Waiwhakareke Natural Heritage Park 2018 Long-term Plot Monitoring: Report on Ecological Restoration Progress

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A client report prepared for Tui 2000 Inc.
& Hamilton City Council

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people+cities+nature
Restoring Indigenous Nature in Urban Environments

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Executive Summary

This report was requested by Tui 2000 Inc. and the Hamilton City Council (HCC) as a means of tracking terrestrial restoration progress at Waiwhakareke Natural Heritage Park (WNHP). WNHP is a cutting-edge urban ecological restoration project in which ecosystems representative of the Waikato region are being reconstructed from scratch on public land (formally pastoral land) in Kirikiriroa Hamilton. Large-scale projects of this nature are becoming more common around the globe due to growing emphasis on restoring nature in urban areas. While this report quantifies the remarkable ecological restoration success achieved at WNHP though investments by Tui 200 Inc., HCC and other partners over the years, it also contributes to scientific theory. Ecological restoration is a newly developing scientific field and hence WNHP presents a unique opportunity for ecologists to improve restoration practice and also learn from the results.

Here we share results from data analysed from 25 permanent monitoring plots (100m^2 each) throughout WNHP, spanning planting years since the beginning of planting in 2004 through to 2017 (14 years of planting). These plots are located across the five main terrestrial ecosystem types (i.e., planting zones) being restored.

We measured key components of forest development including: canopy openness, native tree basal area, non-native herbaceous ground cover, leaf litter, dead trees, native tree seedling abundance and richness, and epiphyte colonisation. Linear regression models revealed statistically significant relationships between all these ecosystem attributes and forest age. We note there appear to be several important ecological thresholds about 10 years after planting: when canopy closure occurred, reducing understorey light, and a subsequent drop in non-native herbaceous weeds (100% to 25%). With these ecosystem changes, important indicators of functioning forests appeared around the same time, like leaf litter accrual (0% to 95% cover), increased early successional tree deaths (0 to 15), and juvenile native plant recruitment. For example, spontaneous native tree seedling regeneration increased both in abundance (0 to ~150 per 4m^2) and species richness (0 to 13 per 4m^2), and epiphytes colonised (0 to 3 individuals).

This information should be used to inform and adapt further management plans for WNHP. These results signal positive restoration progress and that a focus on enrichment planting and care of the next wave of mid/late successional plants is now appropriate and important. Enriching will help secure the investment in initial plantings by starting the longer-term phase of forest development, while also creating a more species diverse ecosystem, resilient to the manifold pressures of the urban landscape.

Background

Waiwhakareke Natural Heritage Park (WNHP) is located on the northwest outskirts of Kirikiriroa Hamilton, Aotearoa New Zealand. The park features low, rolling hills and encapsulates a peat lake (Lake Waiwhakareke/Horseshoe Lake) within a surrounding wetland area, which is characteristic of the Hamilton Basin (Cornes *et al.*, 2008). The Hamilton City Council (HCC) originally purchased the 60 ha section in 1975, however, until the early 2000s, the park existed as pastureland that was leased for farming (Cornes *et al.*, 2011). In 1998, the HCC endorsed a restoration proposal and approved the concept plans for WNHP in 2004. In this plan 50 ha of the original 60 ha purchased was set aside to convert from severely modified farmland into native ecosystems representative of the Waikato region (Cornes *et al.*, 2008; Cornes *et al.*, 2011). An Operative Management Plan was formed to guide this process (HCC, 2011). In 2016 a further 5.5 ha of public land was added to bring the area of the park to 65.5 ha, its total area today.

In partnership with local academic institutions, research organisations, iwi and community groups, the HCC has led the reconstruction of native ecosystems at WNHP (Cornes *et al.*, 2008). The park has been split into topographical polygons (see Figure 4 in Method) that range along an altitudinal gradient from lake-edge sedgelands to ridgetop kauri forest (Nepia & Drage, 2019). Native vegetation has been planted based on these topographical landforms according to the flora that was historically found in the Waikato Region. A small section was initially planted in 2004, surrounding Horseshoe Lake in the centre of the park. This was a semi-swamp riparian planting, dominated by mānuka (*Leptospermum scoparium*) and harakeke flax (*Phormium tenax*) (Cornes *et al.*, 2011).

Successive plantings have taken place annually for the last 16 years and, as of 2020, native vegetation covers 37.3 ha of the park (and 10.7 ha of that has received the next planting stage, enrichment plantings). To monitor the growth and condition of these plantings, twenty-five permanent plots have been established over successive years, increasing in number with the extent of the park that has been planted. Permanent plot setup, monitoring and reporting has previously occurred in 2006, 2008, 2009, and 2010 (see Table 1 in Method) to provide short and long-term feedback to aid management decisions for planting maintenance and future plantings. We report here on the state and condition of the monitoring plots at the time of re-measurement in 2018 to provide information to aid management decisions regarding planting maintenance, plant ordering for future planting, and to determine if the plantings are maturing on a trajectory to eventually resemble late-successional native forest ecosystems. This document therefore describes the findings from monitoring plantings within the full 25 plot network.

Report overview

The main purpose of this report is to assess the progress of forest ecosystem restoration and create a standardized framework for future monitoring. We assess the growth of plantings in the 25 permanent monitoring plots (planted across 14 years from 2004 to 2017) and discuss the future management of the young WNHP forest. The following attributes were assessed in each of the plots and those that rendered interesting or relevant results are reported on in the results section of the report:

- Canopy openness
- Native tree basal area
- Herbaceous ground cover (which is generally non-native)
- Leaf litter and detritus ground cover
- Bare ground cover
- Moss ground cover
- Fern ground cover
- Dead trees
- Native tree seedling abundance
- Non-native tree seedling abundance
- Native tree seedling species richness
- Non-native tree seedling species richness
- Native sapling abundance
- Non-native sapling abundance
- Native epiphyte abundance

Importance of Planting a Lasting Urban Forest

This report focuses on assessing whether the forest at WNHP is maturing into an enduring urban forest that will self-perpetuate and function like a forest should. Therefore, instead of providing only an exhaustive list of species identified (although see Appendix 3 for this), there is a focus here on discovering the patterns of forest structural development and indicators, or signals, of forest maturity (e.g., canopy development, planting self-thinning and presence of dead adult trees and spontaneous tree seedling regeneration). Successive plantings completed over the 14 years included in this report (2004 – 2017) provides a unique opportunity to learn whether current management is appropriately guiding plantings efforts toward a mature forest ecosystem as an endpoint and what new management approaches may be needed.

It is paramount we understand how planted native forests are growing in order to restore them effectively and use resources wisely (Oldfield et al. 2015; Miller et al. 2016; Wallace et al. 2017). This is critical for urban forests like WNHP in particular because of benefits we ultimately need them to provide, such as ecosystem services like flood mitigation (Dobbs et al. 2011; Endreny et al. 2017) enhanced human health and well-being (Alberti 2005; Brown et al. 2014), and havens for native biodiversity (Aronson et al. 2014; Threlfall et al. 2016). About 86% of Aotearoa New Zealand citizens live in cities, where their opportunity to connect with nature regularly is often in a local forested park. However, despite the manifold benefits we now know forests and nature

provide for people, most Aotearoa New Zealand urban centres have very little of their native ecosystem cover remaining (cover ranges from approximately 2% - 10% depending on the city, and Kirikiriroa Hamilton only has about 2% remaining; Clarkson et al. 2007). Forests and other native ecosystems are now mostly left on upland rural areas, so WNHP is especially precious, as much of it will represent the lowland forest ecosystems. Now more than ever, we need to restore new urban forests for the benefit of both people and wildlife.

Urban forests are different from rural forests both ecologically and environmentally. They are also more dynamic than rural forests (Groffman et al. 2016), with frequent changes in plant population sizes and ages due to constant human activity, which occurs on a much shorter timescale than rural forest dynamics usually do. Unique challenges to urban forest restoration include the urban heat island effect (Samuel et al. 2016), fragmented city landscapes (Drinnan 2005), pollution, and constant non-native species invasion (Trammell et al. 2012; La Sorte et al. 2014). Planted urban forests therefore face additional pressures and require consistent monitoring and management to return to a functional, mature, native state and keep them there.

The People, Cities & Nature research team (funded by Ministry of Business, Innovation and Employment Endeavour grant UOWX1601) who conducted this report have found that the underpinnings of urban forest patch planting and restoration should be scientifically researched to ensure long-term success, because little is known about the process of reconstruction of forest from scratch (i.e., generally, plantings in former pasture or mowed urban parkland; Clarkson & Kirby (2016)). Urban forest restoration by trial and error is costly, and can often result in failures that are discouraging to stakeholders and practitioners, and condemning of future funding approval. Instead, we propose taking an evidence-based approach informed by ecological science and applied through best practice, then monitored to observe what works and what doesn't. This completes the full cycle of discovery through to implementation, allowing restoration efforts to be successful. Planting an urban forest is a very worthwhile endeavour, but requires special management to get it right in the long-term. People, purpose, plants, and patience are all required.

Forest Restoration Based on What We Know about Natural Forest Succession

Forests in more natural rural settings can often naturally go through a process called ecological succession on their own. Ecological succession is the process of ecosystem development following a major disturbance, typically beginning as the presence of early-successional (i.e., pioneer) plant species that facilitate changes in their immediate environment to make way for mid and late-successional species (Fig. 1).

Figure 1. Forest ecological succession through time, from early, through mid, to a late-successional forest. The pioneer plant species present during early-succession ameliorate conditions to be suitable for the mid-successional plant species to establish and grow, and then eventually the late-successional plant species, which are long-lived and sensitive, and cannot be planted initially due to their need for protected conditions. Achieving the late-successional stage is vital to promote forest stability long-term and provide maximum biodiversity support and ecosystem services. (Figure borrowed with permission from Hall 2020).

Because there is so much disturbance in altered city environments, we must actively engage in the act of ecological restoration to re-create ecosystems we want there by mimicking this natural successional process. In succession, the growth of the first wave of pioneer plantings and then later regeneration of late-successional native tree, shrub and epiphyte species beneath the canopy of the initial restoration planting is a key process in forest succession, and is therefore a great indicator, or signal, of restoration success. By monitoring planted forests as they grow, we can determine if our plantings are maturing to resemble a forest ecosystem rather than a glorified garden, and when to make management interventions. It is imperative we manage these planted forests in a way that encourages growth of the next generation of forest trees to reach a full, stable forest ecosystem (Fig. 2) that requires less management. Otherwise, the unstable first plantings of pioneer species will fall over after a few decades and weeds will likely dominate once again, requiring extra planting and management.

Figure 2. Reflections on planting an urban forest - don't miss management facilitation of important elements and stages in development after initial plantings occur! **(i)** Planting and management to hasten canopy closure and reduce light gaps to suppress weeds is crucial, **(ii)** Getting trees established fast means you can introduce important late successional plant groups like vines later on, **(iii)** Canopy closure causes sun-loving herbaceous weeds to die back so shade-tolerant native seedlings can regenerate without too much competition, **(iv)** Seeds from external sources may be introduced, and in cities these are often weeds so, vigilance is required to suppress these in early years after planting and that closed canopy that blocks sunlight is vital, **(v)** Maturing trees will shed leaves to create a leaf litter layer on the forest floor, making great conditions for desirable late-successional native tree seedling germination, **(vi)** Enrichment planting of tall (>1m) late-successional plant species is typically vital in cities because forests are too far apart for natural seed dispersal to occur and weed competition or microclimate will suppress delicate smaller plants, and **(vii)** Decomposition of old leaves, sticks and trunks is recycling of nutrients for living plants, constitutes soil rehabilitation, and is important habitat for invertebrates- this 'coarse woody debris' should always be left where it falls. (Figure borrowed with permission from Wallace & Clarkson 2019).

Method

General overview

In 2018 25 permanent plots were measured in Waiwhakareke Natural Heritage Park in areas planted between the years 2004-2017 (a 14-year span) (for locations, see Figs. 3 & 4). This report is the first to tie all the plots from previous monitoring rounds together into one comprehensive long-term monitoring plot network, with all plots marked with metal waratahs at the four corners and ID tags. The complete protocol for the permanent plot set up is detailed in Appendix 1 and should be followed in future monitoring rounds where plots in newly-planted areas are added to the network. A subset of the plots (i.e., those established early on), have been repeatedly measured while more recently-established plots have experienced fewer monitoring rounds (Table 1) because they have existed for a shorter timespan.

In 2018, all twenty-five permanent vegetation plots were measured at WNHP. Prior to the 2018 monitoring period, the last data collection at the plots occurred in 2009. Although previous reports recorded data at WNHP using plots of different shapes and sizes, after 2009 the 25 permanent plots were standardised in size to 10 x 10 m (i.e., 100 m^2).

Table 1. Waiwhakareke Natural Heritage Park permanent plot information. Note the table is ordered chronologically by 'Year Planted', with 'Plot Established' and 'Monitoring Years' occurring in subsequent years, which were not always in chronological order. 'Monitoring Years' are those when the vegetation in the plots was surveyed for other commissioned monitoring reports.

Plot ID	Year Planted	Plot Established	Planting Zone	Monitoring Years	Latitude	Longitude
1	2004	2006	waterlogged	2006;2007;2009;2018	-37.77248	175.2252
2	2005	2006	waterlogged	2006;2007;2009;2018	-37.77229	175.22622
3	2005	2006	waterlogged	2006;2007;2009;2018	-37.7713	175.22491
4	2005	2006	waterlogged	2006;2007;2009;2018	-37.77254	175.22555
5	2006	2009	waterlogged	2007;2009;2018	-37.7706	175.22825
6	2007	2008	waterlogged	2008;2010;2018	-37.77069	175.22858
7	2007	2008	basin	2008;2010;2018	-37.77095	175.22829
8	2007	2008	basin	2008;2010;2018	-37.7715	175.22853
9	2007	2008	basin	2008;2010;2018	-37.77131	175.22788
10	2007	2008	hillslope	2008;2010;2018	-37.77105	175.22426
11	2007	2008	hillslope	2008;2010;2018	-37.77138	175.22408
12	2007	2008	hillslope	2008;2010;2018	-37.77178	175.22439
13	2007	2008	hillslope	2008;2010;2018	-37.77211	175.22466
14	2009	2010	waterlogged	2010;2018	-37.77165	175.21967
15	2009	2010	hillslope	2010;2018	-37.77147	175.21946
16	2009	2010	ridge	2010;2018	-37.77167	175.21901
17	2008	2010	hillslope	2010;2018	-37.77105	175.21984
18	2012	2017	basin	2018	-37.77086	175.2208
19	2012	2014	basin	2014;2018	-37.77069	175.22043
20	2005	2014	basin	2014;2018	-37.77092	175.22462
21	2012	2018	ridge	2018	-37.77235	175.22135
22	2011	2018	ridge	2018	-37.77383	175.21995
23	2017	2018	toeslope	2018	-37.77035	175.22282
24	2013	2018	toeslope	2018	-37.77124	175.22194
25	2016	2018	hillslope	2018	-37.77165	175.22864

Figure 3. The 25 permanent plot locations at Waiwhakareke Natural Heritage Park, each with a unique ID number. The plots span the range of planting years (2004-2017) which had occurred at the time of the 2018 monitoring.

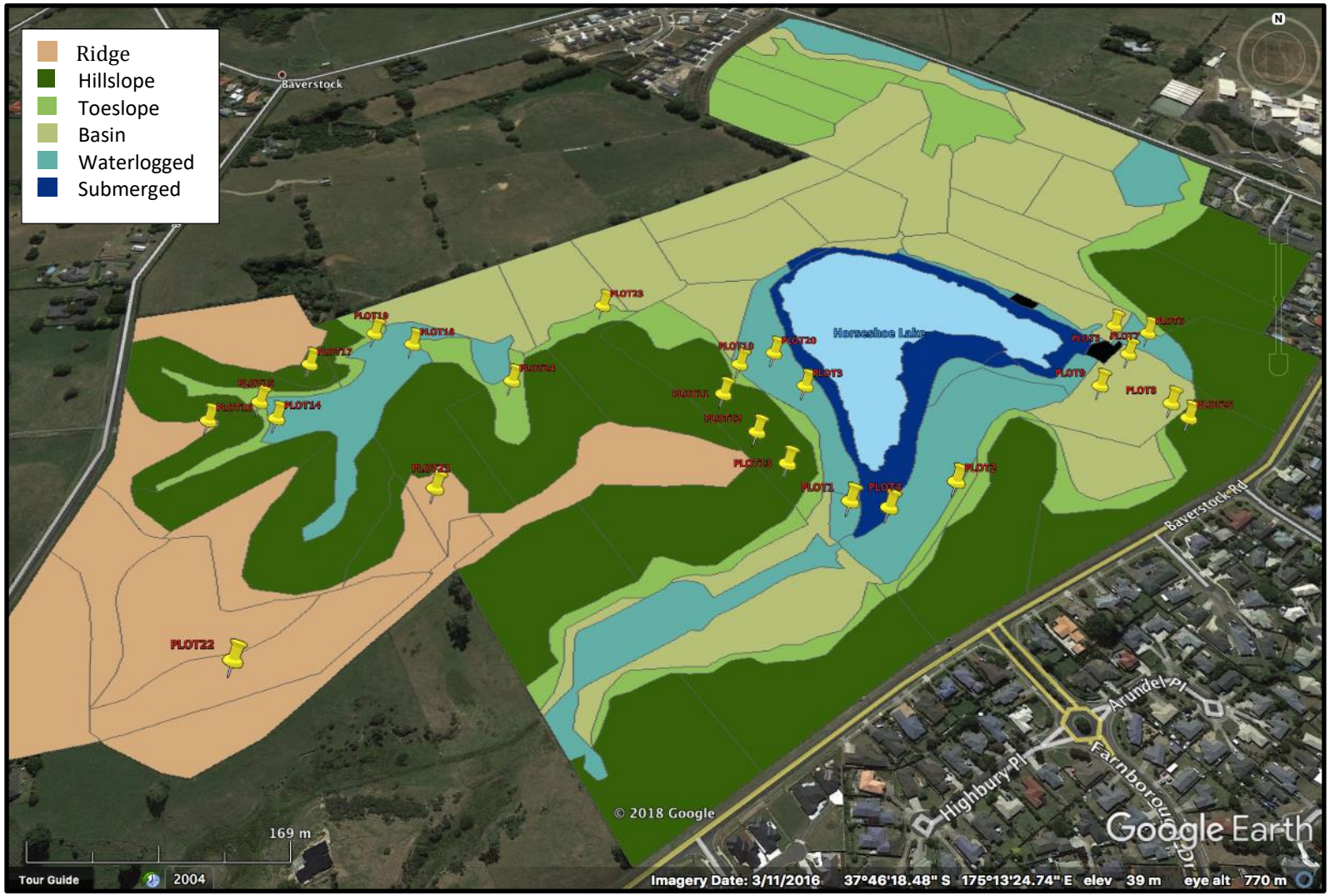


Figure 4. The 25 permanent plot locations at Waiwhakareke Natural Heritage Park with coloured planting zone types overlaid. Plots are distributed across the first five listed forest restoration planting zone types (see inset legend). Dark blue "Submerged" areas were not included in the 25 plot network location setup as they are unsuitable for monitoring the strictly terrestrial forest plant species.

Data collection

For the 2018 monitoring round, all woody plant species were identified within each permanent plot and their morphological characteristics (e.g., sapling height, diameter at 1.35m from the ground for adult trees) were measured and recorded. Plot-level attributes such as ground covers and canopy openness were also measured to gauge general forest ecosystem development, as they can be good signals of forest maturity. Plot-level attributes and adult tree attributes were measured within the full 100 m^2 plot area, while seedling measurements were taken in four subplots (1 m^2 each, located in the four corners of each plot) (see Appendix 2 for details). Data from the four seedling subplots was added together to represent a value for each 100 m^2 plot (our main unit of statistical analysis). The detailed protocol for vegetation surveys conducted at WNHP, including data collection forms, which can be used in future monitoring, is available in Appendix 2.

Data preparation and analysis after collection

To evaluate the relationships between forest age and developmental conditions (e.g., canopy openness) or plant community attributes (tree basal area, ground cover [herbaceous species, leaf litter, bare ground, moss, ferns], dead trees, plant regeneration, and epiphyte colonization), we fitted linear regression models. Prior to fitting the models, variables were log (or log + 1 for data sets with zero values) transformed to normalize the spread of the data and therefore meet assumptions of the statistical tests. One outlier was removed from the native woody seedling abundance data set (extremely high numbers of *Dacrycarpus dacridioides* Kahikatea in plot 1 were skewing analysis general results). Tree basal area (e.g., essentially, cumulative cross section area of all adult trees in each plot) was converted from m^2/100 m (i.e., the unit it was measured in) to m^2/ha, to align with standard measures of basal area in forestry practice. For this conversion, the basal area measurements (i.e., both the numerator and denominator of the m2/100m form it was recorded in) were multiplied by a factor of 100. All statistical analyses were performed in R (R Core Team, 2017) using the "vegan" package (Oksanen et al. 2019).

Results

These results focus on discovering the patterns of forest development and identifying indicators, or signals, of forest maturity over time since initial planting. Therefore, it is important to observe general directions of trend lines in the figures and timescales on which forest development occurred. Figures are only shown here for forest attributes that were found to change significantly over time since planting and may of important management interest. A full species list categorised by plot, forest age and plant growth stage can be found in Appendix 3.

Canopy Changes

As the forest planting age at Waiwhakareke Natural Heritage Park (WNHP) increases, the basal area (m^2/ha) of native adult trees significantly increases, which demonstrates predictable, rapid growth over time after planting (Fig. 5A). The highest basal area

values occurred ten years or more after planting occurred. For example, plot nine (38.5 m^2/ha of basal area; 11 years), plot 14 (31.9 m^2/ha of basal area; 9 years), plot 7 (31.8 m^2/ha of basal area; 11 years) and plot six (31.2 m^2/ha of basal area; 11 years) each had relatively high basal areas, while younger plots (i.e., plots 23 and 25) had the lowest basal area value (0 m^2/ha of basal area; 1 and 2 years respectively) because none of the planted trees were old enough to qualify as adult trees and be measured for basal area.

In contrast, while basal area increases with forest age, we found that the percentage of canopy openness decreases significantly (Fig. 5B). A particularly steep drop (of 76.7%) occurred quickly in our observations, developing in plots ranging from just one to five years old. In the ten-year-old plot, only 6.8% of the canopy remained open and this trajectory indicates the forest is progressing towards a fully closed canopy — a key developmental threshold.

Groundcovers

Like canopy openness, herbaceous groundcover (generally non-native species such as pasture grasses and weeds) also decreases substantially with forest age, particularly within the first ten years after planting (Fig. 5C), where the percentage cover declines from 100% to 25%. It is noteworthy, however, that there is a lot of scatter in the herbaceous cover dataset, suggesting that some herbaceous species may be able to persist for longer in older forests, perhaps being dictated more by canopy openness (shade tolerance) than forest age (e.g., Wandering Willie, *Tradescantia fluminensis*).

Leaf litter and associated coarse woody debris cover significantly increases with forest age (Fig. 5D) and, in five-year-old plots, leaf litter is 20 times greater than when initial planting occurred. The largest expanse of leaf litter and detritus cover was measured in a plot of vegetation that had been planted 11 years ago (95% leaf litter cover). Planted forests typically have very little bare ground (<10% across all plots; Table 2) and the percentage of bare area remains low (typically <15%) throughout time — with the exception of plot 7 (60%). Moss cover is absent for the first seven years and, thereafter, only occurs in low quantities (approx. 1% cover maximum; Table 2). Similarly, forest floor ferns only begin to appear towards the end of the first decade after initial plantings, but then increase in cover to a high of 65% in the years immediately following (Table 2).

Table 2: Ground cover types measured for this monitoring report, categorised into herbaceous plant species, leaf litter and detritus, bare ground, moss or fern and displayed as percent cover of each 100 m^2 plot in relation to forest age.

Forest age (y)	Plot ID	Ground cover type (percent cover)				
		Herbaceous species	*Leaf litter & detritus*	*Bare ground*	*Moss*	*Fern*
1	23	100	0	0	0	0
2	25	100	0	0	0	0
5	24	75	20	5	0	0
6	18	85	10	5	0	0
6	19	70	28	2	0	0
6	21	70	20	10	0	0
7	22	1	38	60	1	0
9	14	70	20	1	1	8
9	15	7	89	2	1	1
9	16	9	73	15	2	1
10	17	25	65	5	1	4
11	6	55	25	4	0	16
11	7	10	65	5	0	20
11	8	0	49	10	1	40
11	9	0	50	8	2	40
11	10	0	95	5	0	0
11	11	1	90	4	0	5
11	12	1	88	10	0	1
11	13	10	73	15	1	1
12	5	70	27	1	1	1
13	2	20	10	5	0	65
13	3	5	24	5	1	65
13	4	79	15	5	0	1
13	20	36.56	54.31	6	3.13	0
14	1	42	15	1	1	41

Tree deaths

The number of dead adult trees per 100 m^2 increases with forest age, particularly after the first ten years (Fig. 5E). Overall, this number of dead trees (approximately 10 per 100 m^2) is expected because these trees are reaching a natural self-thinning stage after planting where they are competing for physical space and resources (e.g., light and water). These dead trees and branches are hardly a loss to the newly developing forest ecosystem however, as they create very important habitat for other species (i.e., invertebrates and fungi), can act as barriers to soil erosion, and are part of the nutrient cycle needed for the next generation of trees. These adult tree deaths should therefore be seen as a critical part of the restoration process and a great indicator that the forest is maturing correctly.

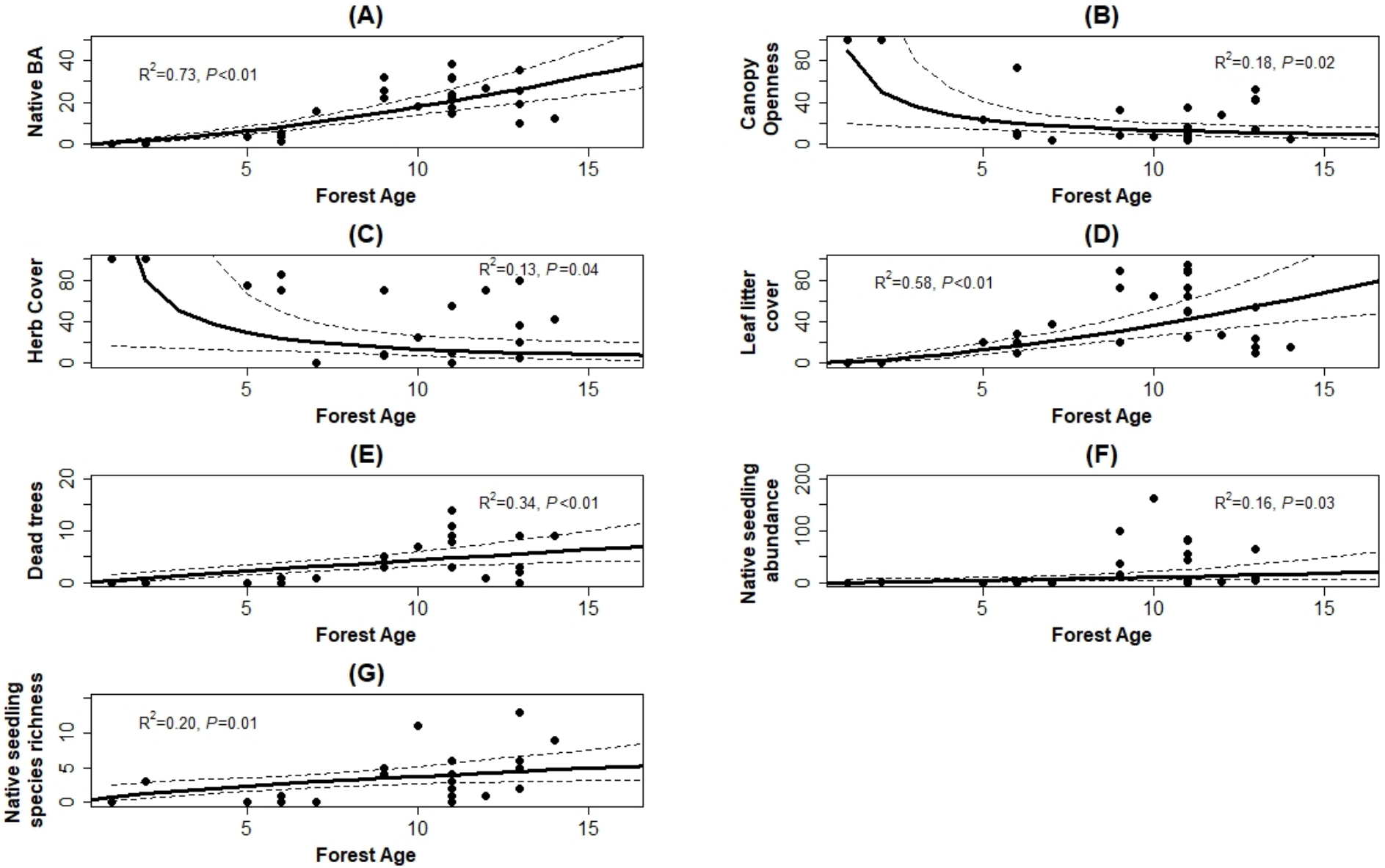


Figure 5. Developmental conditions and plant community attributes within planted plots (plot size = 100 m^2) that range between 1 and 14 years in age since planting at Waiwhakareke Natural Heritage Park. Here we show only the conditions or attributes that have changed significantly since initial planting and are important for management purposes, including **(A)** Native tree basal area (m^2/ha), **(B)** Canopy openness (% cover), **(C)** Herbaceous species (% cover), **(D)** Leaf litter (% cover), **(E)** Dead trees (number per 4 m^2), **(F)** Native seedling abundance (number per 4 m^2), and **(G)** Native seedling species richness (number per 4 m^2). Forest age is shown on the x-axis and units are in years. Scatterplot points represent each of the 25 permanent monitoring plots; the solid lines represent the fitted values from a linear regression model with dashed lines representing 95% confidence intervals where significant relationships (i.e. $P < 0.05$) exist.

Plant Regeneration

Tree Seedlings

The total abundance of native tree seedlings (all native seedling individuals of all species added together) increases significantly with forest age (Fig. 5F). For example, the plot with the greatest number of native seedlings (n = 1416) was also the oldest plot (14 years). Within this plot, the dominant species was *Dacrycarpus dacridioides* (white pine, kahikatea; n = 1270), followed by *Cordyline australis* (cabbage tree, tī kōuka; n = 93). Native seedlings generally did not start to appear in notable quantities until 9 years after the pioneer canopy trees were first planted. Non-native seedling abundance was low across plots of all ages (typically < 15 seedlings when added across the four subplots in each plot) and although non-native tree seedling presence increases slightly in older forest plots, the increase is not statistically significant and therefore not depicted in a figure in this report.

Native seedling species richness (i.e., how many different species were counted across the four subplots) increases with forest age as well, with older forests hosting more species in their understoreys (Fig. 5G). The number of species was greatest in plots over ten years old. For example, the greatest species richness occurred in plot 20 (13 species; 13 years old), followed by plot 17 (11 species; 10 years old). The most abundant seedling species at WNHP was *D. dacridioides* (white pine, kahikatea; total across all plots = 1299), followed by *Melicytus ramiflorus* (māhoe, total across all plots = 297), *C. australis* (cabbage tree, tī kōuka; total across all plots = 164) and *Coprosma tenuicaulis* (swamp coprosma, hukihuki; total across all plots = 130).

By comparison, just like their abundance, the non-native tree seedling species richness does not change significantly with forest age and remains low across all plots (e.g., the maximum number of non-native tree seedling species found in any plot was four, in a 10 year old plot). Overall, fewer non-native species are successfully invading than natives that are regenerating.

Differences in seedling regeneration by planting zone type

The staggered annual planting design at WNHP best lends itself to a chronosequence approach for a quantitative analysis, as we have used in this report. However, we do note that plots in WNHP are set up grouped by five different planting zone types according to topography ('Ridge', 'Hillslope', 'Toeslope', 'Basin', 'Waterlogged';Fig. 4), and plots could be grouped by planting zone type for analysis of regeneration.

Planting zone type could impact planting establishment, growth and later native tree seedling regeneration (e.g., due to drainage and water availability differences during droughts). Unfortunately, annual plantings have not been evenly alternated between planting zone types over the years, and most of the 'Waterlogged' plantings occurred in the early years, making plots in this planting zone generally older than other plantings (Table 1). A direct comparison between planting zone regeneration rates is therefore difficult, since we know planting age also significantly impacts seedling regeneration. It is more likely that older plantings will have more regeneration (Fig. 5F), as we can see in the 'Waterlogged' planting zones, which were also planted early on (Fig. 6). It's difficult to tell how much of an impact planting zone type has on regeneration. However, it is likely that with more maturation time and distribution of plots more evenly across

the planting zone types, further analysis could be useful in understanding impact of planting zone type on native seedling regeneration.

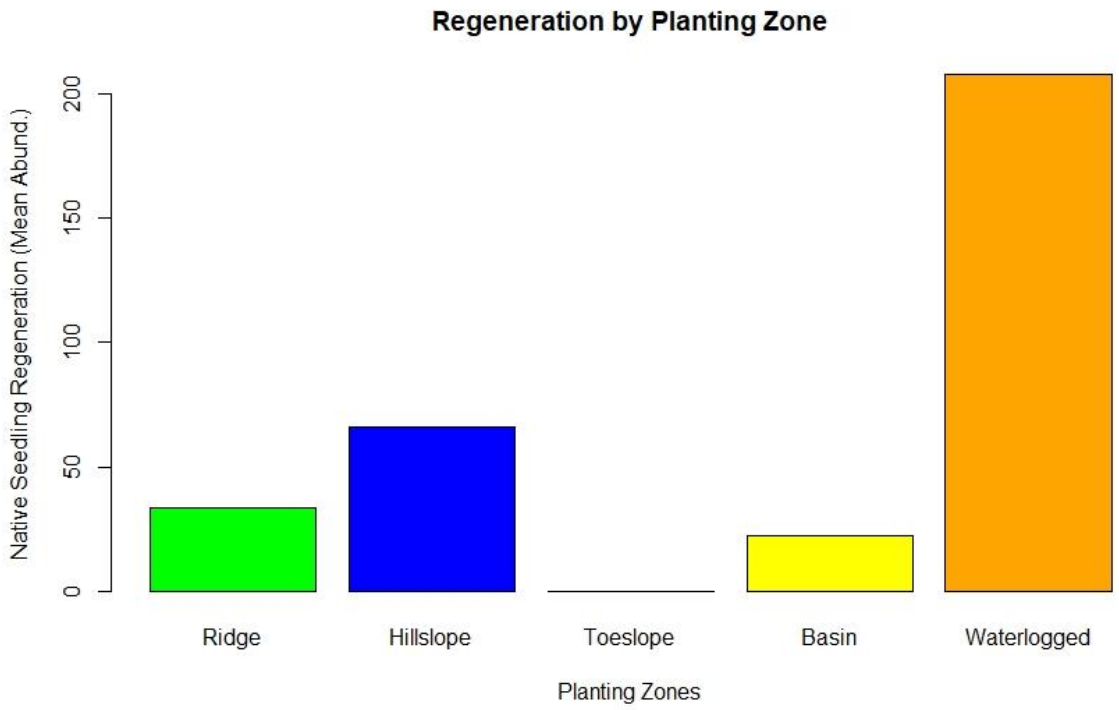


Figure 6. Impact of Planting Zone Type (highest to lowest altitude: 'Ridge', 'Hillslope', 'Toeslope', 'Basin', 'Waterlogged') on native tree seedling regeneration. Note that plantings in the plots in 'Waterlogged' planting zones are typically older, as planting started around the lake and then spread into the surrounding hills over the years. Also note that plot sample sizes for the different planting zone types vary widely (e.g., 'Waterlogged' had 7 plots, 'Toeslope' had 2 plots). Full information about Planting Age, Planting Zone Type, and number in of plots in each Planting Zone Type can be found in Table 1.

Saplings

Native tree saplings are present throughout most plots at WNHP, however there is no statistical relationship between sapling abundance and the age of the planting, so no figure of these data is shown. Sapling presence is good news, however, and the lack of a clear relationship with forest age may likely be due to the source of the saplings – many will be planted enrichment individuals, not just recruitments from the seedling growth stage. Additionally, saplings often do not require the same sheltered, older forest conditions as seedlings, and can therefore be found in a range of forest developmental stages or canopy openness conditions.

Native saplings had the highest abundance in plot 10 (11 years old; 84 saplings), followed by plot 11 (11 years old; 61 saplings) and plot 20 (13 years old; 61 saplings). Very few non-native saplings were present in plots (across all ages maximum abundance across all plots was three saplings). This may reflect invasion pressure (i.e., non-native seed rain), but also could be due to management regimes at WNHP whereby non-native saplings are removed.

Epiphytes
Four individual specimens of native epiphytes (plants that grow on trees) were detected during the 2018 round of monitoring. They were all the same species, *Pyrrosia elaeagnifolia* (leather-leaf fern). Three of these individuals were found in plot eight (plot age: 11 years old) and another was found in plot one (plot age: 14 years old). Although these are small numbers, these spontaneous colonisations of a more specialised, delicate suite of plants (epiphytes) is a good indication that forest conditions are developing along a successful trajectory. Leather leaf fern is known to be one of the earliest epiphytic colonisers during forest succession, followed by the orchid *Earina mucronata*.

Discussion

Canopy Changes

Canopy development is an important indicator of forest maturation and a signal for what forest restoration management is next required. Planted forest plots at Waiwhakareke Natural Heritage Park display a clear increase in tree size (i.e., basal area) and canopy cover with forest age. The larger trees cause canopy closure within the older plantings, and subsequently have many benefits for WNHP, including enhancing nutrient cycling, improving environmental conditions for further seedling establishment, and increasing habitat for a larger variety of native fauna. As trees mature, they are able to host more diverse and abundant invertebrate communities, produce more fruit and nectar resources, and develop robust architectures for perching and nesting by native birds and colonisation by epiphytes. The variety of foraging opportunities and the diversity of microhabitats will be crucial for encouraging bird breeding in these areas undergoing restoration.

The time after initial planting until majority canopy closure is about 10 years, so until then we recommend regular, carefully targeted weed control so that native regeneration is not collateral damage. This time until canopy closure could be shortened slightly by ensuring initial plantings are very dense (one plant per m^2) and tall (>1 m tall). The expense at the outset for this denser, taller planting approach is higher, but will result in fewer plant deaths from pasture weed competition (which necessitate added expense of infill plantings) and fewer years paying for weed control. So overall, dense, tall initial plantings are more economical and have better ecological outcomes. At the 10-year mark post-planting, canopy closure should be evaluated and if at least 70% closed, weed control efforts can be reduced hugely (especially spraying, which can curtail spontaneous seedling regeneration of desirable natives), and enrichment planting of late-successional species should begin.

Groundcovers

As the canopy closes, the area of the forest floor covered by herbaceous plant species diminishes. A closed canopy severely limits light availability on the forest floor, which inhibits the growth of weedy, herbaceous (light-demanding plants) species. Therefore,

encouraging canopy closure is important for reducing competitive pressure on spontaneously regenerating and planted native juvenile plants. As the adult trees mature and drop old foliage and branches, we found that herbaceous weed cover gives way to a forest floor covered in leaf litter and coarse woody debris. The presence of leaf litter is beneficial for forests, as deep layers of leaf litter will accommodate germinating seedlings. Building the litter layer ultimately boosts soil organic material, a primary requirement in forests. Overall, after the forest reaches the first decade since planting, minimal investment will be needed for controlling non-native herbaceous weed species because their presence and competitive pressure on native seedlings is drastically reduced through canopy closure.

As a complex forest structure develops, microclimate conditions such as humidity and temperature stabilize, which contribute to changes in what groundcover is present. For example, the increase in tree size (basal area), and subsequent decrease in canopy openness, blocks sunlight, reduces fluctuations in air temperature, and generates a cool, moist microclimate. At WNHP, the presence of moss at 7 years after planting (Table 2) is an indicator of these newly-developing conditions created by forest development . Similarly, fern presence is an ecological indicator of change in microclimate (becoming sheltered, stable, moist & cool), and our observations of increased fern cover signals that the continual closure of the canopy is changing the understorey microclimate. These conditions should assist the spread of ferns as the forest continues to age, and ferns usually self-introduce due to their wind-dispersed spores. Moss and fern presence is another signal to say the forest is developing properly, and management can now shift to a focus on enrichment planting of other late successional species that need the new microclimate conditions but can't self-introduce over large distances due to lack of seed sources in the urban environment.

Tree deaths

In typical forest successional dynamics, tree species turnover will occur with time, with early successional species giving way to mid and late successional species. At WNHP, this process should be expected to occur, and will become evident as the early successional species (e.g., *Leptosperum scoparium* mānuka, *Aristotelia serrata* makomako) begin to self-thin, die out, as they are being replaced by long-lived mid-late successional species (e.g. *Laurelia novae-zealandia*, pukatea, *Piper excelsum* kawakawa). Adult tree deaths should therefore be seen as a valuable part of the restoration process, and a signal that the forest is developing as expected. In more rural or wild forests, there is often successful late-successional seed introduction and germination through bird and wind dispersal from nearby forests at this point. However, in urban contexts, introduction of mid and late successional species through enrichment planting must typically be done by people because urban forests are much more isolated from natural seed sources and urban bird movement (and species type) is reduced. Enrichment planting should be done in a timely fashion (at WNHP by year ten) to take up canopy gaps caused by dying and dead early successional trees as soon as possible. In urban contexts, pioneer tree species often seem to die sooner than in rural areas, so enrichment planting plans must be in place early.

The fallen dead trees, or coarse woody debris, is also important for avifaunal recolonization at restored sites as it can provide shelter for ground foraging birds, a

degree of protection against avian predators (e.g. Australasian harrier, kāhu, *Circus approximans*, or New Zealand falcon, kārearea, *Falco novaeseelandiae*) and increases invertebrate (e.g., insects, worms) abundance and diversity, which increases food resources for birds. Dead trees also form "nurse logs" which shelter very young tree seedlings and can therefore bolster regeneration.

Plant Regeneration

Tree Seedlings

Canopy closure is a key for creating forest understorey conditions suitable for native tree seedling regeneration. These fundamental changes in the understory environment are evident in the older plots at WNHP, where the greater density and species number of regenerating seedlings are surviving. The abundance of small seedlings is higher in plots without herbaceous ground cover, most likely due to the lack of competitive pressure for resources. Non-native tree seedling abundance was low across plots of all ages, indicating that the forest is forming in a manner that promotes resilience to invasion by non-native invasive plant species. This likely reflects a dominance of native trees in the surrounding landscape (possibly from reproductively-mature planted trees elsewhere in WNHP), causing native seed rain to be many times greater than non-native seed rain into the plots. Low numbers of non-native tree seedlings may also be attributed to good weed management practices at WNHP, such as removal of reproductively mature non-native tree seed sources through selective control.

Saplings

Mid and late successional seedlings and saplings have different light requirements and tolerances to understorey microclimates. While a closed canopy promotes conditions that have a positive effect on seedlings, this effect breaks down once seedlings grow into saplings. These larger plants have greater light demands, and are more tolerant of environmental stresses such as large swings in temperature (due to their larger carbon and water reserves). Saplings are therefore typically tolerant of a wider range of forest conditions and do not rely on the protected conditions that forests of an older age can provide (e.g., canopy cover; wind, heat and dryness protection). Implications for management here are that saplings (plants taller than 1.35m) can be planted in younger, more open forests than seedlings are seen to be regenerating and surviving in. Additionally, in the opposite cases of extremely closed, sheltered forests, in order to accelerate forest maturation and encourage enrichment sapling growth, some canopy thinning or very small canopy gaps can be made to encourage late-successional plantings to grow up into the canopy. This should only be done conservatively however, as light infiltration caused by canopy gaps will also encourage herbaceous weed growth.

Epiphytes

The presence of spontaneously-colonising epiphytes at WNHP can be seen as a definite positive indicator of forest development. Typically, obligate epiphytes (i.e., they must grow on trees) do not colonise until forests are at least 20 years old because these epiphytes are sensitive, needing stable microclimate conditions and large trees to grow on so their roots do not desiccate. Although the leather-leaf fern (found within four plots at WNHP) is not an obligate epiphyte, its presence indicates that conditions within the older restored plots are becoming increasingly suitable for other species of more specialised epiphytes to colonise. However, similar to other species that are planted as

enrichment species because seed dispersal from elsewhere is limited, epiphytes may need to be actively introduced to WNHP once conditions are suitable.

Conclusion & Recommendations

The current forest structure at Waiwhakareke Natural Heritage Park is generally heading along a trajectory of successful restoration. Monitoring from 2018 at WNHP indicates that plantings are showing important signals of forest development including: (1) increase in basal area and reduced canopy openness, (2) decrease of non-native herbaceous cover, (3) appearance of tree deaths and movement towards the next stage of succession and (4) development of microclimatic conditions that are promoting mid and late successional native seedling regeneration.

Implications for managers

- A long-term perspective is important in planning WNHP forest reconstruction, with important additional steps required to facilitate forest development after the first step of pioneer planting occurs.

- Monitoring is necessary to determine whether forest development is on track. Continue to use this long-term chronosequence plot network as a method for monitoring forest restoration so that the restoration of vegetation can be compared through time and best management practises refined for further management. We recommend budgeting $15K to contract monitoring and a report every 3-4 years to capture important ecological changes. One or two new plots should be added to the network each round of monitoring, to continue building the chronosequence by including newly planted areas. With new plots added, the monitoring effort and budget will also need to increase proportionally.

- Maintain layers of leaf litter, coarse woody debris and dead trees as habitat for invertebrates and birds and to encourage more desirable seedling germination. Allowing tree fall to remain *in situ* will be extremely beneficial for encouraging forest flora and fauna establishment at Waiwhakareke Natural Heritage Park.

- Do not spray for weeds in areas where canopy is sufficiently closed (i.e., generally 10 years after planting), as the sun-loving weed cover will be naturally lower in these shaded areas and desirable regenerating native seedlings need to be protected (i.e., not sprayed).

- Once canopy closure has reached at least 70% (at WNHP, this appears to be around 10 years old), enrichment planting of mid and late successional species should be done to secure earlier planting investment and ensure forest ecosystem maturation. Enrichment planting should always be prioritized over planting completely new areas of early successional species because without

establishing enrichment species the pioneer species will die back and forest development will cease, and initial planting investment is wasted.

- Once these reconstructed forests host an understory with established native juvenile trees, practitioners should evaluate whether light is sufficient for continued growth, and consider strategic canopy thinning through removal of branches if not.

- Enrichment planting should be done using a wide variety of species and plant suites (i.e., as many as possible as listed in the WNHP planting tool, and including trees, shrubs, vines etc.). A large array of plant species are required to form a fully-functioning forest ecosystem that can support a wide array of fauna and be resilient to weed invasion.

References

Alberti, M. (2005). *The effects of urban patterns on ecosystem function.* International Regional Science Review **28**(2): 168-192.

Aronson, M. F. J., La Sorte, F. A., Nilon, C. H., Katti, M., Goddard, M. A., Lepczyk, C. A., Warren, P. S., Williams, N. S. G., Cilliers, S., Clarkson, B. D., et al. (2014). *A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers*. Proceedings of the Royal Society B: Biological Sciences 281(1780): 20133330.

Brown G., Schebella M. F. , Weber D. (2014). *Using participatory GIS to measure physical activity and urban park benefits.* Landscape and Urban Planning. 121:34-44.

CBER (2011). *Waiwhakareke Natural Heritage Park Operative Management Plan*. Hamilton, New Zealand, The University of Waikato, Centre for Biodiversity and Ecology Research.

Clarkson B. D., Wehi P. M., Brabyn L. K. (2007). *A spatial analysis of indigenous cover patterns and implications for ecological restoration in urban centres, New Zealand.* Urban Ecosystems. 10(4):441-457.

Clarkson, B. D. and C. L. Kirby (2016). *Ecological restoration in urban environments in New Zealand.* Ecological Management & Restoration **17**(3): 180-190.

Cornes, T., Kramer-Walter, K., & Clarkson, B. D. (2011). *Waiwhakareke Restoration Plantings: Re-measurement of Monitoring Plots 2009.* The University of Waikato, Centre for Biodiversity and Ecology Research. 19p.

Cornes, T., Wehi, P. M., & Clarkson, B. D. (2008). *Waiwhakareke Restoration Plantings: Re-measurement of Monitoring Plots 2007/08.* The University of Waikato, Centre for Biodiversity and Ecology Research. 14p.

Dobbs, C., Escobedo, F. J., and Zipperer, W. C. (2011). *A framework for developing urban forest ecosystem services and goods indicators*. Landscape and Urban Planning 99(3–4): 196-206.

Drinnan, I. N. (2005). *The search for fragmentation thresholds in a Southern Sydney Suburb. Biological Conservation.* 124: 339-349.

Endreny, T., Santagata, R., Perna, A., Stefano, C. D., Rallo, R. F., Ulgiati, S. (2017). Implementing and managing urban forests: A much needed conservation strategy to increase ecosystem services and urban wellbeing. Ecological Modelling 360: 328-335.

Groffman, P. M., et al. (2016). *Moving Towards a New Urban Systems Science.* Ecosystems 20(1): 38-43.

Hall, M.M. (2020). *Enrichment planting of late-successional plant species within restored urban forests*. University of Waikato, Hamilton, New Zealand. MSc Thesis. 79 pp.

La Sorte, F. A., et al. (2014). *Beta diversity of urban floras among European and non-European cities.* Global Ecology and Biogeography 23(7): 769-779.

Miller, B. P., Sinclair, E. A., Menz, M. H. M., Elliott, C. P., Bunn, E., Commander, L. E., Dalziell, E., David, E., Davis, B., Erickson, T. E. et al. (2016). *A framework for the practical science necessary to restore sustainable, resilient, and biodiverse ecosystems.* Restoration Ecology. 25(4):605-617.

Nepia, R., & Drage, P. (2019). *Waiwhakareke Natural Heritage Park 2019 ground truthing.* School of Science, The University of Waikato, Environmental Research Institute. 26p.

Oksanen, J *et al*. (2019). vegan: *Community Ecology Package*. R package version 2.5-6. https://CRAN.R-project.org/package=vegan

Oldfield, E.E., Felson A. J., Auyeung D.S.N., Crowther T.W., Sonti N.F., Harada Y., Maynard D.S., Sokol N.W., Ashton M.S., Warren R.J. et al. (2015). *Growing the urban forest: tree performance in response to biotic and abiotic land management.* Restoration Ecology. 23(5):707-718.

R Core Team. (2017). *R: A language and environment for statistical computing*. https://www.R-project.org/.

Samuel, C. Z., Jason, S., Aditya, S., Christopher, J. K., Philip, A. T., Steven, P. L. II, (2016). *Urban heat island impacts on plant phenology: intra-urban variability and response to land cover.* Environmental Research Letters. 11(5):054023.

Threlfall, C. G., Williams, N. S. G., Hahs, A. K., Livesley, S. J. (2016). *Approaches to urban vegetation management and the impacts on urban bird and bat assemblages.* Landscape and Urban Planning 153: 28-39.

Trammell, T. L., Ralston, H. A., Scroggins, S. A., Carreiro, M. M. (2012). *Foliar production and decomposition rates in urban forests invaded by the exotic invasive shrub,* Lonicera maackii*.* Biological Invasions **14**(3): 529-545.

Wallace, K. J. and Clarkson, B. D. (2019). *Urban forest restoration ecology: a review from Hamilton, New Zealand. Journal of the Royal Society of New Zealand*, 49(3): 347-369.

Wallace, K. J., Laughlin, Daniel C. and Clarkson, B. D. (2017). *Exotic weeds and fluctuating microclimate can constrain native plant regeneration in urban forest restoration.* Ecological Applications 27(4): 1268-1279.

Appendix 1: Permanent plot setup protocol

WAIWHAKAREKE NATURAL HERITAGE PARK

PERMANENT PLOT SET-UP PROTOCOL

APRIL 2018

Kiri Joy Wallace

Plots are 10m x 10m, see plot schematic below. Plot placement guidelines:

A) should be as far from forest edge/paths/fences as feasible, minimum 1 m
B) cannot contain streams or seepages, and should run parallel to any that are present
C) is accessible/safe for regular surveys
D) is as flat as possible to avoid understorey damage from surveyors and soil instability

PLOT PERIMETER LINES

1. If the restored planted area is large, plot orientation should be random. Use a random number generator app (set to min 1 m, max 10 m), stand on one "corner" of restored planted area and generate pair of random numbers (one for distance in from edge, and one for distance over).

2. **FIRST LINE:** Run a 10m tape line from the chosen starting position. Use red and white tape holders as temporary corners. Starting at 0 meters, this first tape is run along a random compass bearing (e.g. 15 °) to the 10 meter mark to achieve straightest line possible.

3. **SECOND LINE:** The next 10 metre line then follows after a right angle (90 degree) turn, using both compass bearings and the Pythagoras theorem to ensure the corner between first and second line is an accurate 90 degree right angle from previous line. If the first line's compass bearing was 15 degrees, the next line should be along 285 degrees.

   The "3-4-5 triangle" is a math tool used to assist accuracy in setting out right angles (see schematic). The Pythagoras' theorem tells us that the squares of the sides of a right triangle sum to give to the square of the hypotenuse (the longest side of the right-angle triangle): $3^2 + 4^2 = 5^2$. To check corners, use a second tape to measure corner accuracy using Pythagoras theorem (see schematic on final page).

4. **THIRD & FOURTH LINE:** continue repeating steps 2-3 such that the tape ends meet to form square with sides totalling to 40 meters. The total should be within 30cm of 40 meters on flat terrain, or 60cm on a slope. It can be difficult on sites with a topography that is terraced/steep/undulant, however, be as accurate as possible while also considering fieldwork time restraints.

PLACING WARATAHS AND METAL NUMBER TAGS WITH COMPASS BEARINGS

5. Place a waratah into the ground in each corner (use rammer and ear muffs). Cable tie a yellow safety cap on top.

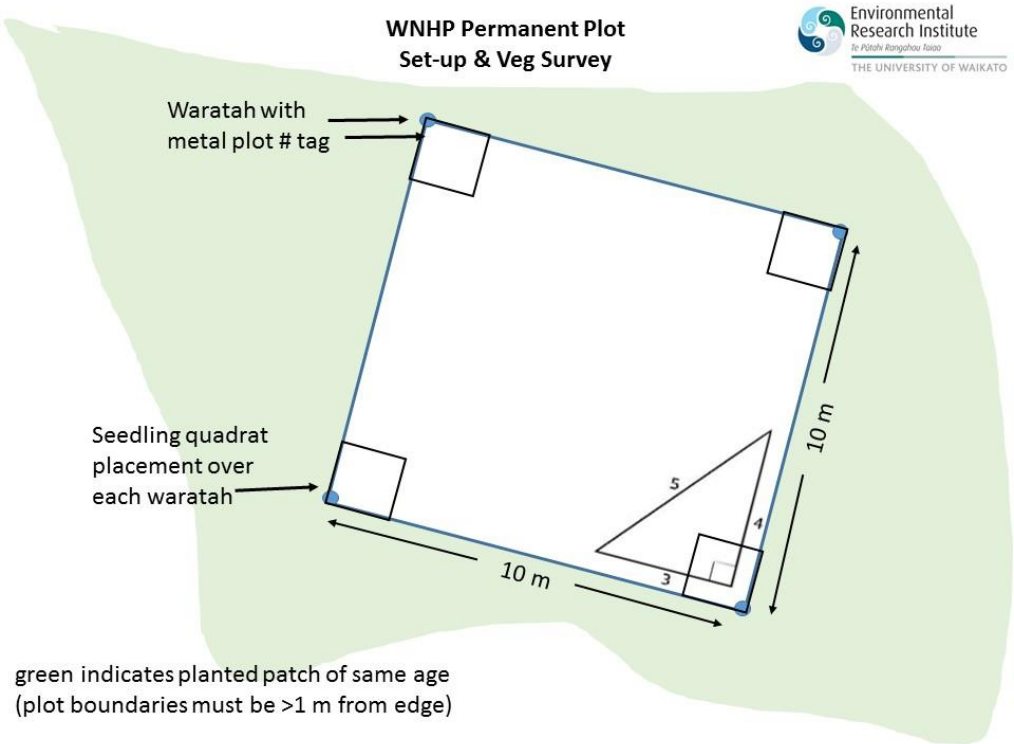
6. Measure compass bearings from each waratah to the next one, moving in a counterclockwise fashion. For each waratah, scratch the bearing (e.g. " 15° ") to the next waratah onto the back of the metal tag that already has the unique plot ID number on it (e.g. plot #1 has metal tags at corners that have a 1 on them, each with bearings to the next waratah. You can use a sharp nail tip. Only three of the waratahs get metal tags (any three), each tag with the unique compass bearing to the next waratah in the plot).

7. Attach the metal plot number tag with the scratched-on compass bearing to a top hole of the waratah with a cable tie.

TAKE GPS COORDINATES

8. Use a handheld GPS-capable device to take the latitude and longitude of the plot. Do this in the centre of the plot.

9. Add GPS coordinates and all other data about plot ID number and type into the master plot list in the Google Team Drive "Waiwhakareke Central Repository"



Appendix 2: Vegetation Survey Protocol & Gear List

WAIWHAKAREKE NATURAL HERITAGE PARK

VEGETATION MONITORING PROTOCOL

APRIL 2018

Kiri Joy Wallace

For all plant records use species six letter codes in lowercase with no spaces.
Follow National Vegetation Survey naming conventions.

Before survey begins, run bright-coloured string/rope around all corner waratahs and across plot to divide into quarters.

I. GROUND COVER – Entire Plot

1. Assessed from a bird's eye view, estimate proportion (% cover) for five ground cover types:
   herbaceous, leaf litter/detritus, bare ground, moss, ferns
   Herbaceous species may be tall (e.g. arum lily, flax), as long as they're not woody.
2. The summed % cover across all categories must equal 100%.

II. DEAD TREES – Entire Plot

3. Tally all dead woody plants, any species, nativity or size. They are dead if there is no visible live foliage. Can be upright or prostrate. Must be rooted in plot, and a root base clearly evident if prostrate, to ensure they are not just fallen branches.

III. SEEDLINGS – Four Quadrats per Plot

4. Seedlings are classified as all individual woody plants that have at least one true leaf and are <1.35m (DBH) tall. Seedlings are tallied by species.
5. Place quadrat over/around waratah and position so waratah is nestled in outside corner of quadrat (see schematic on final page). Species tally is cumulative over the four quadrats.
6. Seedlings with multiple stems growing from a visible singular root/ base above ground are counted as a single plant. Seedlings with multiple stems that separate below ground are counted as separate plants.
7. If seedling stems are leaning or bent over, the stem is measured to its highest point in its 'natural' position (e.g. stems are not pulled upwards along the measuring stick).

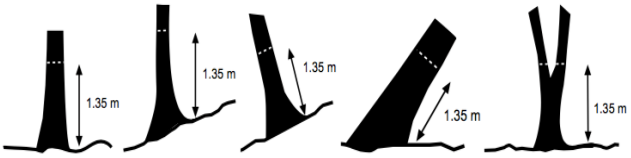
IV. SAPLINGS – Entire Plot

8. Saplings are defined as plants taller than >1.35m, but thinner than <2.5cm DBH and tallied by species. Woody vines are not included.

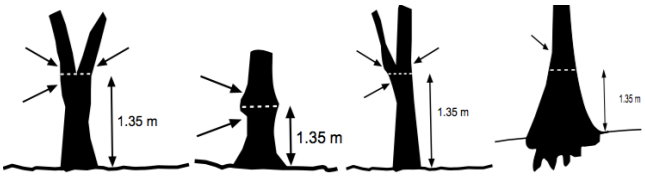
9. If a sapling is on sloping ground, plant height is measured on the uphill side of the plant. If the stems are on a lean or bent over, the stem height is measured at its highest point in its 'natural' position (stems are not pulled upwards along the measuring stick).
10. Saplings with multiple stems/main branches growing from a visible singular root/ base are classified as one stem. Saplings with multiple stems/main branches growing but may be joined below ground level are counted as separate stems. Epicormic stems on larger tree trunks are NOT counted as saplings.
11. Once a sapling is tallied, mark at DBH with brightly-coloured chalk pen.

V. TREES – Entire Plot

12. Record species and DBH of all woody plants (e.g. trees and tree ferns) with stems >2.5cm DBH.
13. Multi-stemmed trees must have at least one stem > 2.5 cm at DBH to be included in the survey, and all other stems on that tree >2.5 cm DBH must then also be measured. Woody vines are not included.
14. If trees are on sloping ground, DBH is measured on the uphill side.
15. If the tree splits into two or more stems below the 1.35m mark that are >2.5 cm DBH, each stem DBH is measured separately. Record these stems in the spreadsheet with sequential numbering (e.g. "stem1", "stem2", etc).
16. If trees are on a lean, measure 1.35 m along stem and take DBH (see figure below).
17. Once a stem is measured, mark at DBH with brightly-coloured chalk pen



Leaning and multi-stemmed trees. Measure DBH at 1.35 along stem



Measure the closest possible position above or below 1.35 if stem at that point is deformed or irregular.

VI. EPIPHYTES – Entire Plot

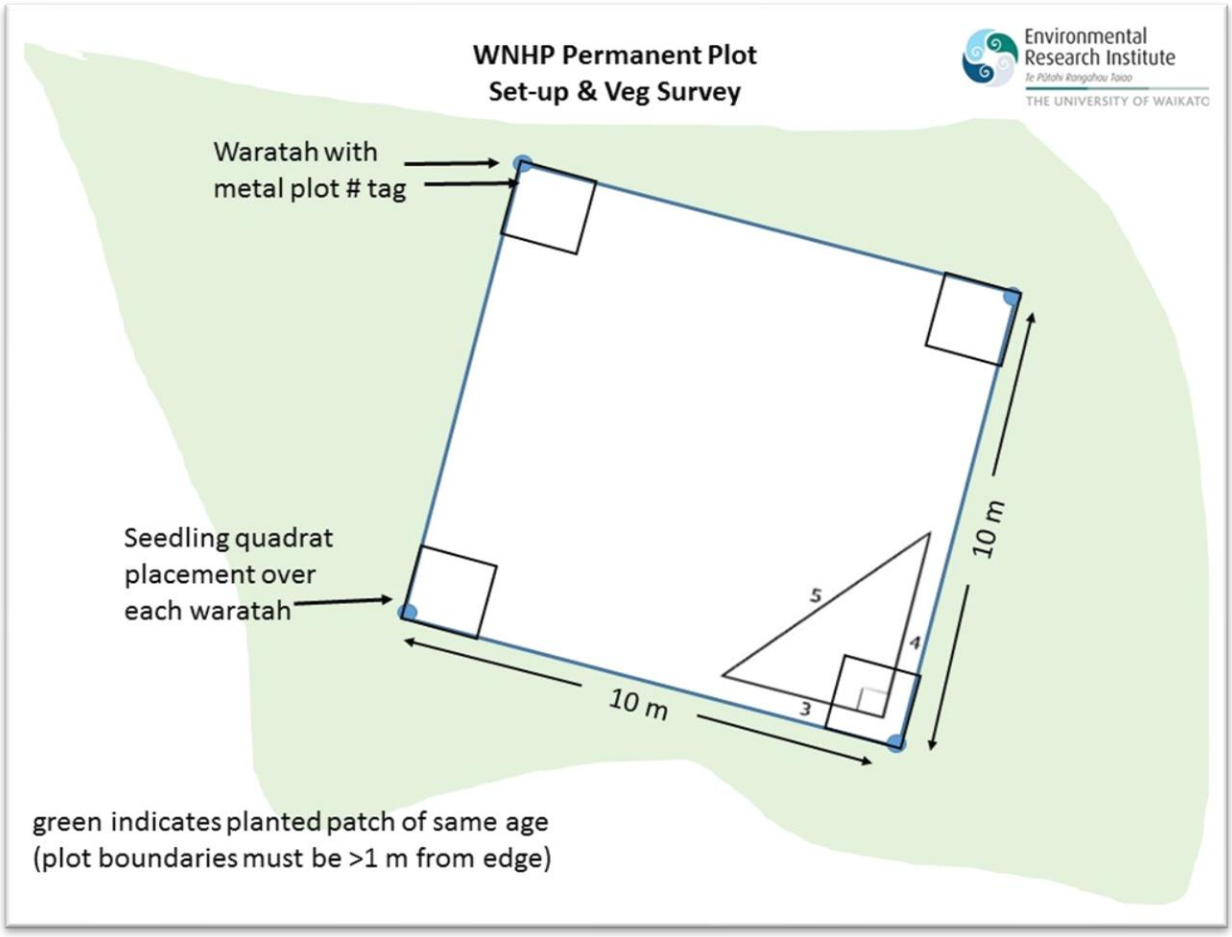
18. Tally and ID all epiphytes on living trees that are > 2.5cm DBH and rooted within the plot. The tally occurs by how many trees each species occupies (e.g. a tree will be tallied as one regardless of having 1 or 5 plants of a single epiphyte species on it).
19. An epiphyte is any vascular plant growing entirely or partially on a tree. It counts even if the epiphyte itself is rooted in the ground (e.g. *Griselinia lucida*, with a root sent down the trunk to the ground would still be an epiphyte).

UNKNOWN SPECIES

All plants that are not identifiable on the day from surveyor knowledge or aids (e.g., Seek App or reference books) are recorded on the data sheet as 'unk' with a description added in the notes column (e.g. leaves entire or serrated, single or compound?). Number the unks consecutively ('unk1', 'unk2', 'unk3') for each plot. When possible, take photos for later identification via posting on iNaturalist or by colleagues, along with the plot number of the unknown species.

VII. LIGHT TRANSMITTANCE MEASUREMENT

Use a densiometer to measure canopy cover, taking a reading inside each plot corner. Stand 1 m from corner and face out of the plot. Follow instructions on the densiometer lid EXCEPT only one measurement needs to be taken at each corner, NOT four.



Appendix 3: Plant Species list

Species scientific name	Species common name (Māori/English)	Plot #	Forest age (years)	Plant growth stage (Adult, Sapling, Seedling)
Alectryon excelsus	titoki, New Zealand ash	1	14	Seedling
Aristotelia serrata	makomako, wineberry	1	14	Seedling
Berberis glaucocarpa	barberry	1	14	Seedling
Coprosma robusta	karamu, glossy karamu	1	14	Seedling
Coprosma tenuicaulis	hukihuki, swamp coprosma	1	14	Sapling
Coprosma tenuicaulis	hukihuki, swamp coprosma	1	14	Seedling
Cordyline australis	ti kouka, cabbage tree	1	14	Adult
Cordyline australis	ti kouka, cabbage tree	1	14	Sapling
Cordyline australis	ti kouka, cabbage tree	1	14	Seedling
Dacrydium cupressinum	rimu, red pine	1	14	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	1	14	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	1	14	Seedling
Laurelia novae-zelandiae	pukatea	1	14	Adult
Leptospermum scoparium	manuka	1	14	Adult
Leptospermum scoparium	manuka	1	14	Seedling
Melicytus ramiflorus	mahoe, whitey wood	1	14	Seedling
Myrsine australis	mapau, red matipo	1	14	Seedling
Rubus fruticosus	blackberry	1	14	Seedling
Solanum aviculare	poroporo	1	14	Sapling
Coprosma autumnalis	kanono	2	13	Seedling
Coprosma robusta	karamu, glossy karamu	2	13	Adult
Coprosma robusta	karamu, glossy karamu	2	13	Seedling
Coprosma tenuicaulis	hukihuki, swamp coprosma	2	13	Seedling
Coprosma tenuicaulis	hukihuki, swamp coprosma	2	13	Seedling
Cordyline australis	ti kouka, cabbage tree	2	13	Adult
Cordyline australis	ti kouka, cabbage tree	2	13	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	2	13	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	2	13	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	2	13	Seedling
Fuchsia excorticata	kotukutuku, tree fuschia	2	13	Seedling
Leptospermum scoparium	manuka	2	13	Adult
Melicytus ramiflorus	mahoe, whitey wood	2	13	Seedling
Pittosporum tenuifolium	kohukohu, black matipo	2	13	Seedling
Aristotelia serrata	makomako, wineberry	3	13	Sapling
Aristotelia serrata	makomako, wineberry	3	13	Seedling
Coprosma lucida	karamu, shining karamu	3	13	Sapling
Coprosma tenuicaulis	hukihuki, swamp coprosma	3	13	Seedling
Cordyline australis	ti kouka, cabbage tree	3	13	Sapling
Cordyline australis	ti kouka, cabbage tree	3	13	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	3	13	Adult

Dacrycarpus dacrydioides	kahikatea, white pine	3	13	Seedling
Dicksonia squarrosa	wheki, rough tree fern	3	13	Adult
Dicksonia squarrosa	wheki, rough tree fern	3	13	Sapling
Laurelia novae-zelandiae	pukatea	3	13	Sapling
Leptospermum scoparium	manuka	3	13	Adult
Melicytus ramiflorus	mahoe, whitey wood	3	13	Sapling
Melicytus ramiflorus	mahoe, whitey wood	3	13	Seedling
Myrsine australis	mapau, red matipo	3	13	Seedling
Coprosma robusta	karamu, glossy karamu	4	13	Seedling
Coprosma tenuicaulis	hukihuki, swamp coprosma	4	13	Sapling
Cordyline australis	ti kouka, cabbage tree	4	13	Adult
Dacrydium cupressinum	rimu, red pine	4	13	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	4	13	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	4	13	Sapling
Laurelia novae-zelandiae	pukatea	4	13	Adult
Leptospermum scoparium	manuka	4	13	Adult
Leptospermum scoparium	manuka	4	13	Seedling
Coprosma robusta	karamu, glossy karamu	5	12	Sapling
Coprosma robusta	karamu, glossy karamu	5	12	Seedling
Cordyline australis	ti kouka, cabbage tree	5	12	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	5	12	Adult
Leptospermum scoparium	manuka	5	12	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	6	11	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	6	11	Sapling
Cordyline australis	ti kouka, cabbage tree	6	11	Adult
Cyathea dealbata	ponga, silver fern	6	11	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	6	11	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	6	11	Sapling
Leptospermum scoparium	manuka	6	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	6	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	6	11	Sapling
Coprosma robusta	karamu, glossy karamu	7	11	Seedling
Cordyline australis	ti kouka, cabbage tree	7	11	Adult
Cyathea medullaris	mamaku, black tree fern	7	11	Sapling
Hedycarya arborea	porokaiwhiri, pigeonwood	7	11	Sapling
Leptospermum scoparium	manuka	7	11	Adult
Leptospermum scoparium	manuka	7	11	Sapling
Coprosma propinqua	mingimingi	8	11	Sapling
Coprosma rigida	No common name	8	11	Adult
Coprosma rigida	No common name	8	11	Sapling
Coprosma robusta	karamu, glossy karamu	8	11	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	8	11	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	8	11	Sapling
Cyathea dealbata	ponga, gully tree fern	8	11	Seedling
Cyathea dealbata	ponga, silver fern	8	11	Sapling

Hedycarya arborea	porokaiwhiri, pigeonwood	8	11	Sapling
Laurelia novae-zelandiae	pukatea	8	11	Sapling
Leptospermum scoparium	manuka	8	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	8	11	Sapling
Pseudopanax hybrid	No common name	8	11	Seedling
Coprosma areolata	thin-leaved coprosma	9	11	Sapling
Coprosma tenuicaulis	hukihuki, swamp coprosma	9	11	Seedling
Cordyline australis	ti kouka, cabbage tree	9	11	Adult
Cordyline australis	ti kouka, cabbage tree	9	11	Sapling
Cordyline australis	ti kouka, cabbage tree	9	11	Seedling
Cyathea dealbata	ponga, silver fern	9	11	Sapling
Cyathea dealbata	ponga, silver fern	9	11	Seedling
Dicksonia squarrosa	wheki, rough tree fern	9	11	Sapling
Leptospermum scoparium	manuka	9	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	9	11	Sapling
Alectryon excelsus	titoki, New Zealand ash	10	11	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	10	11	Seedling
Cordyline australis	ti kouka, cabbage tree	10	11	Sapling
Cordyline australis	ti kouka, cabbage tree	10	11	Seedling
Hedycarya arborea	porokaiwhiri, pigeonwood	10	11	Sapling
Hedera helix	ivy	10	11	Seedling
Hoheria sexstylosa	houhere, lacebark	10	11	Adult
Hoheria sexstylosa	houhere, lacebark	10	11	Sapling
Hoheria sexstylosa	houhere, lacebark	10	11	Seedling
Kunzea robusta	rawirinui, kanuka	10	11	Adult
Kunzea robusta	rawirinui, kanuka	10	11	Sapling
Ligustrum sinense	Chinese privet	10	11	Seedling
Melicytus ramiflorus	mahoe, whitey wood	10	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	10	11	Sapling
Melicytus ramiflorus	mahoe, whitey wood	10	11	Seedling
Myrsine australis	mapau, red matipo	10	11	Adult
Myrsine australis	mapau, red matipo	10	11	Sapling
Pennantia corymbosa	kaikomako	10	11	Sapling
Pittosporum tenuifolium	kohukohu, black matipo	10	11	Adult
Pseudopanax arboreus	whauwhaupaku, five finger	10	11	Sapling
Pseudopanax arboreus	whauwhaupaku, five finger	10	11	Seedling
Pseudopanax hybrid	No common name	10	11	Seedling
Alectryon excelsus	titoki, New Zealand ash	11	11	Adult
Coprosma robusta	karamu, glossy karamu	11	11	Adult
Cordyline australis	ti kouka, cabbage tree	11	11	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	11	11	Adult
Hoheria sexstylosa	houhere, lacebark	11	11	Adult
Ligustrum sinense	Chinese privet	11	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	11	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	11	11	Adult

Melicytus ramiflorus	mahoe, whitey wood	11	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	11	11	Seedling
Myrsine australis	mapau, red matipo	11	11	Adult
Myrsine australis	mapau, red matipo	11	11	Adult
Myrsine australis	mapau, red matipo	11	11	Sapling
Pittosporum tenuifolium	kohukohu, black matipo	11	11	Adult
Kunzea robusta	rawirinui, kanuka	12	11	Adult
Leptospermum scoparium	manuka	12	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	12	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	12	11	Sapling
Melicytus ramiflorus	mahoe, whitey wood	12	11	Seedling
Myrsine australis	mapau, red matipo	12	11	Seedling
Pittosporum tenuifolium	kohukohu, black matipo	12	11	Adult
Alectryon excelsus	titoki, New Zealand ash	13	11	Adult
Alectryon excelsus	titoki, New Zealand ash	13	11	Sapling
Alectryon excelsus	titoki, New Zealand ash	13	11	Seedling
Coprosma robusta	karamu, glossy karamu	13	11	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	13	11	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	13	11	Sapling
Cordyline australis	ti kouka, cabbage tree	13	11	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	13	11	Seedling
Hoheria sexstylosa	houhere, lacebark	13	11	Seedling
Leptospermum scoparium	manuka	13	11	Adult
Ligustrum sinense	Chinese privet	13	11	Seedling
Melicytus ramiflorus	mahoe, whitey wood	13	11	Adult
Melicytus ramiflorus	mahoe, whitey wood	13	11	Sapling
Melicytus ramiflorus	mahoe, whitey wood	13	11	Seedling
Myrsine australis	mapau, red matipo	13	11	Sapling
Myrsine australis	mapau, red matipo	13	11	Seedling
Pittosporum tenuifolium	kohukohu, black matipo	13	11	Adult
Pittosporum tenuifolium	kohukohu, black matipo	13	11	Sapling
Carpodetus serratus	putaputaweta, marbleleaf	14	9	Sapling
Coprosma robusta	karamu, glossy karamu	14	9	Sapling
Coprosma robusta	karamu, glossy karamu	14	9	Seedling
Coprosma rotundifolia	No common name	14	9	Sapling
Coprosma tenuicaulis	hukihuki, swamp coprosma	14	9	Sapling
Coprosma tenuicaulis	hukihuki, swamp coprosma	14	9	Seedling
Cordyline australis	ti kouka, cabbage tree	14	9	Adult
Cordyline australis	ti kouka, cabbage tree	14	9	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	14	9	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	14	9	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	14	9	Seedling
Laurelia novae-zelandiae	pukatea	14	9	Sapling
Leptospermum scoparium	manuka	14	9	Adult
Melicytus ramiflorus	mahoe, whitey wood	14	9	Sapling

Melicytus ramiflorus	mahoe, whitey wood	14	9	Seedling
Pittosporum crassifolium	karo	14	9	Sapling
Pittosporum crassifolium	karo	14	9	Seedling
Alectryon excelsus	titoki, New Zealand ash	15	9	Sapling
Aristotelia serrata	makomako, wineberry	15	9	Adult
Berberis glaucocarpa	barberry	15	9	Seedling
Coprosma robusta	karamu, glossy karamu	15	9	Adult
Coprosma robusta	karamu, glossy karamu	15	9	Sapling
Coprosma robusta	karamu, glossy karamu	15	9	Seedling
Cordyline australis	ti kouka, cabbage tree	15	9	Adult
Cordyline australis	ti kouka, cabbage tree	15	9	Sapling
Crataegus monogyna	hawthorn	15	9	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	15	9	Seedling
Hoheria sexstylosa	houhere, lacebark	15	9	Adult
Kunzea robusta	rawirinui, kanuka	15	9	Adult
Leptospermum scoparium	manuka	15	9	Adult
Leptospermum scoparium	manuka	15	9	Sapling
Melicytus ramiflorus	mahoe, whitey wood	15	9	Adult
Melicytus ramiflorus	mahoe, whitey wood	15	9	Sapling
Melicytus ramiflorus	mahoe, whitey wood	15	9	Seedling
Myrsine australis	mapau, red matipo	15	9	Sapling
Nestegia lanceolata	white maire	15	9	Adult
Nestegia lanceolata	white maire	15	9	Sapling
Pittosporum crassifolium	karo	15	9	Seedling
Pittosporum tenuifolium	kohukohu, black matipo	15	9	Adult
Pittosporum tenuifolium	kohukohu, black matipo	15	9	Sapling
Pseudopanax arboreus	whauwhaupaku, five finger	15	9	Seedling
Veronica stricta	koromiko	15	9	Adult
Veronica stricta	koromiko	15	9	Adult
Veronica stricta	koromiko	15	9	Sapling
Coprosma robusta	karamu, glossy karamu	16	9	Adult
Coprosma robusta	karamu, glossy karamu	16	9	Sapling
Cordyline australis	ti kouka, cabbage tree	16	9	Adult
Cordyline australis	ti kouka, cabbage tree	16	9	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	16	9	Seedling
Knightia excelsa	rewarewa, NZ honeysuckle	16	9	Adult
Kunzea robusta	rawirinui, kanuka	16	9	Adult
Leptospermum scoparium	manuka	16	9	Adult
Leptospermum scoparium	manuka	16	9	Sapling
Melicytus ramiflorus	mahoe, whitey wood	16	9	Adult
Melicytus ramiflorus	mahoe, whitey wood	16	9	Sapling
Melicytus ramiflorus	mahoe, whitey wood	16	9	Seedling
Pittosporum tenuifolium	kohukohu, black matipo	16	9	Adult
Pittosporum tenuifolium	kohukohu, black matipo	16	9	Sapling
Rubus fruticosus	blackberry	16	9	Seedling

Veronica stricta	koromiko	16	9	Seedling
Agathis australis	kauri	17	10	Adult
Agathis australis	kauri	17	10	Sapling
Alectryon excelsus	titoki, New Zealand ash	17	10	Sapling
Beilschmiedia tawa	tawa	17	10	Seedling
Berberis glaucocarpa	barberry	17	10	Seedling
Coprosma propinqua	mingimingi	17	10	Seedling
Coprosma robusta	karamu, glossy karamu	17	10	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	17	10	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	17	10	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	17	10	Seedling
Hedycarya arborea	porokaiwhiri, pigeonwood	17	10	Sapling
Hedera helix	ivy	17	10	Seedling
Hoheria sexstylosa	houhere, lacebark	17	10	Sapling
Hoheria sexstylosa	houhere, lacebark	17	10	Seedling
Kunzea robusta	rawirinui, kanuka	17	10	Adult
Leptospermum scoparium	manuka	17	10	Adult
Leptospermum scoparium	manuka	17	10	Sapling
Ligustrum sinense	Chinese privet	17	10	Seedling
Melicytus ramiflorus	mahoe, whitey wood	17	10	Adult
Melicytus ramiflorus	mahoe, whitey wood	17	10	Sapling
Melicytus ramiflorus	mahoe, whitey wood	17	10	Seedling
Melicope simplex	poataniwha	17	10	Sapling
Melicope simplex	poataniwha	17	10	Seedling
Myrsine australis	mapau, red matipo	17	10	Sapling
Piper excelsum	kawakawa, pepper tree	17	10	Seedling
Pittosporum tenuifolium	kohukohu, black matipo	17	10	Adult
Prunus campanulata	Taiwan cherry	17	10	Seedling
Pseudopanax arboreus	whauwhaupaku, five finger	17	10	Seedling
Pseudopanax hybrid	No common name	17	10	Seedling
Pseudopanax laetus	No common name	17	10	Sapling
Coprosma robusta	karamu, glossy karamu	18	6	Adult
Coprosma robusta	karamu, glossy karamu	18	6	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	18	6	Sapling
Leptospermum scoparium	manuka	18	6	Adult
Coprosma robusta	karamu, glossy karamu	19	6	Seedling
Coprosma tenuicaulis	hukihuki, swamp coprosma	19	6	Saplings
Cordyline australis	ti kouka, cabbage tree	19	6	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	19	6	Saplings
Leptospermum scoparium	manuka	19	6	Adult
Aristotelia serrata	makomako, wineberry	20	13	Seedling
Carpodetus serratus	putaputaweta, marbleleaf	20	13	Seedling
Coprosma robusta	karamu, glossy karamu	20	13	Seedling
Coprosma species		20	13	Seedling
Coprosma sapthulata	No common name	20	13	Seedling

Coprosma tenuicaulis	hukihuki, swamp coprosma	20	13	Adult
Coprosma tenuicaulis	hukihuki, swamp coprosma	20	13	Sapling
Coprosma tenuicaulis	hukihuki, swamp coprosma	20	13	Seedling
Cordyline australis	ti kouka, cabbage tree	20	13	Adult
Crataegus monogyna	hawthorn	20	13	Seedling
Dacrycarpus dacrydioides	kahikatea, white pine	20	13	Adult
Dacrycarpus dacrydioides	kahikatea, white pine	20	13	Sapling
Dacrycarpus dacrydioides	kahikatea, white pine	20	13	Seedling
Fuchsia excorticata	kotukutuku, tree fuschia	20	13	Seedling
Hedycarya arborea	porokaiwhiri, pigeonwood	20	13	Seedling
Laurelia novae-zelandiae	pukatea	20	13	Adult
Leptospermum scoparium	manuka	20	13	Adult
Leptospermum scoparium	manuka	20	13	Seedling
Ligustrum sinense	Chinese privet	20	13	Seedling
Melicytus ramiflorus	mahoe, whitey wood	20	13	Sapling
Melicytus ramiflorus	mahoe, whitey wood	20	13	Seedling
Myrsine australis	mapau, red matipo	20	13	Seedling
Pennantia corymbosa	kaikomako	20	13	Seedling
Prumnopitys taxifolia	matai, black pine	20	13	Seedling
Pseudopanax hybrid	No common name	20	13	Seedling
Coprosma areolata	thin-leaved coprosma	21	6	Sapling
Coprosma robusta	karamu, glossy karamu	21	6	Adult
Coprosma robusta	karamu, glossy karamu	21	6	Sapling
Cordyline australis	ti kouka, cabbage tree	21	6	Sapling
Hoheria sexstylosa	houhere, lacebark	21	6	Adult
Kunzea robusta	rawirinui, kanuka	21	6	Adult
Kunzea robusta	rawirinui, kanuka	21	6	Sapling
Leptospermum scoparium	manuka	21	6	Sapling
Nestegia lanceolata	white maire	21	6	Sapling
Pittosporum tenuifolium	kohukohu, black matipo	21	6	Adult
Pittosporum tenuifolium	kohukohu, black matipo	21	6	Sapling
Podocarpus totara	totara	21	6	Sapling
Veronica stricta	koromiko	21	6	Sapling
Coprosma robusta	karamu, glossy karamu	22	7	Adult
Coprosma robusta	karamu, glossy karamu	22	7	Sapling
Cordyline australis	ti kouka, cabbage tree	22	7	Adult
Cordyline australis	ti kouka, cabbage tree	22	7	Sapling
Hoheria sexstylosa	houhere, lacebark	22	7	Adult
Kunzea robusta	rawirinui, kanuka	22	7	Adult
Leptospermum scoparium	manuka	22	7	Adult
Leptospermum scoparium	manuka	22	7	Sapling
Phyllocladus trichomanoides	tanekaha, celery pine	22	7	Sapling
Pittosporum tenuifolium	kohukohu, black matipo	22	7	Sapling
Podocarpus totara	totara	22	7	Sapling
Sophora microphylla	kowhai	22	7	Sapling

Veronica stricta	koromiko	22	7	Adult
Veronica stricta	koromiko	22	7	Sapling
Leptospermum scoparium	manuka	23	1	Sapling
Coprosmas rigida	No common name	24	5	Sapling
Coprosma robusta	karamu, glossy karamu	24	5	Adult
Coprosma robusta	karamu, glossy karamu	24	5	Sapling
Cordyline australis	ti kouka, cabbage tree	24	5	Sapling
Hoheria sexstylosa	houhere, lacebark	24	5	Adult
Hoheria sexstylosa	houhere, lacebark	24	5	Sapling
Kunzea robusta	rawirinui, kanuka	24	5	Adult
Kunzea robusta	rawirinui, kanuka	24	5	Sapling
Leptospermum scoparium	manuka	24	5	Adult
Leptospermum scoparium	manuka	24	5	Sapling
Sophora microphylla	kowhai	24	5	Sapling
Veronica stricta	koromiko	24	5	Sapling
Hoheria sexstylosa	houhere, lacebark	25	2	Seedling
Kunzea robusta	rawirinui, kanuka	25	2	Sapling
Kunzea robusta	rawirinui, kanuka	25	2	Seedling
Leptospermum scoparium	manuka	25	2	Sapling
Leptospermum scoparium	manuka	25	2	Seedling

Notes: Plots 23 and 25 had no adult trees
Plots 6, 18, 21, 22, 23, 24 had no seedlings