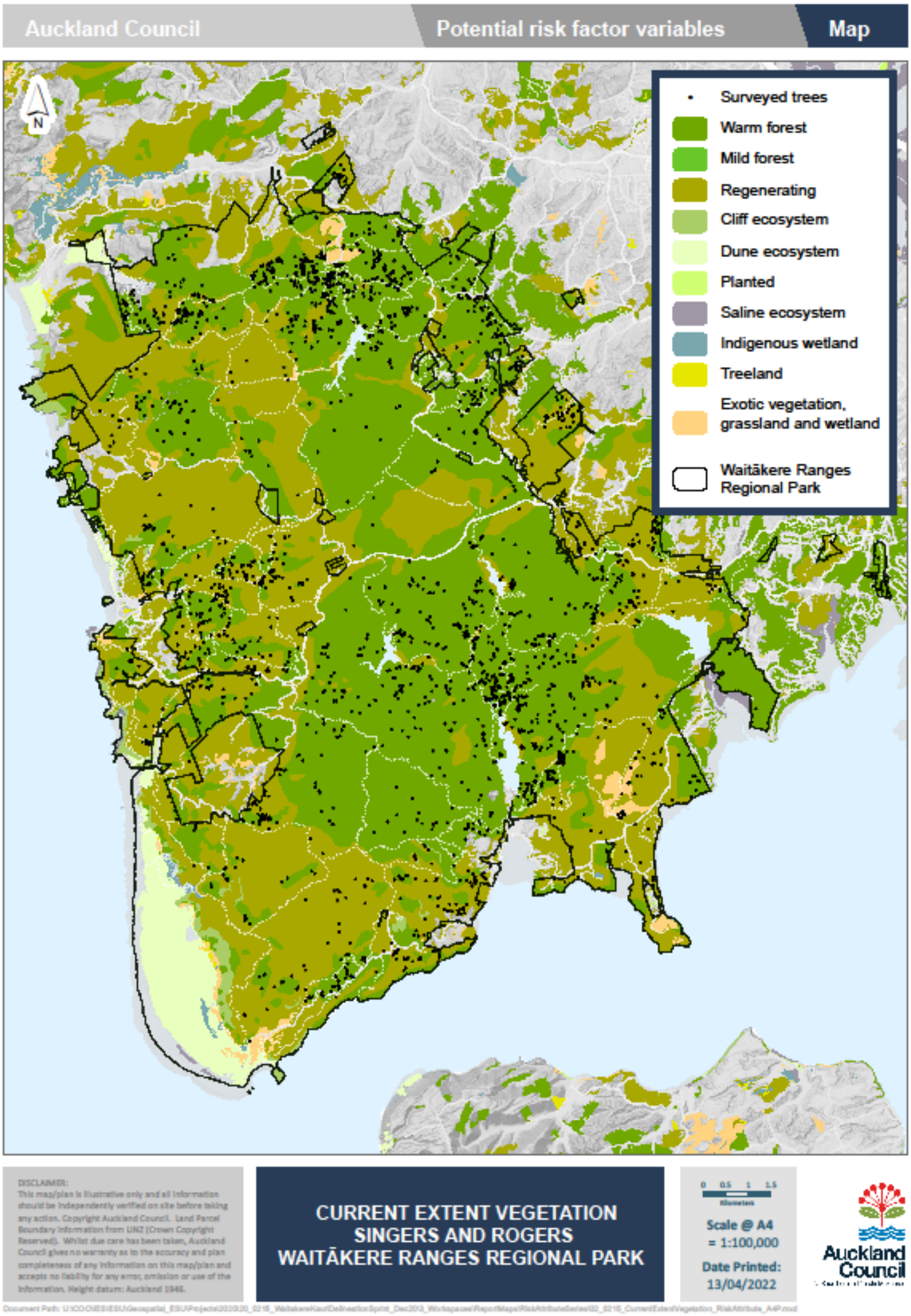
G5 Confirmed all *P. cinnamomi* sites risk map (including historical detections)

Te mahere ā-tūraru mō ngā wāhi katoa i whakatauria rā te kitea o te puruheka patu paiaka (tae noa ki ngā kitenga o mua)



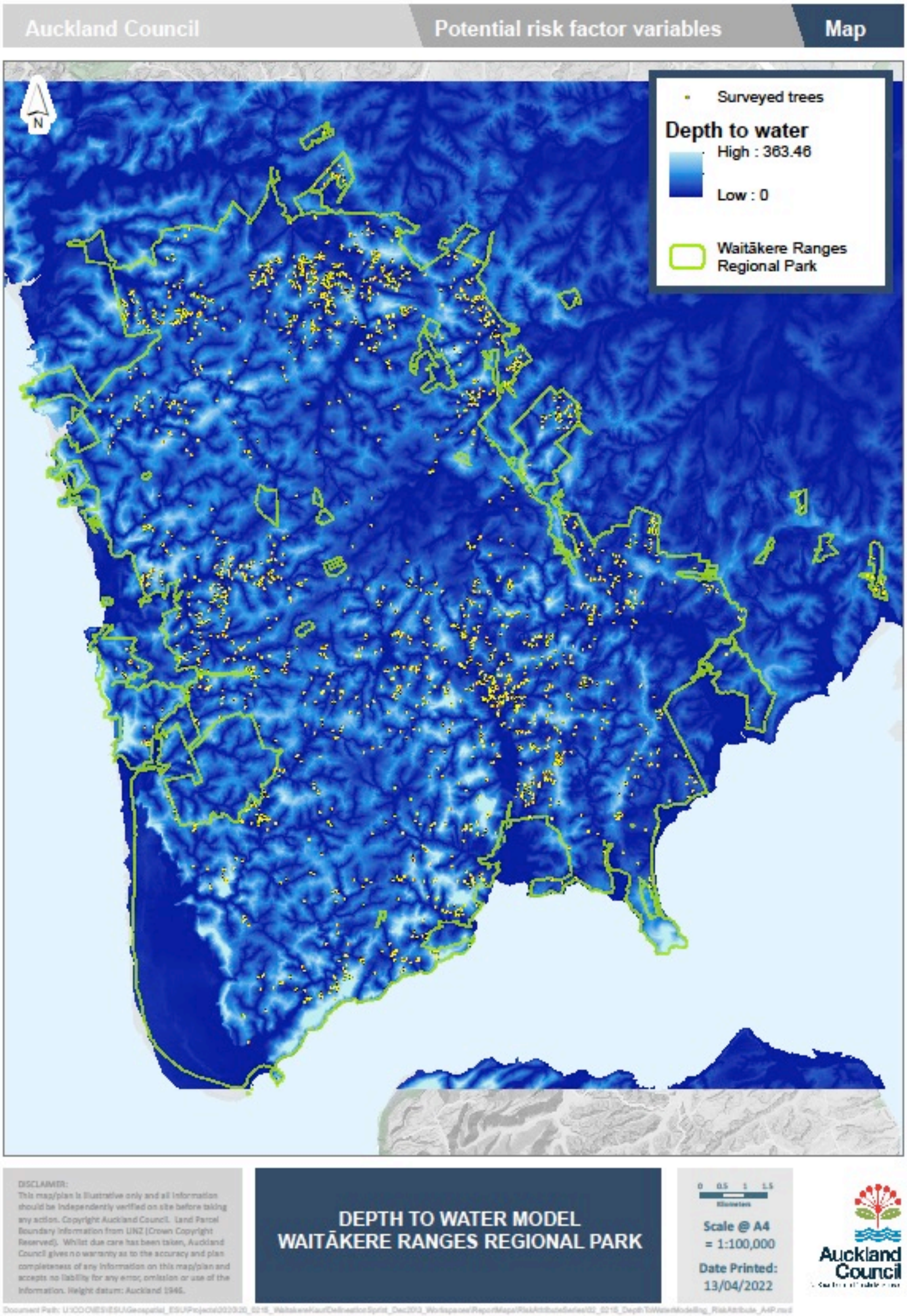
G6 Current extent vegetation risk map

Te mahere ā-tūraru mō te korahi o ngā otaota i tēnei wā



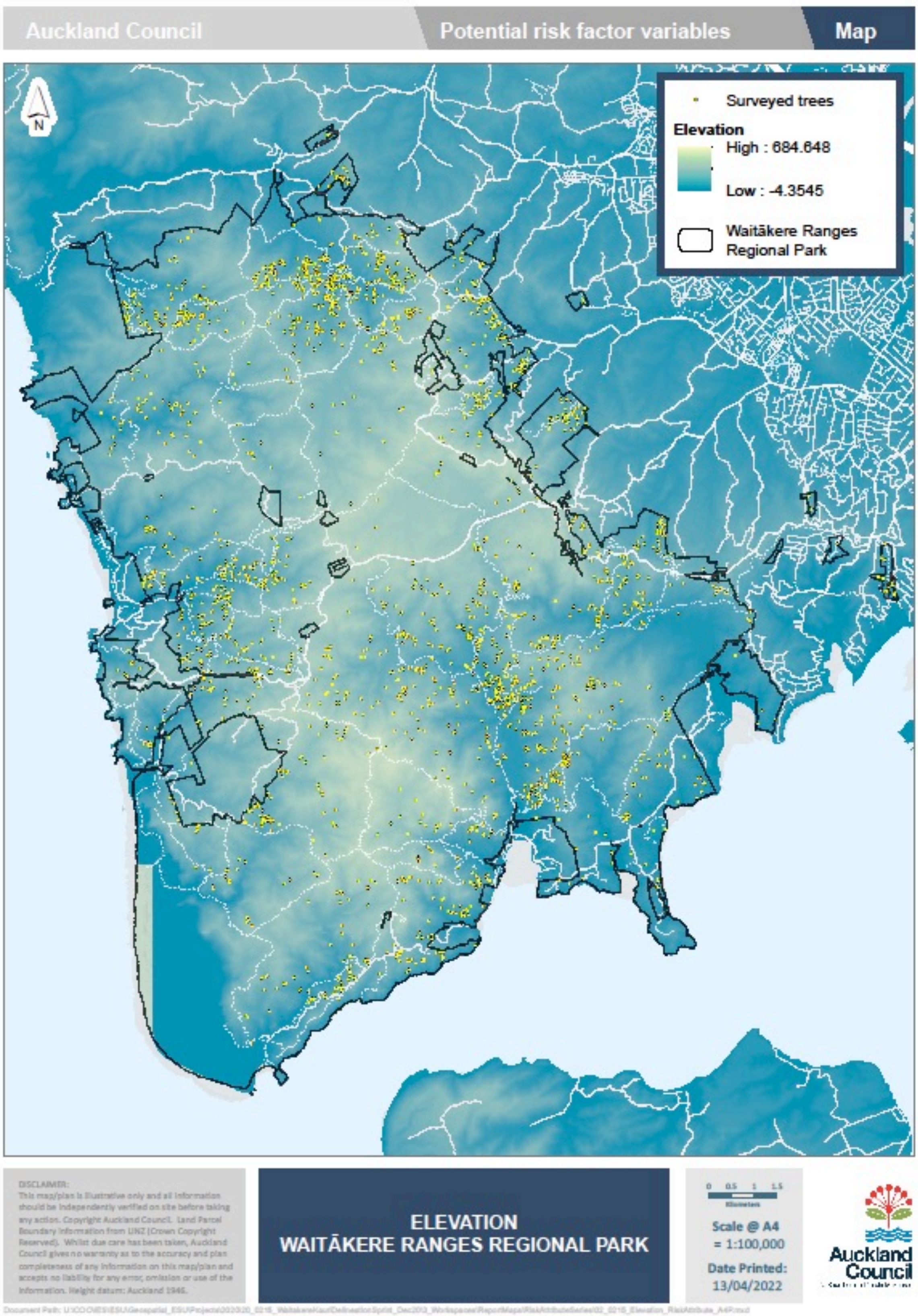
G7 Depth to water model risk map

Te mahere ā-tūraru mō te tauira o te hōhonu o te wai



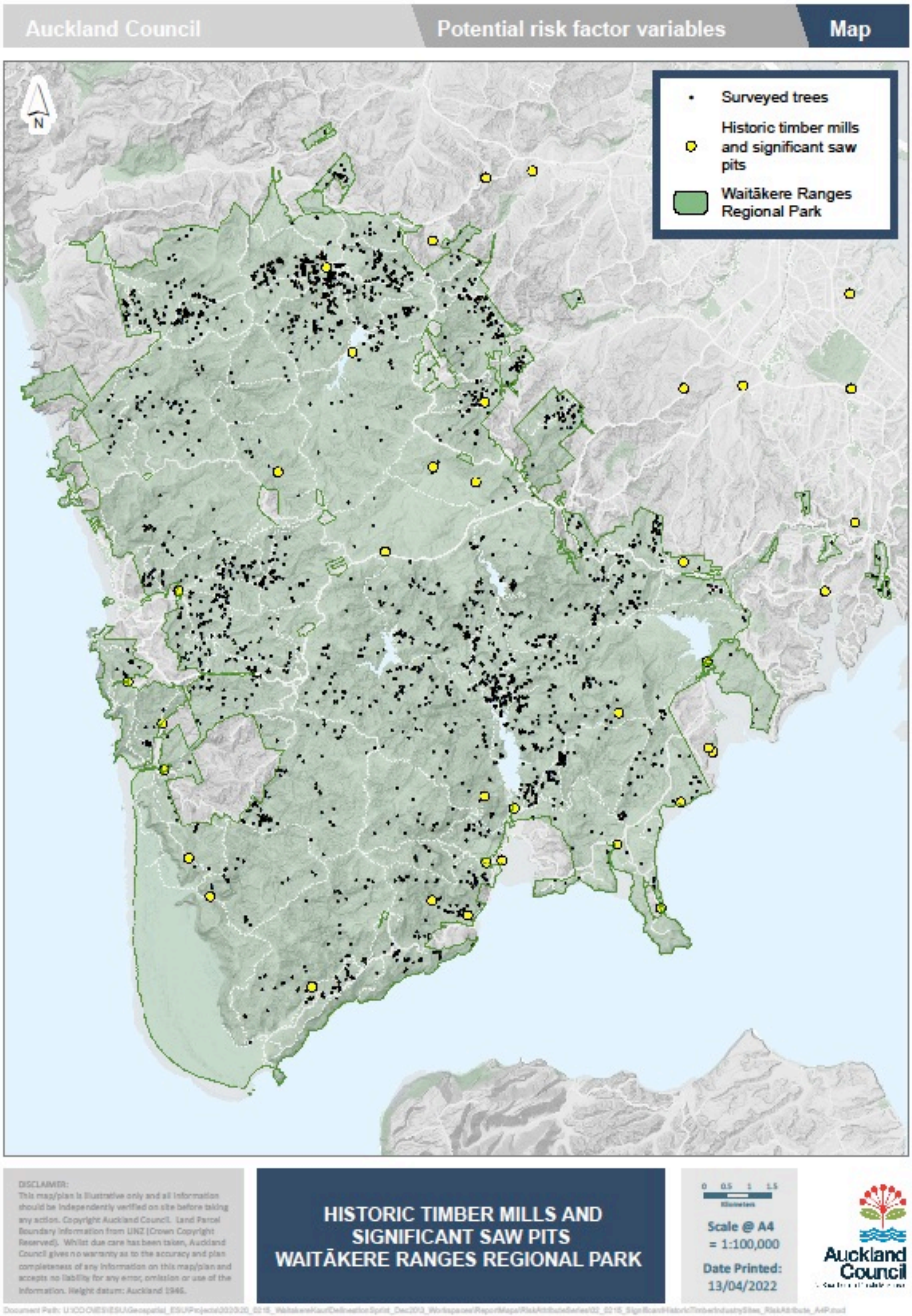
G8 Elevation risk map

Te mahere ā-tūraru mō te rewanga



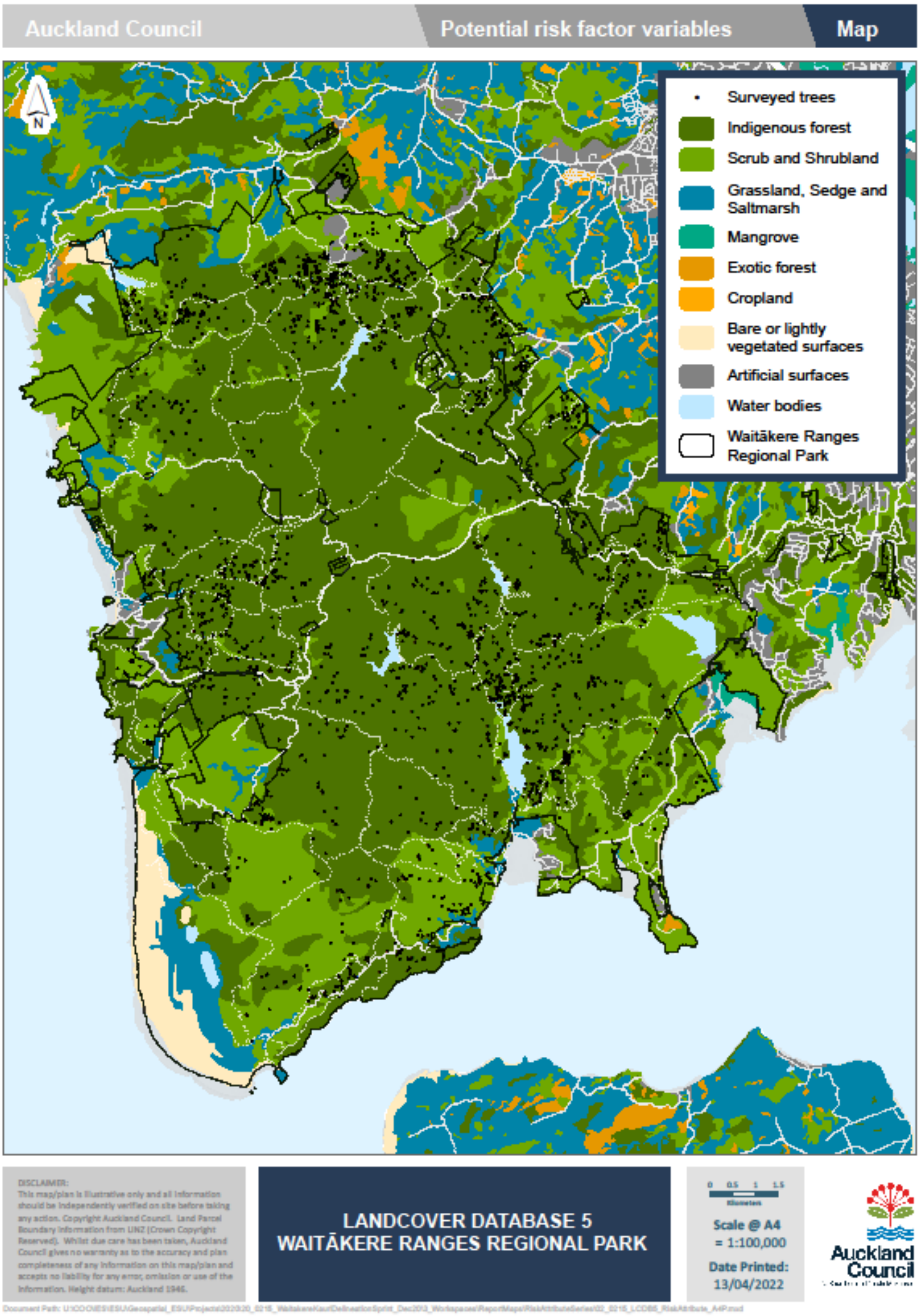
G9 Historic timber sites risk map

Te mahere ā-tūraru mō te wāhi mō ngā rākau tawhito



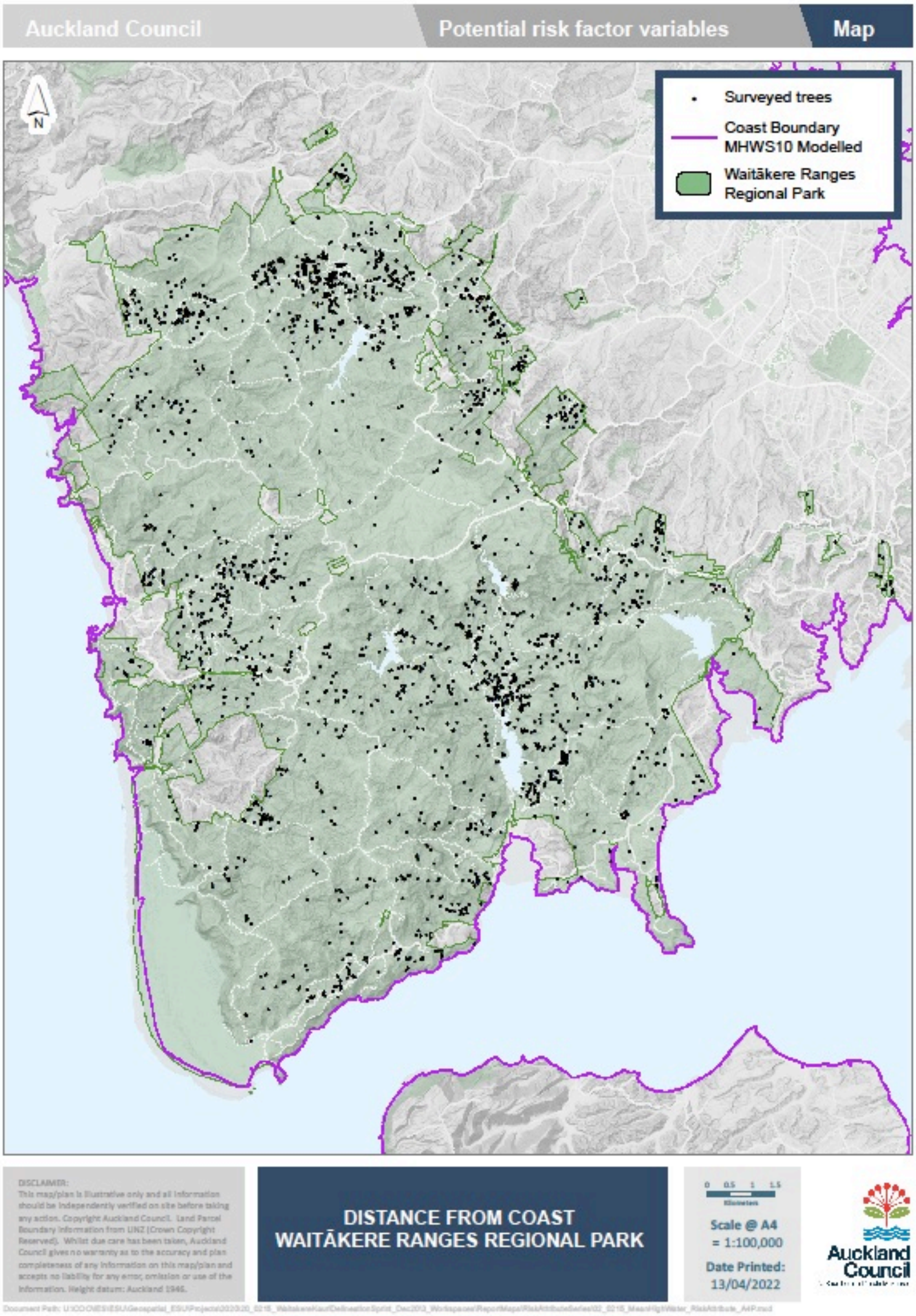
G10 Landcover database risk map

Te mahere ā-tūraru mō te pātengi raraunga mō te pātengi raraunga mō te whakakapinga whenua



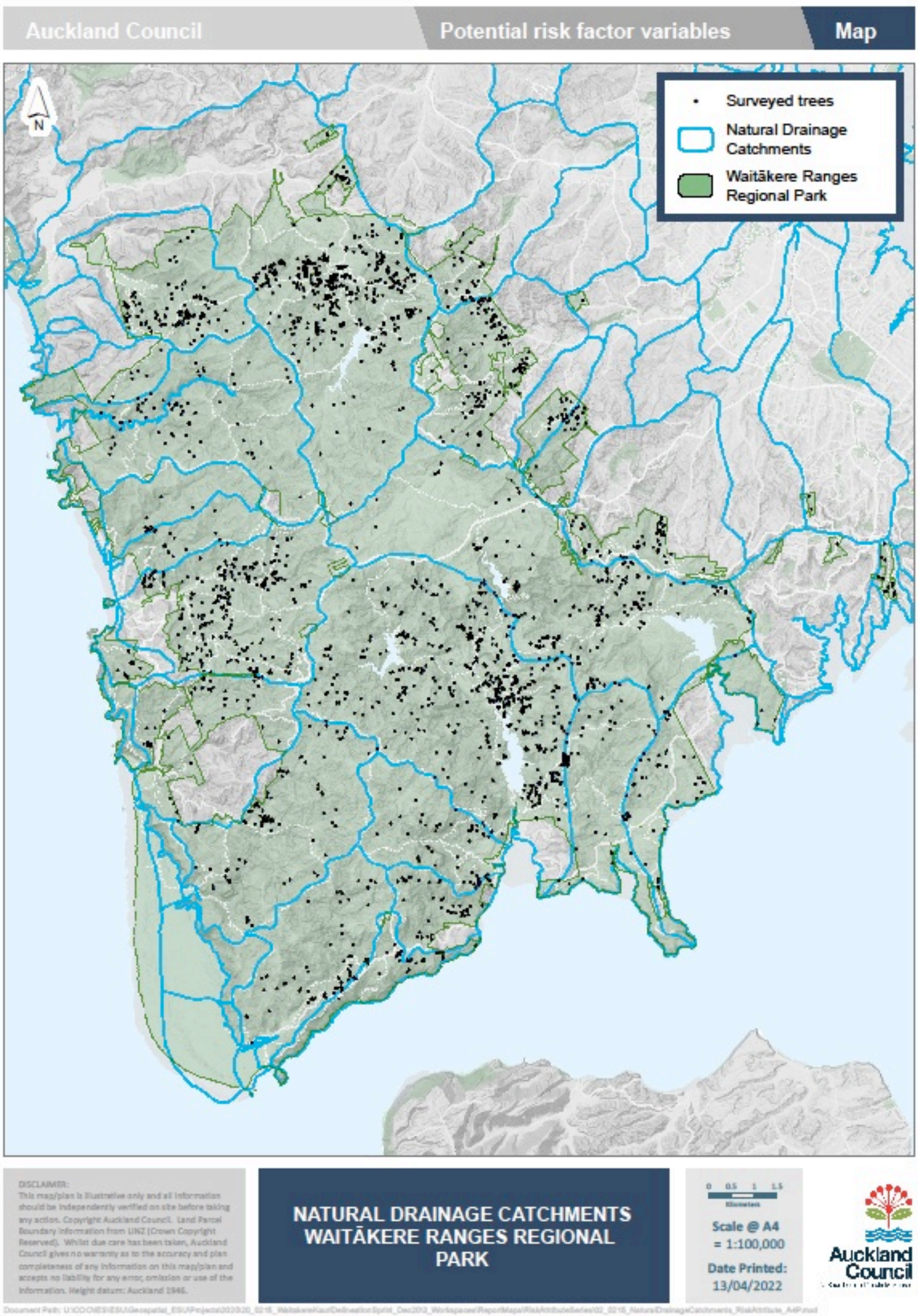
G11 Mean high water risk map (coast boundary)

Te mahere ā-tūraru mō te toharite o te teitei o te wai



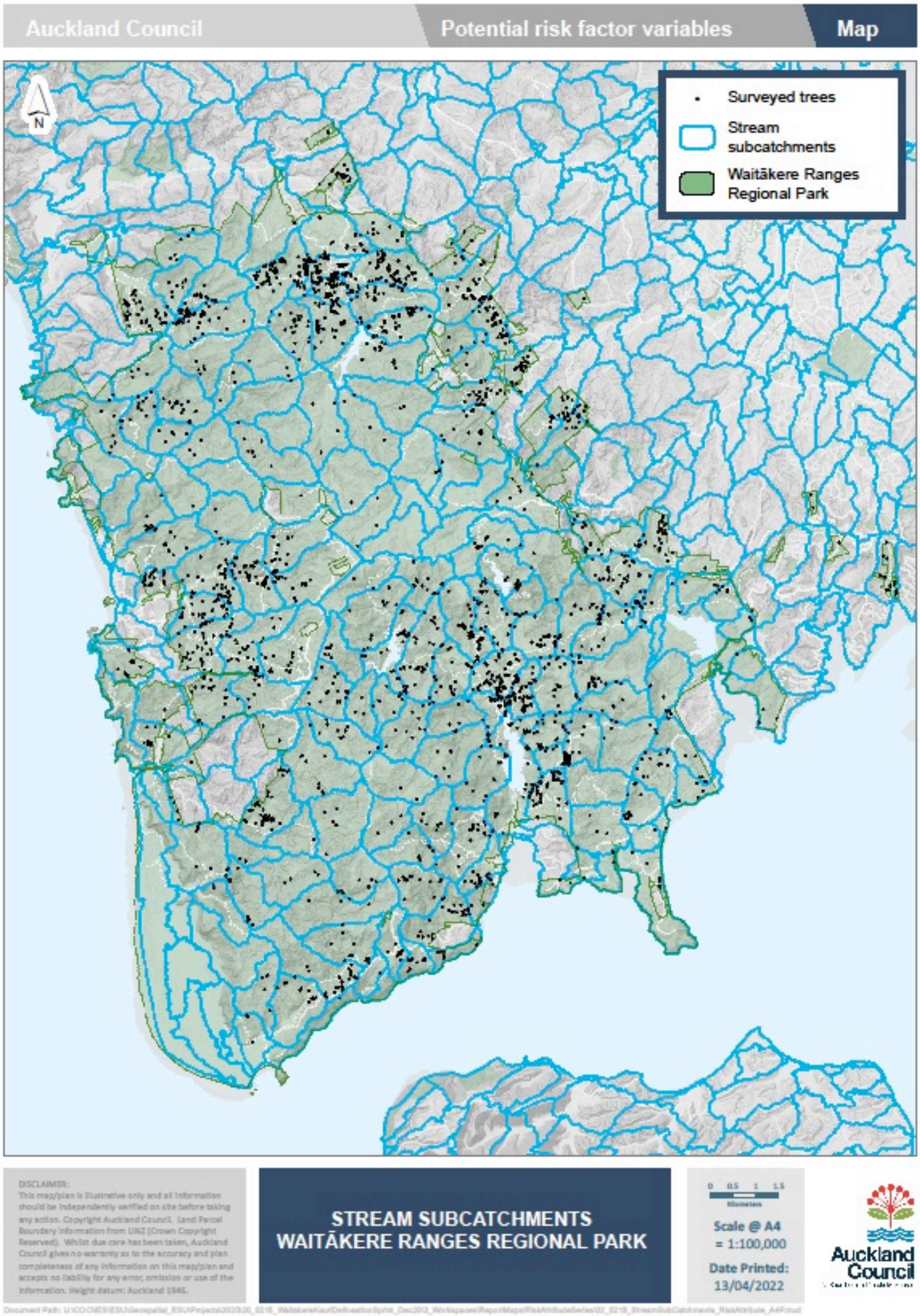
G12 Natural drainage risk map

Te mahere ā-tūraru mō te waikeritanga māori o te wai



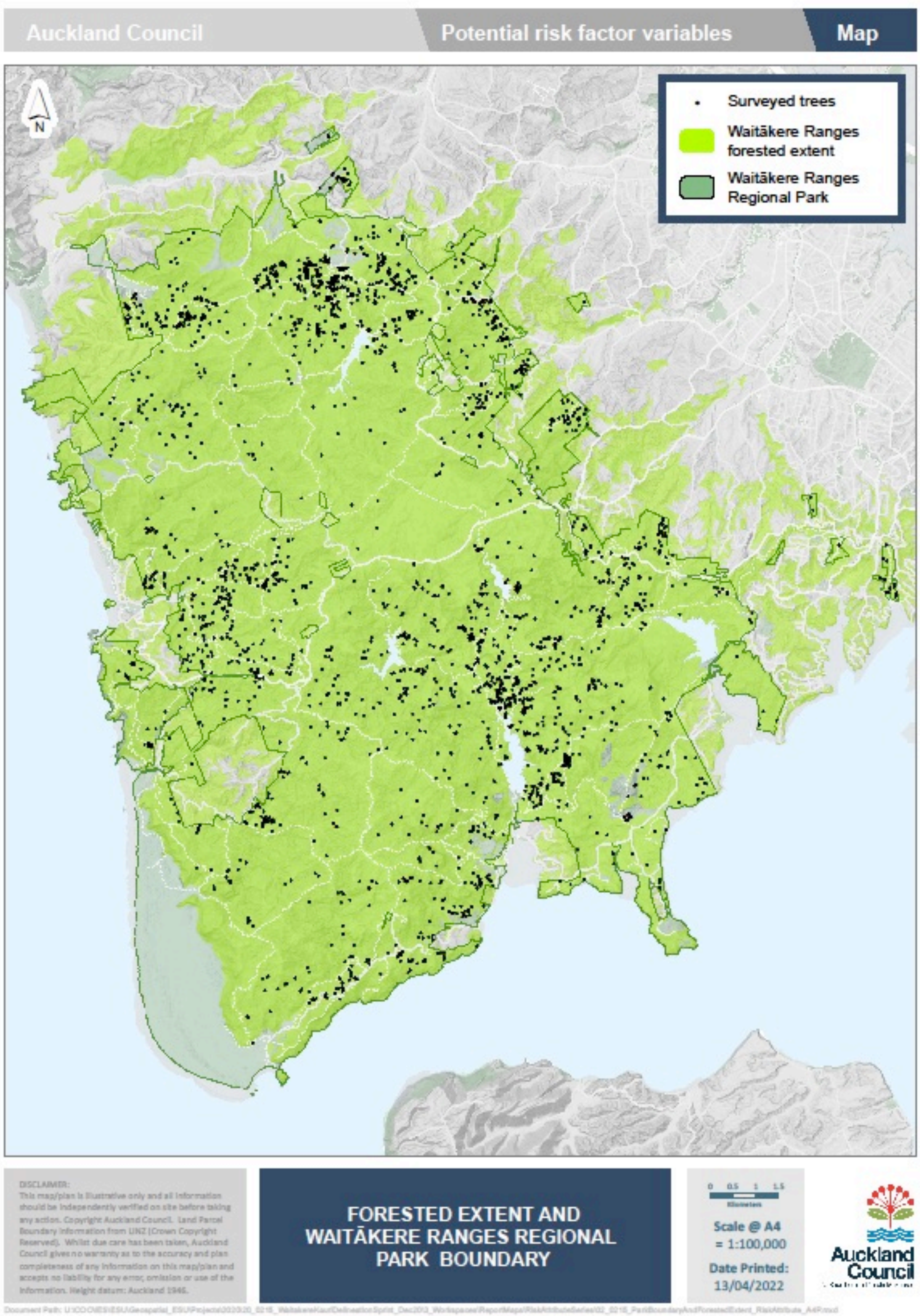
G13 Stream sub-catchments risk map

Te mahere ā-tūraru mō te riu hopuwai iti o te roma



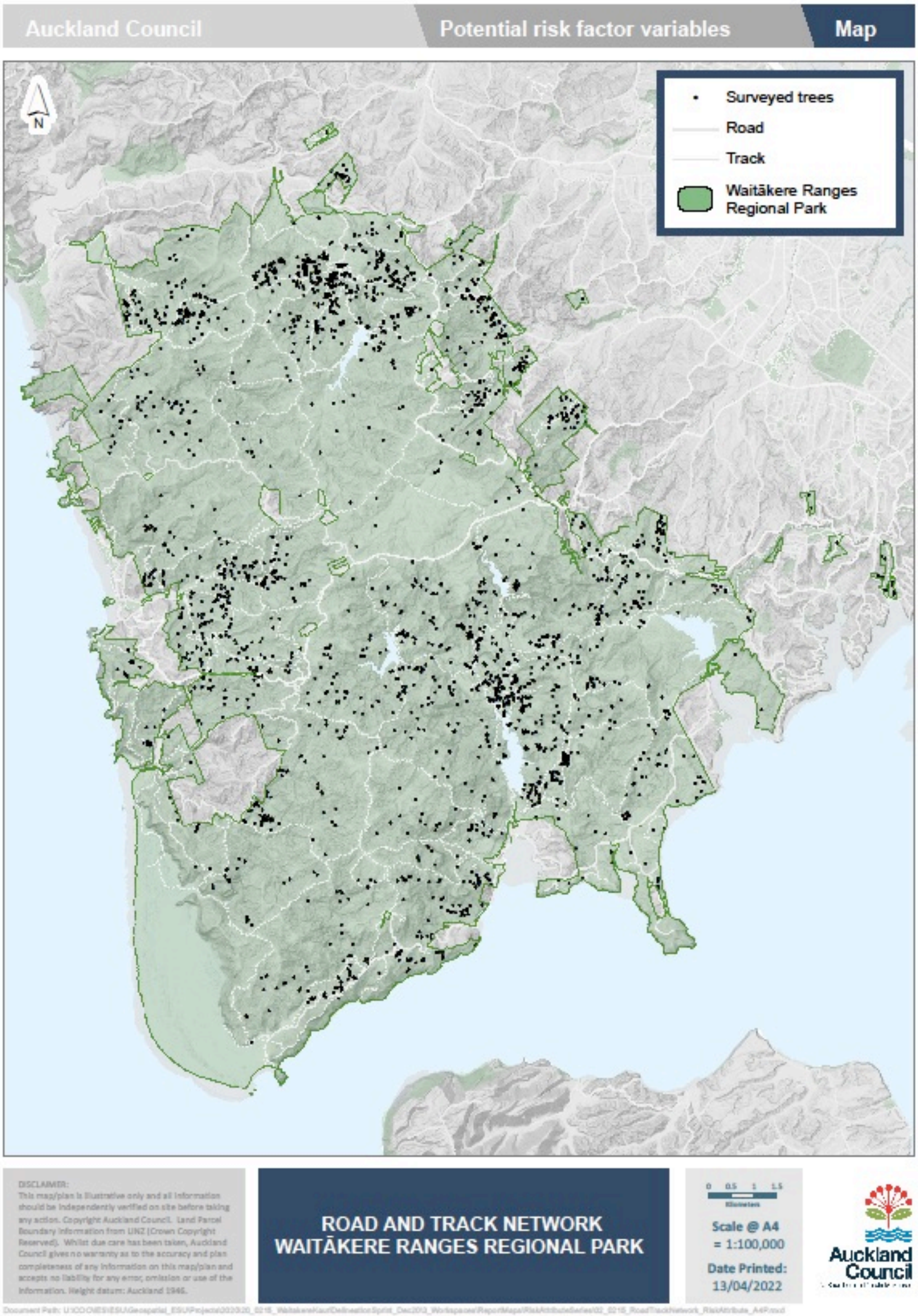
G14 Park boundary and forested extent risk map

Te mahere ā-tūraru mō te rohenga ā-papa rēhia me te korahi o te wao



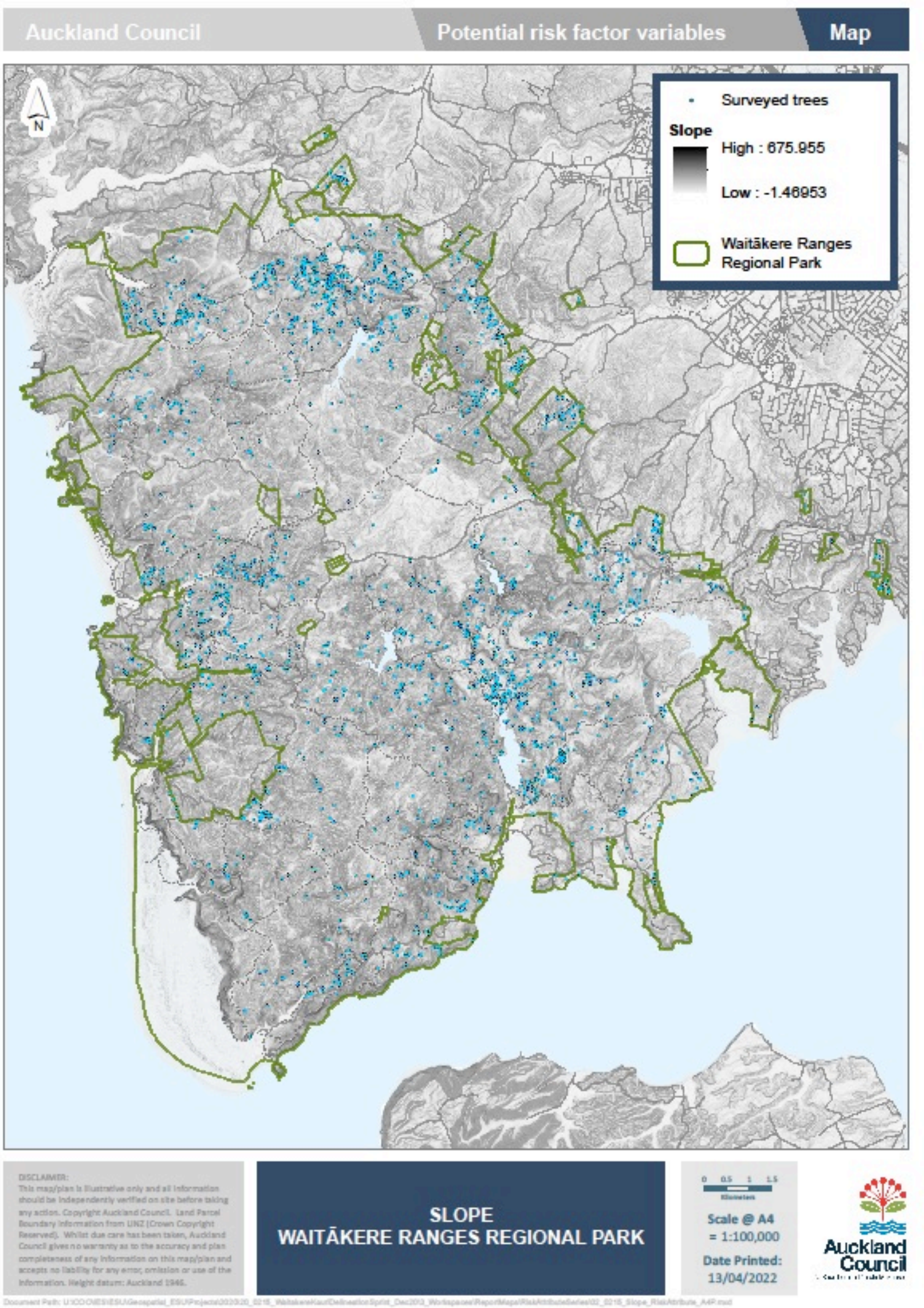
G15 Road and track network risk map

Te mahere ā-tūraru mō te pūtahitanga o te huarahi me te ara



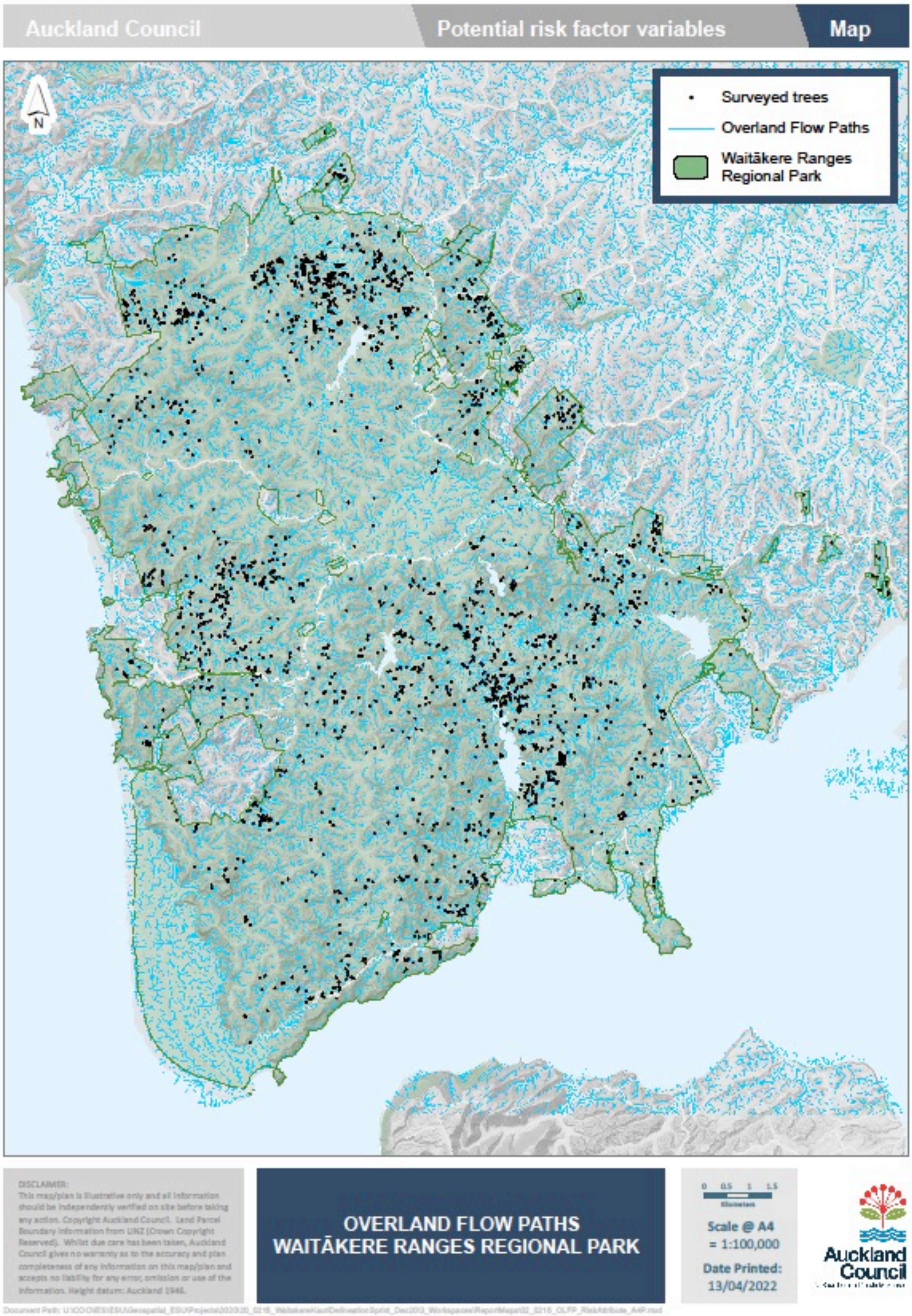
G16 Slope risk map

Te mahere ā-tūraru mō te pīnakitanga



G17 Overland flow path risk map

Te mahere ā-tūraru mō te rerenga iho o te wai ua-tāta



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or visit knowledgeauckland.org.nz and
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