Water quality improvement in the Waiwiri catchment through strategic establishment of native ecosystems with bioactive properties used at a land treatment site

Final report – January 2023

Authors:

Alexandra Meister, Brett Robinson, María Jesús Gutiérrez-Ginés

Report prepared for Freshwater Improvement Fund – Ministry for the Environment

Report number: FW23002

Water quality improvement in the Waiwiri catchment through strategic establishment of native ecosystems with bioactive properties used at a land treatment site

Reviewed by: Hamish Lowe

Director, Lowe Environmental Impact

Approved by: Wim Nijhof **Date:13 February 2023**

Interim GM Environment, Institute of Environmental Science and Research

Executive summary

The Horowhenua District Council was the first to establish a pressurised spray irrigation system for treated municipal wastewater (TMW) in New Zealand. The system was established for the Levin community at a site commonly referred to as “The Pot”. TMW from the Levin wastewater treatment plant has been irrigated onto ca. 40 ha of Radiata pine plantation since 1986, at rates of ca. 4,000 mm/yr. As a consequence of the TMW irrigation and the agricultural activity in the catchment, the water quality in the Waiwiri stream is degraded. The stream is of cultural importance and local iwi aspire to restore the stream to its former state.

After the harvest of Radiata pine at The Pot in 2017/2018 the site was replanted. At the time consideration was given to alternative tree crops, with a trial aimed at establishing a kānuka and mānuka-dominated ecosystem over 10 ha of the site proposed. Previous studies show that kānuka and mānuka can reduce contaminant losses from soil. However, there is a lack of knowledge on their performance under high-rates of TMW irrigation onto the plant foliage.

A 10-ha trial over a 5-year period was undertaken, with a range of experiments conducted to determine (1) the growth of native vegetation with wastewater irrigation through sprinklers, and (2) whether kānuka and mānuka can potentially reduce water pollution through the reduction of contaminant losses, in particular nitrogen and pathogens.

A preliminary trial indicated that none of the tested species were restricted in their growth by TMW application at ca. 3500 mm/yr through sprinklers. Similarly, plant monitoring from the large-scale planting showed that plants were not directly impaired by the irrigation of TMW onto the plant foliage. However, the high application rate of TMW resulted in accelerated growth of semi-woody weeds, predominantly inkweed and nightshade species. Native plant survival was negatively correlated with weed cover after one year of growth. The weeds formed a dense canopy at ca. 1.5 m in height, and, in combination with TMW irrigation, created a dark and humid environment for the underlying native seedlings. Consequently, native plant mortality was up to 90% in some areas, and plant establishment was restricted to certain areas, resulting in a clumped distribution of native plants.

Plant monitoring two and three years after planting showed that most mortality occurred in the first year after planting. Thereafter, their survival rate did not significantly decline further. Therefore, weed control is a critical success factor in the first year after planting to allow the native seedlings to grow tall enough to compete for light. Once most native plants overtop the weeds, weed control can be reduced, and when the canopy is closed, weed control will no longer be necessary because of the limited availability of light underneath the native canopy restricts weed growth. Weeding may occur manually or chemically, although care is required with the latter to avoid spray drift resulting in mortality of native plants, which appeared to have occurred at The Pot. A trial with different preventative weed control options including weed mats and tree guards showed that a combination of wool weed mats and tree guards can significantly increase the survival of native seedlings, while black polypropylene weed mats significantly increased plant growth. Therefore, a combination of tree guards and black weed mats may be most beneficial to support early plant development.

Using kānuka, mānuka, and pasture at different distances from sprinklers, we aimed to determine the effect of varying rates of TMW irrigation on the growth of these species. In

addition, we analysed the distribution of nutrients and trace element contaminants in the soil-plant system. There was no correlation between relative TMW irrigation rate and plant height/biomass for any of the tested plants. However, the height of kānuka and mānuka was negatively correlated with the concentration of sodium in their foliage. This potentially indicates some toxic effects of high Na application on these species, likely due to irrigation rates in excess of the preliminary trial. These findings reflect that irrigation rates require restrictions to avoid adverse effects on native vegetation.

The soil concentrations of nutrients and trace elements did not differ between species, indicating that application of TMW compounds was too high for any plant to mitigate. Water flux meters were used to compare contaminant leaching under kānuka and pasture. The results indicated that there was no significant difference in leaching of nitrate and *Escherichia coli* between the two plants. Any potential effects of kānuka and mānuka on nitrogen and pathogen losses were therefore outweighed by the high application rates.

Overall, this research has demonstrated that native plants can tolerate ca. 4,000 mm/yr TMW irrigation through sprinklers, however, survival is dependent on weed control in the first year. Irrigation rates >5,000 mm/yr are likely unsuitable for the survival of NZ-native vegetation. Temporary increases in irrigation rates resulted in surface ponding and created conditions that did not allow for growth of higher plants. It is likely that reduced irrigation rates in combination with rigorous weed control would allow the successful establishment of native vegetation. Further research should determine optimal irrigation rates and most suitable management strategies for good survival and rapid establishment of native vegetation.

Research outputs

The following publications and presentation derived from this project:

Meister, A., Gutiérrez-Ginés, M. J., Lowe, H., & Robinson, B (2023). The potential of Myrtaceae species for the phytomanagement of treated municipal wastewater. *Plants*, 12(15), 2844. https://doi.org/10.3390/plants12152844

Gutiérrez-Ginés, M. J., Robinson, B., & Lowe, H. (2023, March 21-23). *Nutrient balance in soil-plant systems after 30 years of wastewater irrigation* [Conference presentation]. New Zealand Land Treatment Collective Conference, Blenheim.

Meister, A., Lowe, H., Gutiérrez-Ginés, M. J., Rodriguez, J., Bourke, M., & Robinson, B. (2022). *Native vegetation: a new paradigm for wastewater land application systems?* Water New Zealand Conference & Expo, 18-20 October 2022, Christchurch.

Meister, A. (2022). *Soil-plant interactions of New Zealand native vegetation irrigated with treated municipal wastewater*. [Doctoral thesis, University of Canterbury]. UC Research Repository. http://dx.doi.org/10.26021/12826

Meister, A., Gutiérrez-Ginés, M. J., Gaw, S., Dickinson, N., & Robinson, B. (2021, May 4-6). *Native vegetation to manage nutrients in wastewater land application schemes* [Conference presentation]. New Zealand Land Treatment Collective Conference, Palmerston North.

Horswell, J., Gutiérrez-Ginés, M. J., & Robinson, B. (2019). *The Pot at Levin part of a nationwide study. Putting waste to work.* A Centre for Integrated Biowaste Research Publication. Issue 20, June 2019. p 2.

Meister, A., Cass, S., Bohm, K., & Gutiérrez-Ginés, M. J. (2019). *Native vegetation for the land treatment of municipal wastewater – an update from "The Pot".* Putting waste to work. A Centre for Integrated Biowaste Research Publication. Issue 21, Nov 2019. pp 2-3.

Lowe, H., Gutiérrez-Ginés, M. J., Sitz, C., Halford, S., Alderton, I., Ambrose, V., Horswell, J., Cass, S., Saidy, G., Gerrard, D., Robinson, B., & Northcott, G. (2018, December 3-6). *30 years of effluent land-application* [Conference presentation]. New Zealand Society of Soil Science Conference, Napier.

Gutiérrez-Ginés, M. J. (2018). *Mānuka and kānuka for the land-treatment of municipal wastewater – an update.* Putting waste to work. A Centre for Integrated Biowaste Research Publication. Issue 18, June 2018. p 3.

Gutiérrez-Ginés, M. J. (2017). *Mānuka and kānuka for the land-treatment of municipal wastewater.* Putting waste to work. A Centre for Integrated Biowaste Research Publication. Issue 16, Oct 2017. p 6.

Content

1. Introduction

In 1986, the Horowhenua District Council built the first pressurised wastewater spray irrigation system in New Zealand. The system was established for the Levin community at a site locally referred to as the “The Pot”. Treated municipal wastewater (TMW) from the Levin wastewater treatment plant is stored in an effluent pond from where it is irrigated onto 40 ha of land through overhead sprinkler irrigation.

The TMW irrigation at The Pot affects the water quality in the nearby Waiwiri Stream. Nutrients from TMW enter the stream via drains and subsurface flows following irrigation. The influx of nutrients and contaminants from The Pot and pastoral farmland degrades the water quality of the Waiwiri Stream and exacerbates the loss of biodiversity in and along the stream as well as at the coast near the stream’s mouth (Allen et al., 2012). The land around Waiwiri Stream and Lake Papaitonga, from where the stream originates, is of ecological and cultural significance (Allen et al., 2012). It provides a habitat to endangered native land snails (*Powelliphanta* spp.), rare leafless mistletoe (*Korthalsella salicornioides*), brown mudfish (*Neochanna apoda*), and longfin eel (*Anguilla dieffenbachia*) (Horowhenua District Council, 2011; NIWA, 2021). The Waiwiri Stream is a historic fishing site embedded in a highly valued ancestral landscape. However, with the degradation of their habitat, eels and shellfish have disappeared from the stream and the coast surrounding the stream’s mouth. This is a significant issue for local iwi, who wish to rehabilitate the Waiwiri Stream to once again harvest eel and shellfish from the area (Allen et al., 2012).

Plant species differ in their ability to reduce nutrient losses from soil. Different concentration of exchangeable nitrogen, phosphorus and other potential contaminants in the soil in and under the root systems of different plants can indicate a contrasting risk of surface- and groundwater contamination (Franklin et al., 2019; Meister et al., 2022; Tzanakakis et al., 2009). Research by ESR and Lincoln University has demonstrated that the root systems of mānuka and kānuka have unique properties that do more than just filter pollutants; they inhibit nitrification and denitrification and kill bacteria. The antimicrobial properties of these species have been shown to kill soil-borne pathogens associated with the land application of treated human wastes (Gutierrez-Gines et al., 2021; Prosser et al., 2016) and alter nitrogen cycling in soil, leading to a significant decrease in nitrate leaching (Esperschuetz, Balaine, et al., 2017). These species also inhibit the emission of the greenhouse gas nitrous oxide (Franklin et al., 2017). Moreover, the growth of kānuka and mānuka is significantly enhanced following the land-application of organic waste (Meister et al., 2022; Seyedalikhani et al., 2019).

The irrigation infrastructure at The Pot utilised best engineering solutions when it was designed, irrigating TMW into Radiata pine (*Pinus radiata*) plantation forest. Utilising current and advanced technology, the irrigation system can be upgraded to significantly improve performance to reduce leaching of contaminants in the Waiwiri catchment. With the Radiata pine reaching maturity and being felled in 2017/2018, there was an opportunity to re-design the irrigation infrastructure and establish New Zealand’s first large-scale wastewater land discharge onto native plants. Funded by the Freshwater Improvement Fund from the Ministry for the Environment, and the Horowhenua District Council, this project aimed to investigate a kānuka and mānuka dominated planting irrigated with TMW, with a view to significantly reduce the leaching of wastewater contaminants from The Pot and contribute to improving the health and wellbeing of the Waiwiri catchment as a whole and protect it from further degradation.

2. Objectives

The main goal of this project was to determine whether native vegetation could be strategically established in wastewater land application systems to reduce adverse impacts on local waterways. Specifically, the two main objectives were to:

(1) Determine how plant health and growth of native vegetation is affected by irrigation with treated municipal wastewater through overhead sprinklers.

(2) Quantify the effects of kānuka and mānuka on the leaching of nitrogen and pathogens from TMW-irrigated land.

3. Materials and methods

3.1. Site description

The Levin wastewater treatment plant has an output of >2 M m^3 TMW per annum. After treatment, the TMW is transferred into a 7-ha pond at The Pot. The unlined pond can hold 425,000 m^3 of TMW and allows for irrigation of controlled volumes of TMW onto land, while leaching about 19% of the TMW influx into groundwater (Horowhenua District Council, 2018). From the pond, the TMW is irrigated onto 40.5 ha of land. The average TMW irrigation rate in 2018 was 4,667 mm/yr (Horowhenua District Council, 2018). The composition of the TMW and respective application rates are shown in Table 1. The overhead sprinkler irrigation system is operating over-night. Plots are irrigated alternatingly, and irrigation of each plot occurs 1-3 times per week, depending on the water level in the pond.

Table 1 Concentrations of nutrients and contaminants in treated municipal wastewater (TWM) irrigated onto land at The Pot.

Parameter	**Concentration in TMW (mg/L)**[a]	**Application (kg/ha/yr)**[b]
NO_3^--N	10 ± 1.1	468
NO_2^--N	0.04 ± 0.01	1.9
NH_4^+-N	8.0 ± 1.1	373
Total N	33 ± 9.5	1540
PO_4^{3-}-P	1.2 ± 0.19	56
Total P	6.6 ± 0.91	308
Na	61 ± 3.2	2847
K	25 ± 1.9	1167
Ca	12 ± 0.19	560
Mg	3.2 ± 0.13	149
B	0.16 ± 0.01	7.5
Chloride	86 ± 15	4014
Total suspended solids (TSS)	13 ± 6.3	607
Electrical conductivity (EC)	74 ± 5.1 ($mS\ m^{-1}$)	-
Sodium adsorption ratio (SAR)[b]	8.1	-
Escherichia coli	3408 ± 1767 (cfu 100 mL^{-1})	-
As, Cd, Cr, Cu, Pb, Hg, Ni	<0.01	<0.47

Mean ± standard error (*n*=4-148). Data was provided by Lowe Environmental Impact Ltd.

[a] unless otherwise indicated.

[b] Based on TMW irrigation at 4,667 mm/yr (Horowhenua District Council, 2018).

[c] The SAR shows the concentration of Na relative to Ca and Mg, calculated after Ayers and Westcot (1985).

The Pot is located on parabolic dunes on the sand plains of the Manawatu (Boffa Miskell, 2018). Most of the area are well-drained sand dunes and sand plains (>75%). The rest consists of imperfectly to very poorly drained sandy and organic soils in the inter-dune areas (McLeod, 2018), which are not irrigated. Soils in the experimental areas were well-drained Sandy Recent soils (McLeod, 2018). The median annual temperature at the site is 13.5 °C, and the annual rainfall is 1163 mm (Chappell, 2015).

Since The Pot was established, TMW was irrigated into Radiata pine plantation forest. In 2017/2018 all of the trees were removed from the site. The remaining slash was pushed into windrows. However, stumps and logs were left throughout the site. In some areas there are mature stands of native plants that were left in place, including 4.2 ha of kānuka, as well as 2.0 ha of *Carex* spp. wetland, both considered regionally threatened habitat types (LEI, 2017). After harvest, 10 ha were planted in native vegetation for this project, while the remaining land was re-planted with Radiata pine.

3.2 Species selection and planting

Kānuka and mānuka combined represented 60% of the trees planted, due to their potential to reduce nitrate and *E. coli* leaching (Esperschuetz, Balaine, et al., 2017; Prosser et al., 2016). It was shown that both species can benefit from the application of biosolids (Esperschuetz, Anderson, et al., 2017) and tolerate TMW irrigation at rates of 1000 mm/yr (Meister et al., 2022). Kānuka naturally occurs in dune systems, and is the main native species present in mature stands at The Pot, as reported by Boffa Miskell (2018). Mānuka is adapted to raised ground areas of dune wetlands and can handle occasional waterlogging (KCDC, 1999). Both species are able to establish on disturbed sites, where they are early species in the succession to forest (Stephens et al., 2005; Wilson, 1994), providing a suitable habitat for other native species (Evans, 1983).

The remaining 40% of the trees was composed by species of 12 different genera (Table 2). These species were selected according to the following criteria; a) naturally growing in different environments of the dune system: high drier parts of the dunes, wetlands, swamp areas, or banks of drains, b) hardy species able to grow in exposed areas that were identified in a site visit to the remnant native vegetation around Lake Papaitonga, c) available in commercial nurseries, and d) tolerating TMW irrigation onto the foliage as determined in a preliminary experiment (see Section 3.3.1).

Table 2 Composition of the mānuka/kānuka dominated ecosystem at The Pot

Species [a]	**Vernacular**	**%** [b]	**Native habitat within dunelands (KCDC, 1999)**
Kunzea robusta	Kānuka	49.1	Dry duneland (on younger dunes & dry sand plains)
Leptospermum scoparium	Mānuka	11.0	Duneland wetlands (damp raised ground or occasional waterlogging)
Coprosma spp.	Mingimingi Karamu Taupata	9.5	Foredunes (seaward side & in the lee), dry duneland (on younger dunes & dry sand plains), duneland wetlands (damp raised ground or occasional waterlogging)
Carex spp.	Sand sedge Pukio	5.7	Foredunes (seaward side), dry duneland (moist sand plains & hollows), duneland wetlands (wet or damp edges & hollows)
Cordyline australis	Tī kōuka	4.6	Dry dunelands (moist sand plains & hollows), duneland wetlands (damp edges & hollows, damp raised grounds or occasional waterlogging)
Phormium tenax	Harakeke	4.0	Dry duneland (moist sand plains & hollows), dune wetlands (damp edges & hollows)
Melicytus ramiflorus	Mahoe	3.9	Dry duneland (older dunes with soils)
Dodonaea viscosa	Akeake	3.5	Foredunes (in the lee), dry duneland (on younger dunes & dry sand plains)
Veronica stricta	Koromiko	3.1	Duneland wetland (damp raised ground or occasional waterlogging), banks of duneland streams
Myoporum laetum	Ngaio	2.1	Foredunes (in the lee), dry duneland (on younger dunes & dry sand plains), banks of duneland streams
Austroderia richardii	Toetoe	2.0	Dry duneland (moist sand plains & hollows), banks of duneland streams, duneland wetlands (damp raised ground or occasional waterlogging)
Corynocarpus laevigatus	Karaka	0.5	Dry duneland (moist sand plains & hollows)
Juncus pallidus	Giant rush	0.5	Coastal to lowland. Usually in damp swampy hollows, on the margins of wetlands and lakes, in open shrubland on damp ground, or near saltmarshes in places that can be flooded by king tides [c]
Plagianthus regius	Manatu	0.5	Coastal to lower montane, often a prominent tree in lowland alluvial forest [c]

[a] Percentage of tree of this species in the experiment at The Pot.

[b] This species has been experimentally grown in soil amended with biowaste or fertiliser.

[c] Information obtained from http://nzpcn.org.nz on 25 January 2023.

Planting occurred in two phases, in June 2018 and October 2018. Native seedlings were planted at a density of 10,000 stems/ha. This is recommended to achieve a relatively quick canopy closure (KCDC, 1999). The plants were sourced from three suppliers: Kauri Park Nurseries, Lynwood Nursery, and Tanenuiarangi Manawatu Incorporated - Te Ao Turoa Environment Centre & Lake Horowhenua Trust. The seedlings were raised in root trainers and were 30-60 cm tall at planting. Seedlings were planted in rows with three rows of kānuka and three rows of mixed species alternating. Interplanting with some 17,000 seedlings from a mixture of species occurred across the site between July and September 2019. An additional 1,500 mixed seedlings were added in June 2020, and 800 kānukas and mānukas in August 2020. All remaining areas of The Pot were re-planted with Radiata pine.

3.3 Plant establishment and growth

3.3.1 Effect of sprinkler irrigation on plant health: preliminary trial

A selection of plant species that were presumably going to be included in the large-scale 10-ha planting, were selected for the preliminary experiment (Table 3). 138 native seedlings were planted in two circles within the irrigation area of one sprinkler (treatment) and one circle outside of the irrigation area (control), on the 7th of May 2018 (Figure 1). The sprinkler irrigated TMW from the pond once per week. The amount of TMW irrigation and precipitation was measured weekly with a rain gauge. Plants were harvested on the 22nd of August, after 15 weeks of growth.

Table 3 Selected plants for the preliminary trial

Plant species	**Vernacular name**	***n* control**	***n* TMW outer circle**	***n* TMW inner circle**
Cordyline australis	Cabbage tree	5	3	2
Coprosma robusta	Karamu	5	4	1
Coprosma repens	Taupata	5	3	2
Hebe stricta	Koromiko	4	3	2
Corynocarpus laevigatus	Karaka	4	2	2
Melicytus ramiflorus	Mahoe	5	3	2
Myoporum laetum	Ngaio	5	3	2
Kunzea robusta	Kānuka	18	10	9
Leptospermum scoparium	Mānuka	17	8	9
Total		68	39	31

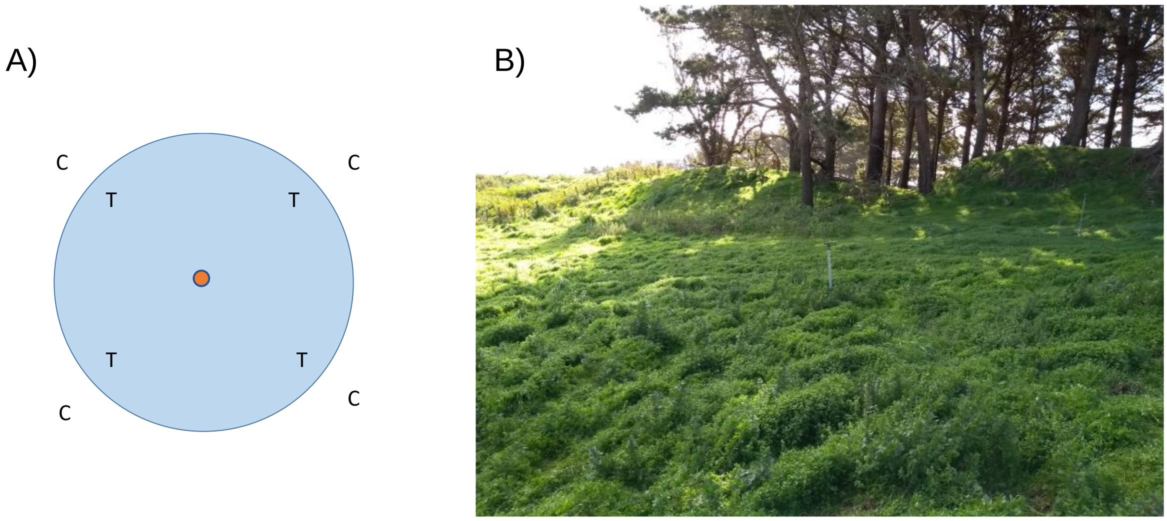

Figure 1 A) Experimental design of the preliminary trial, T: irrigated plants within the reach of the sprinkler, C: non-irrigated control plants; B) Photo of the sprinkler with surrounding plants.

Aerial parts of plants were cut and carried to the laboratory in paper bags. Plants in the irrigated treatment were separated between the inner and outer circles. Any signs of stress and disease on the leaves were observed and written down, and plants were oven-dried at 35 °C for 15 days. When plants were dried, leaves were separated from stems and weighted separately. For the analysis of results, only mānuka and kānuka had enough number of plants in the inner and outer irrigated circles as to analyse the results separately. The rest results for the rest of species were just analysed for irrigated and non-irrigated control treatments.

3.3.2 Weed management trial

To investigate alternative weed management options to improve plant survival, a trial was established in August 2020. A total of 192 mānuka seedlings were planted in three plots of 10 m x 10 m. The plots were arranged at equal distances from the sprinkler heads to ensure even TMW irrigation. Each plot was subdivided into four areas of different weed control treatments with 16 plants each (Figure 2); (a) no weed control, (b) wool mulch mats, (c) a combination of wool mulch mats and CombiGuards (polythene sheaths supported by bamboo stakes), and (d) black polypropylene weed mats. One-year old seedlings of mānuka were planted on 26th August 2020. After 12 weeks of growth, the height of each seedling was measured. Plant health was determined using a semi-quantitative visual assessment, rating plants from “1” (heavily chlorotic or necrotic) to “5” (healthy). If a plant had died, a “0” was assigned on the health index. Plants that could not be found were assumed to be dead and recorded as “0”. Survival rates were calculated for each treatment.

Figure 2 Weed management trial with four different treatments. A) no weed control; B) wool mulch mats; C) wool mulch mats and CombiGuards; D) black polypropylene weed mats.

3.3.3. Plant survival and growth monitoring in the 10-ha plot

Plant survival, plant height, and weed cover were measured in May 2019, May 2021, and May 2022 using transects of 25 m^2 (12.5 m x 2 m) that were randomly chosen in different parts of the experimental area. Plants within 1 m from a 12.5 m tape were recorded and their height was measured with a measurement stick (Figure 3). The coverage of weeds was visually estimated based on a percentage of total ground area covered by each weed species.

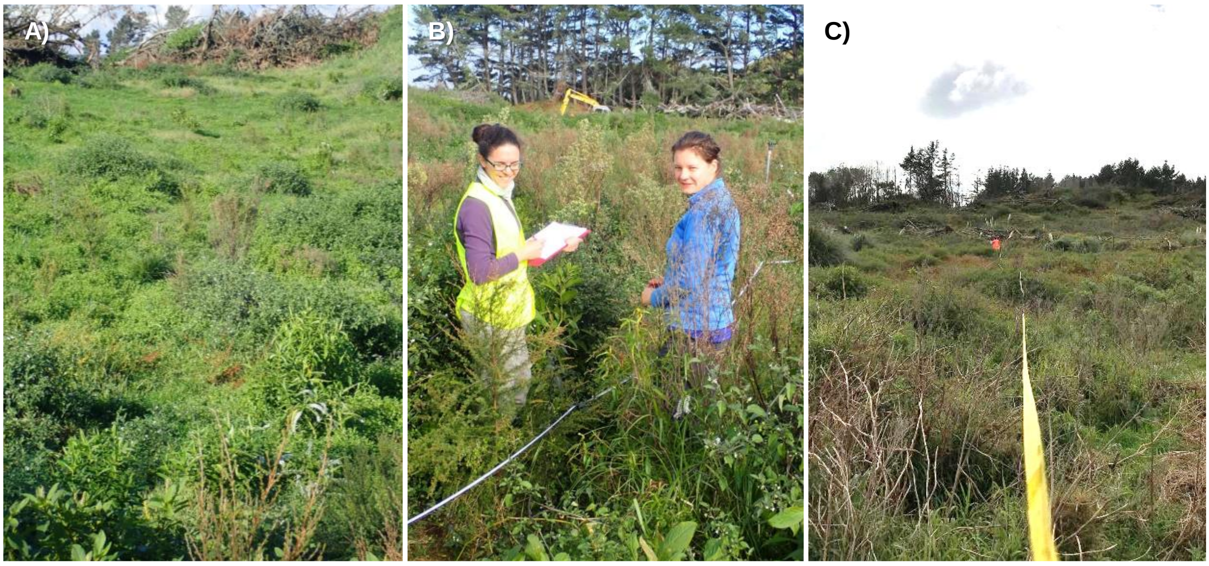

Figure 3 A) Area with irrigated natives planted into pasture in May 2019; B) area with visible weed management in May 2019; C) transect monitoring.

In May 2019, approx. one year after plant establishment, transects were conducted in four different vegetation management types; (1) non-irrigated, (2) irrigated with weed management, (3) irrigated without weed management, and (4) irrigated with natives planted into pasture. Weed management included manual weeding (hand releasing and scrub cutting) and herbicide spot spraying with Haloxyfop, Terbuthylazine, and Glyphosate. A total of 21 transects was recorded, with a minimum of three transects per vegetation management type.

In May 2021, 24 transects were conducted in plots of vegetation management type 3. The other types could not be assessed due to additional in-fill plantings of native seedlings in these areas after 2019. The transects were measured in three separate areas that had been left without weed management to represent the “worst case” planting outcome.

In May 2022, 60 transects were conducted, thereof 52 in six separate sections of the TMW-irrigated experimental area, and 8 outside of the experimental area in same-aged native vegetation without irrigation (Figure 4). In this monitoring campaign, the non-irrigated area sampled was located next to the main entrance gate to The Pot.

Figure 4 Location of transects recorded in May 2022 (red lines). The non-irrigated control area is next to the entrance and not shown here.

3.4 Plant growth and contaminant fluxes in kānuka and mānuka *vs* pasture with different rates of TMW irrigation

3.4.1 Plant growth

It was not possible to establish experimental plots with different irrigation rates to investigate the effect of TMW irrigation rate on plant growth because irrigation rates were highly variable within a plot. Therefore, we addressed this question by instead selecting areas that received different rates of irrigation due to their proximity to sprinkler heads. In November 2020, 17 specimens each of kānuka and mānuka, as well as 17 areas of pasture (dominated by *Holcus lanatus* and *Lolium perenne*) were selected at varying distances from central sprinklers. This was conducted in an area that received weed management (Figure 5). A rain gauge was placed beside each specimen/pasture area to record the relative TMW irrigation rate during one run of overnight irrigation (Figure 6). There was no rainfall during this period. The height of kānuka and mānuka specimens was measured with a measuring tape.

Figure 5 Aerial image showing the reach of the irrigation sprinklers in white circles, and sampling points in small red circles (mānuka), green circles (kānuka) and purple circles (pasture). Numbered points show the location of the Water Flux Meters (WFMs, Section 3.5).

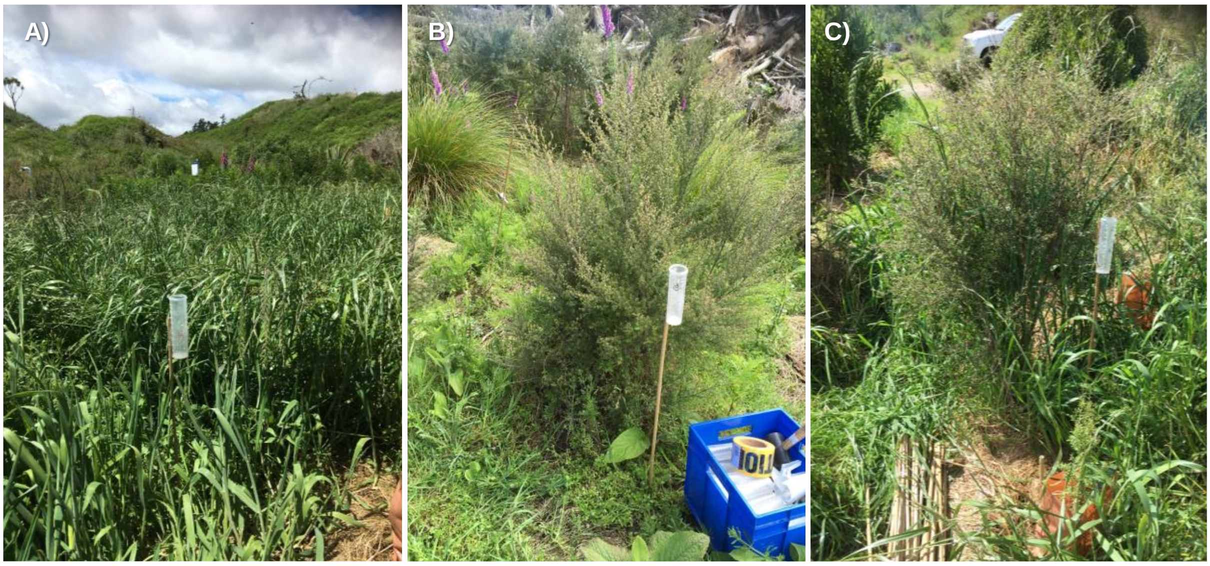

Figure 6 Rain gauges installed in A) pasture; B) kānuka; C) mānuka.

3.4.2 Soil and plant chemistry

Soil and plant samples were collected from kānuka, mānuka and pasture receiving varying TMW irrigation rates at the same time as plant monitoring occurred. Determining the concentration and distribution of nutrients and contaminants in the soil-plant allows the estimation of plant effects on potential nutrient and contaminant losses due to interspecific differences in nutrient cycling and contaminant leaching and/or emissions (Esperschuetz, Balaine, et al., 2017; Franklin et al., 2017; Meister et al., 2022).

Foliage was sampled from each of the 17 specimens of mānuka and kānuka selected by cutting 10 individual branches of varying age and aspect using secateurs. All branches had a diameter of <5 mm and were cut near the trunk. To collect pasture samples, a rectangle of 0.2 m x 0.2 m was placed on the ground and all pasture within that rectangle was cut 10 mm above the soil surface. Plant samples were washed with deionised water and dried at 60 °C for one week. Leaves of kānuka, and mānuka were separated from the stems after drying. There were no flowers or fruits on the sampled foliage.

Ten subsamples from the topsoil (0-10 cm) around the stem of each of the 17 mānuka and kānuka plants were collected with a bucket soil sampler and pooled into one sample (Figures 7A & B). A similar process was used to sample the topsoil under pasture cover in an area of approximately 0.25 m^2 after removing the vegetation cover. Soil from below the root systems (30-45 cm) was collected with a soil corer (Figure 7C) in the same areas where the topsoil was collected. Soil samples were transported to the laboratory in a chilly bin with icepacks and frozen at -20°C until further analysis.

Figure 7 A) Collection of soil sample from the top soil (0-10 cm) with a bucket soil sampler; B) pooled sample in the bucket soil sampler; C) Collection of soil sample from the sub soil (30-45 cm) with a soil corer

Soil nitrate (NO_3^-) and exchangeable ammonium (NH_4^+) were extracted from the thawed soil with 2 M KCl (Blakemore et al., 1987) and their concentration determined by colorimetric methods (NO_3^--N after Miranda et al. (2001), and NH_4^+-N after Mulvaney (1996), using a Cary 100 Bio UV-visible spectrophotometer (Agilent Technologies, Santa Clara, CA, USA). The soil moisture content was determined by drying a subsample at 105 °C for 24 hours and recoding the change in weight (Blakemore et al., 1987). Remaining soils were spread on aluminium trays, dried at 40 °C for 4 days and sieved to <2mm. Soil pH and EC were determined in deionised water in a 1:5 soil: water extract using a HQ 440d Multi-Parameter Meter with pH probe PHC735 and EC probe CDC40101 (HACH, Loveland, CO, USA).

Dried soil and plant samples were ground with a Rocklabs Bench Top Ring Mill (Scott, Dunedin, New Zealand). A LECO CN828 Carbon/Nitrogen analyser (LECO, St. Joseph, MI, USA) was used to determine total carbon and nitrogen contents. Soil and plant samples were digested in ultrapure nitric acid (HNO_3) with a ultraWAVE microwave digester (Milestone Srl, Sorisole, Italy) to determine pseudo-total concentration of elements. Soil samples were extracted with 0.05 M calcium nitrate ($Ca(NO_3)_2$) to determine the exchangeable fraction (Gray et al., 1999). The elemental concentrations in the digests and extracts were determined by ICP-MS (Agilent 7500 CX). Certified reference materials were included for quality assurance (SRM1573a – Tomato Leaves and SRM2710a – Montana I Soil, National Institute of Standards and Technology, U.S. Department of Commerce).

3.5 Water flux meters

In May 2019 eight Water Flux Meters (WFMs, Figure 8A) were installed in two TMW-irrigated flat areas at 10-20 m distance from the road. The exact locations are shown in Figure 5.

Figure 8 A) Water flux meter (WFM) ready for installation; B) Digging the trench for the installation of the WFM; C) installing the WFM.

For each WFM a 1.8 m deep pit was dug using a small digger (Figure 8B). The WFMs measured 1.5 m from the top of the cylinder to the bottom of the drainage reservoir, with a total height ca. 3 m. They were carefully lowered into the pits by hand and kept vertical using a spirit level while the pits were refilled manually (Figure 8C). The cylinders of the WFMs were carefully repacked and the whole apparatus interred, with the top of the WFM 30 cm below the surface of the soil. Tubing to extract the drainage was installed as were the electronic sensors (pressure, temperature, and conductivity meters).

The installation of the WFM was challenging due to the high water table in some excavated areas. Pits that reached the water table had to be re-dug as they were not suitable for WFM installation. Ultimately the water table in the 8 selected areas near the road was not visible and was hence assumed to be lower than 1.8 m.

In August 2019, kānuka seedlings were densely planted (25 seedlings at 0.5 m spacing) on 2.5 x 2.5 m areas above four of the WFM (Figure 9A). The areas above the other four WFM was sown with a mixture of perennial ryegrass (*Lolium perenne*) and Yorkshire fog (*Holcus lanatus*). A similar seed mixture was applied around the kānuka seedlings and other areas of the experimental plots to prevent the germination of other weeds. The drainage in the WFM reservoirs was emptied by hand pump (Figure 9B). Four METER Environment® ZL6 data loggers were installed, and each was connected to two WFMs (Figure 9C). These data loggers allowed the collection of data on drainage volume, drainage electrical conductivity (EC), drainage temperature, and logger temperature.

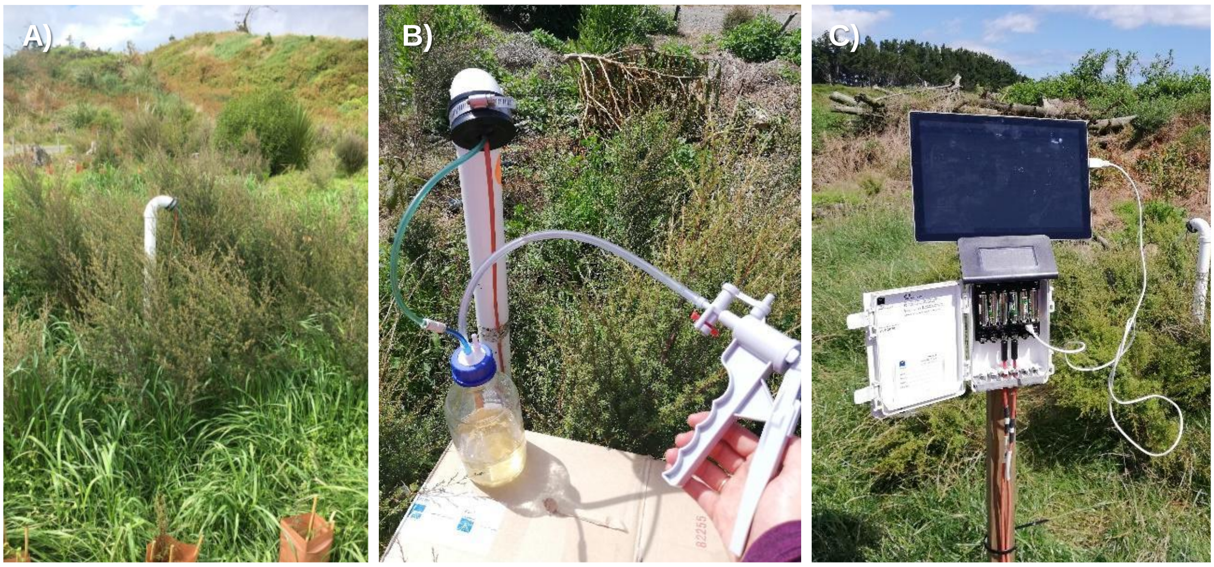

Figure 9 A) WFM with kānuka plants; B) Collecting leachate samples from the WFMs by handpump; C) Retrieving data from the data logger.

Drainage from the WFMs was emptied approximately monthly and the leaching rate and contaminant concentrations determined. Two of the lysimeters (one pasture and one kānuka) showed evidence of groundwater ingression as they refilled almost immediately after they were emptied. These lysimeters were excluded from the experiment and the results. In May 2021, the lysimeters were emptied and irrigation was increased to ca. 14 mm/day for three consecutive days. During this time, drainage samples were collected daily, transported to the UC laboratory in chilly bins with ice-packs and analysed for nitrate concentration by ion chromatography (Dionex ICS-2100, Thermo Fisher Scientific, Waltham, MA, USA). From October 2021, the lysimeters were emptied monthly and sub-samples of the leachate were collected. The samples were transported to the ESR laboratories in chilly bins and analysed immediately for coliforms and *E. coli* prior to being frozen at -20°C until further analysis of nitrogen. Inorganic nitrogen in the leachate was measured on samples collected on 17/11/21, 13/12/21, and 26/01/22 by Flow Injection Analyser at Lincoln University. Total coliforms and *E. coli* were measured on samples collected on 22/02/2022, 22/03/2022, and 27/04/2022, and analysed using the Colilert® method.

4. Results and discussion

4.1 Effect of sprinkler irrigation on plant health

Over the 15 weeks of the experiment, cumulative rainfall was 365 mm, and cumulative irrigation was 1008 mm (Figure 10). The irrigation was equivalent to an application rate of 3494 mm/yr, which was 25% lower than the average irrigation rate at The Pot. With an average nitrogen and phosphorus concentration in the TMW of 39 mg N/L and 5.6 mg P/L, respectively (Table 1), the application of those nutrients was equivalent to 393 kg N/ha and 56 kg P/ha.

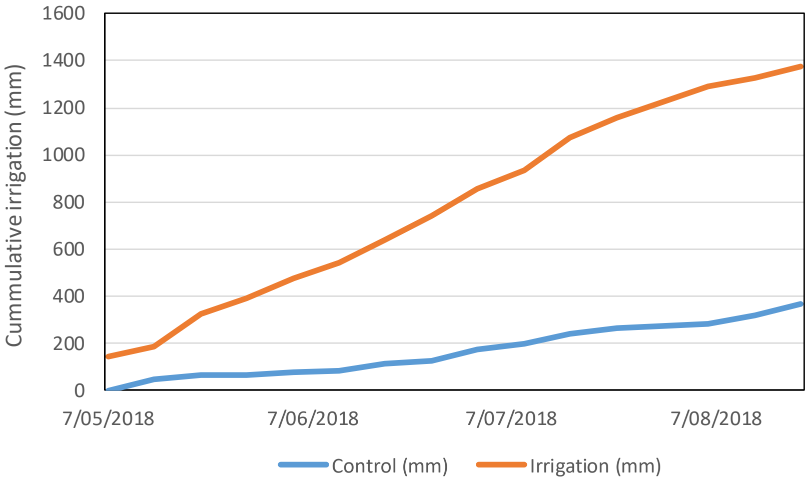

Figure 10 Cumulative rainfall (control) and TMW irrigation in the preliminary plant health trial.

Plant survival was 97% and unaffected by TMW irrigation. On average, plant biomass increased by 39% with TMW irrigation. None of the species showed a biomass decrease with the application of water and nutrients through TMW, which is consistent with another field site (Meister et al., 2022). Karamu, karaka, and taupata even produced significantly more biomass, with a 75-100% increase in the irrigated treatment (Figure 11). However, although it was demonstrated that native vegetation can benefit from nutrient application (Franklin, 2014), it is not clear if this was the result of irrigation or fertilisation by TMW application. Kānuka and mānuka biomass did not differ between treatments. Kānuka plants looked less healthy than mānuka plants and lost many leaves. These results are not consistent with previous research that showed that kānuka biomass was increased following TMW irrigation at 1000 mm/yr (Meister et al., 2022). It is evident that the additional irrigation and addition of nutrients with higher TMW irrigation rates were not beneficial for kānuka in the short term. However, root disturbance during planting may also have affected early plant development of kānuka and mānuka, which can be sensitive to root disturbance (Boffa Miskell, 2017). The growth of these species may therefore be more affected by general environmental conditions than TMW irrigation. Given that kānuka was going to be the main species planted at the 10-ha site, its survival and growth would be essential for the outcome of the 10-ha planting.

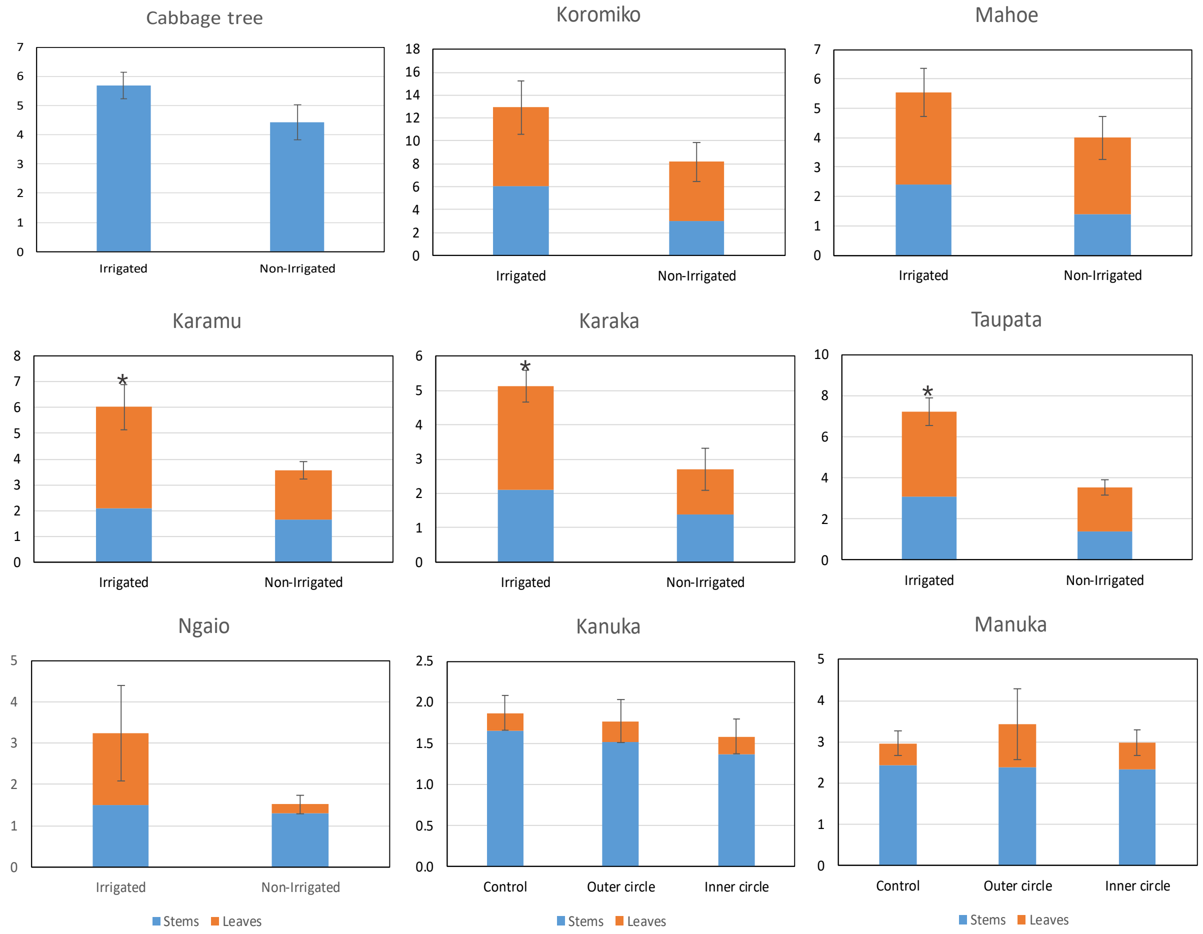

Figure 11 Dry weight (g) of the plant species in the minitrial. Bars show average dry weight in stems and leaves. Error bars represent standard error of the average dry weight of the aerial part (stems + leaves).

Cabbage tree, mahoe, and koromiko didn't show signs of stress or disease in either treatment. One koromiko plant had some leaves cut, probably eaten. This specimen was not included in the data analysis. For karaka and taupata, most specimens presented some stress symptoms in the leaves, such as yellow and/or brown spots, or chlorosis. Two karaka plants seemed to have been eaten. One of them had the tip cut, the other had slugs on the leaves. Ngaio plants had many leaves missing, primarily in the control plants, mostly likely due to being eaten. Consequently, the difference in biomass between the TMW-irrigated and control treatments was affected more by animal browsing than TMW irrigation. There were no signs of animal browsing in any of the TMW irrigated plants. Two irrigated specimens had some black and brown spots on their leaves, but they grew well, so there was no evidence of negative effects of TMW irrigation on ngaio.

Overall, TMW irrigation was more beneficial for the growth of species with large leaves. However, these plants are also more palatable to pest species, which can affect overall survival (Smale et al., 1995). Special care should be taken to control pests and minimise impaired growth and survival of plants through browsing.

4.2 Weed management trial

Of the three plots used in the weed management trial, plants in the eastern-most plot, were less healthy in all four treatments than the plants in the middle and western plots (Table 4). This might indicate an influence from the sea wind exposure, with The Pot only being a few kilometres from the sea. Westerly winds are prevalent at the site and can result in significant sea spray. It was demonstrated that sea spray can affect the chemical composition of plants up to 50 km distance (Jensen et al., 2019).

Table 4 Survival, average height, and average health of mānuka seedlings in the weed management trial (survival and health: *n*=16).

Plot	Treatment	Survival (%)	Average height (cm)	Average health (0-5)
West	Black	25	39	0.3
Middle	Black	94	37	1.0
East	Black	56	41	0.9
West	Combi	69	39	1.4
Middle	Combi	100	39	2.3
East	Combi	94	37	3.7
West	Mat	13	34	0.2
Middle	Mat	19	41	0.6
East	Mat	50	38	1.6
West	None	19	32	0.5
Middle	None	38	31	1.4
East	None	63	38	1.8

The black weed mats significantly increased plant height compared to the control, while the other treatments showed no effect (Figure 12A). Plant health and survival were significantly higher in the plants that had a combination of wool mulch mats and CombiGuards than all other treatments (Figures 12B & C). The survival in all other treatments was below 60%. Findings are consistent with other research that showed that the use of CombiGuards in native plantings are more effective than weed mats alone and can reduce overall costs of native plantings due to reduced mortality of seedlings (Dollery et al., 2018; Lai & Wong, 2005).

The weed growth in all the plots was high and many plants were not found even after spending a lot of time looking for them. For the data analysis the unfound plants were recorded as dead. The plants in the CombiGuards were the easiest to find, followed by the ones with black weed mats. The plants with wool mats were as difficult to find as the ones without weed control. In the case of the black weed mats, we could find all plants, in the other treatments we could only find about half of the plants. This can be significant for weed treatment. Once native seedlings are established, the ability to locate native seedlings among weeds is essential for both chemical and mechanical weed control to avoid high mortality of native seedlings and reduce overall costs of native plantings.

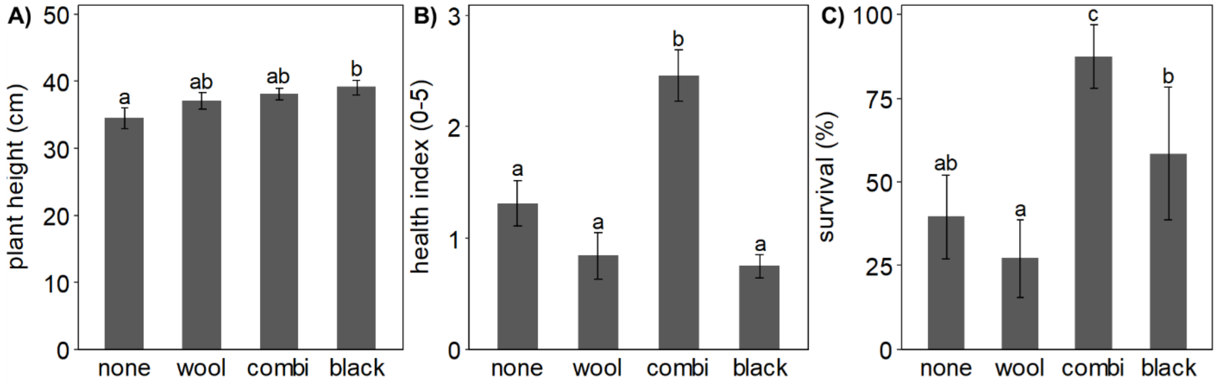

Figure 12 Effect of weed treatments on a) plant height (cm); b) health index (0-5); and c) survival (%) of mānuka seedlings after 12 weeks of growth with TMW irrigation. Values shown are means and standard errors, *n*(A & B)=48 and *n*(C)=3. None: no weed control, wool: wool mulch mats, combi: wool mulch mats and CombiGuards, black: black polypropylene weed mats.

4.3 Plant survival and growth in the 10-ha plot

4.3.1 Monitoring 2019

During plant monitoring in May 2019 few natives were evident in the experimental plot due to the overgrowth of weeds (Figures 13A & B). Plant survival in the TMW irrigated plots with and without weed control was lower (27% and 2.2%, respectively) than in the non-irrigated plots (65%) (Figure 14A). Plant mortality in the non-irrigated treatment was comparable to other native restoration sites in NZ, where seedling mortality typically ranges from 11-38% in the first year (Anton et al., 2015). However, the lower plant survival in the TMW-irrigated areas was unlikely a direct consequence of irrigation, but rather a result of weed competition, which can significantly reduce native plant survival. There was an inverse relationship between native plant survival and weed coverage (Figure 14B). While other studies found belowground competition to be dominating interactions between invasive species and native seedlings (Costa et al., 2019), competition for water and nutrients is unlikely with irrigation of TMW. Instead, the effect of weeds on native plant survival likely resulted from the competition for light (Williams & West, 2000), as well as the high-humidity conditions created by TMW irrigation underneath a dense weed canopy.

Figure 13 A) Overgrown part of the experimental plot; B) area planted in natives but non-irrigated, with fleabane.

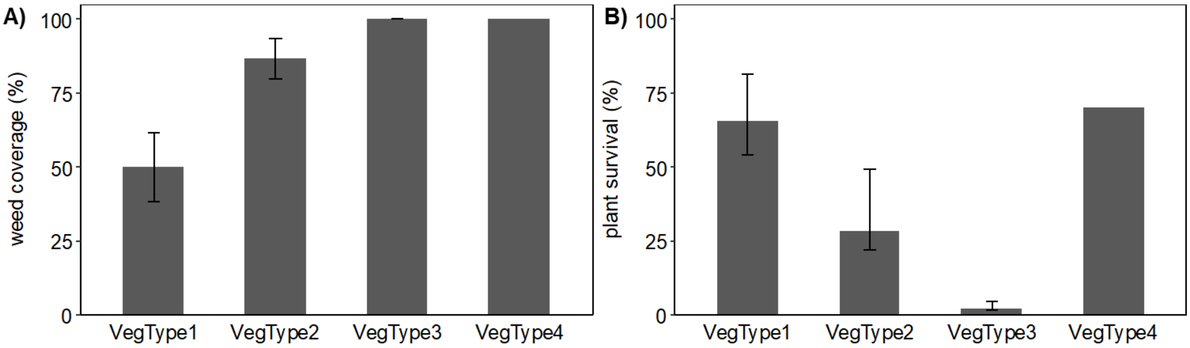

Figure 14 Weed coverage (A) and plant survival (B) in native plantings at The Pot in May 2019, approx. one year after planting. VegType1: non-irrigated, VegType2: irrigated with weed management, VegType3: irrigated without weed management, and VegType4: irrigated with natives planted into unmanaged pasture. Values for VegType4 are estimate-based.

The disturbance of soil from clear-felling of the Radiata pine plantation in combination with high nutrient application through TMW irrigation likely created optimal conditions for weed growth (Porteous, 1993; Prober & Wiehl, 2012). The main weeds observed were nightshades (*Solanum* spp., Figure 15A), mostly black nightshade (*Solanum nigrum*) and velvety nightshade (*Solanum chenopodioides*), as well as inkweed (*Phytolacca octandra*, Figure 15B). Nightshades comprised ca. 60-70% of the weed cover, while inkweed covered 20-30% of the plot. Other observed weeds were fleabane (*Conyza sumatrensis*), gorse *(Ulex europaeus*), pampas (*Cortaderia selloana*), a perennial lupin and a variety of grasses. Nightshades are annual to perennial herbs, that can regenerate after frost and smother other plants (Healy, 1974). They grow well in fertile soils under high moisture conditions (Mwai et al., 2007). Opiyo (2004) reported that nitrogen fertilisation increased the vegetative growth of black nightshade (*Solaneum nigrum*). This indicates that TMW likely benefited the growth of this weed at our study site. Woolly nightshade (*Solanum mauritianum*) was found to suppress seed germination of koromiko (van den Bosch et al., 2004). It is therefore possible that nightshades if not managed, may suppress the natural regeneration of native species. Inkweed is a perennial shrub that grows up to 1.5 m high and typically occurs in coastal sand dune environments and likely benefits from fertilisation (Duncan, 1962). The results clearly show that weeds need to be intensively managed for the successful establishment of NZ-native plants at TMW-irrigated sites. This has to occur before the weeds make it impossible to locate native plants and smother them.

Figure 15 A) Nightshade species overgrowing weeds; B) Inkweed berries, which are eaten by birds and the seeds dispersed.

Plant survival was extremely heterogeneous, with small patches of near total survival but with the vast majority of the site without any significant native plant growth. There was insufficient survival to assess the performance of individual cultivars (or varieties) of mānuka or kānuka. However, we have counted the numbers of some species (Figure 16). The proportions of the species counted broadly reflected the numbers planted.

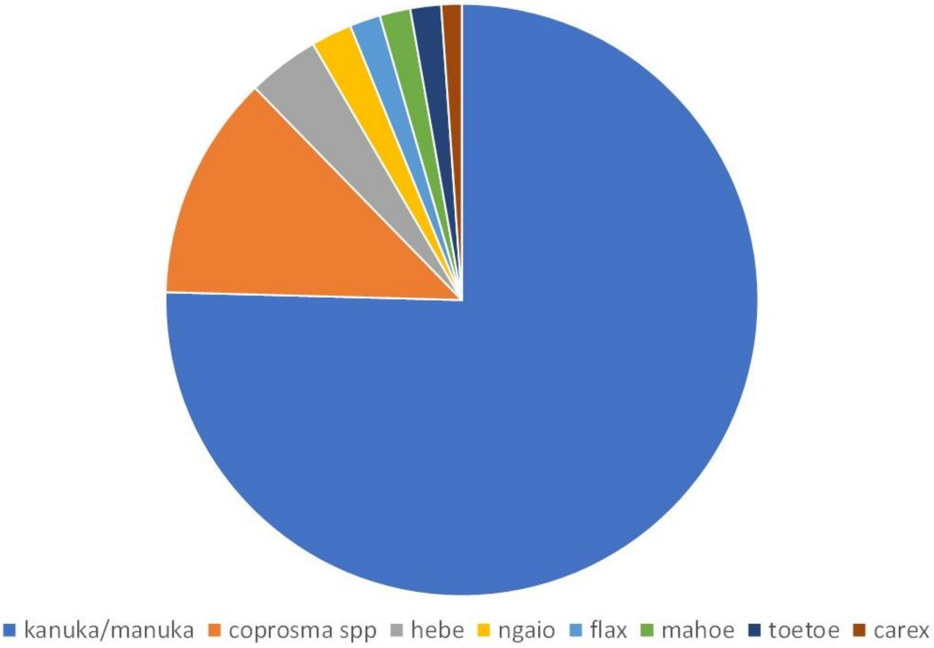

Figure 16 The species distribution of the surviving plants from the 2019 plant monitoring.

The height of the native plants differed between non-irrigated control and TMW irrigated plants (Figure 17). Plants were higher when they received TMW and weed management (VegType2) compared to a non-irrigated control (VegType1). Kānuka was the only species found in irrigated areas without weed control. Its average plant height was higher than the non-irrigated control. This was not unexpected, because kānuka is known to establish on disturbed sites as an early successional species (Aimers et al., 2021) and was planted at the highest percentage in this study.

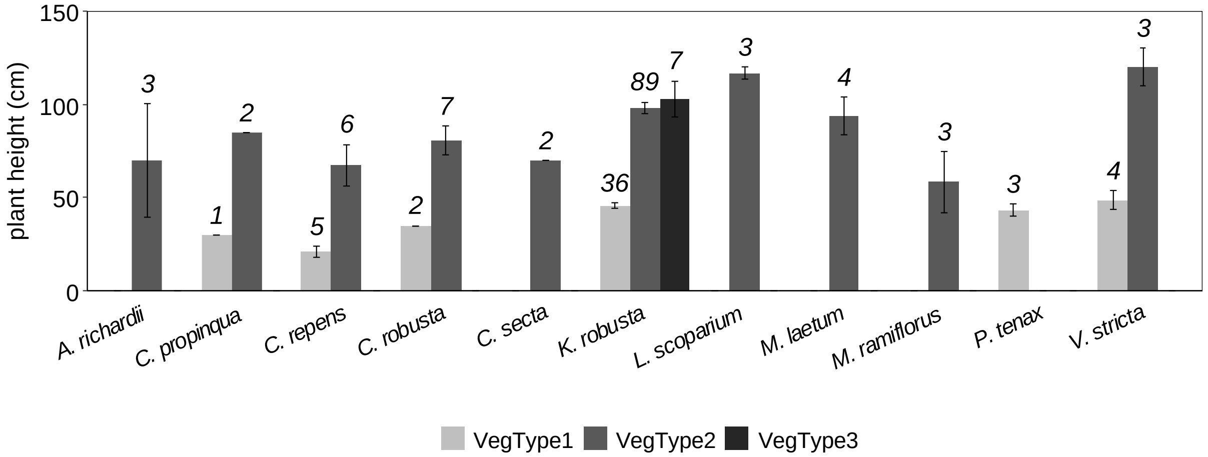

Figure 17 Plant height of individual native species in different vegetation management types (VegTypes) at The Pot in May 2019, approx. one year after planting. VegType1: non-irrigated, VegType2: irrigated with weed management, VegType3: irrigated without weed management. Values are means ± standard errors, with n shown above error bars.

4.3.2 Monitoring 2021

Transects conducted in May 2021 revealed survival rates in three separate areas were 12%, 10% and 5.5%, respectively, which is similar to the survey from May 2019. The overall plant survival in 2021 was 6.1% without weed management. This was slightly higher than the 3.3% survival rate measured in 2019. The apparent increase in plant survival observed between 2019 and 2021 is likely due to the dense weed cover in 2019, which made it hard to locate native plants that were overgrown. The inability to locate native seedlings can significantly skew survival rates (Anton et al., 2015). In addition, it is possible that some heterogeneity in planting occurred.

These results indicate that the plants that survived the first six-months to one-year after planting were highly likely to survive for at least three years. This is likely due to the plants becoming tall enough to overshadow the inkweed and nightshade. Figure 18 shows that the height of the surviving plants was 1 - 2 m in May 2021, with an average height of 1.4 m. These findings demonstrate that intensive weed control is critical in the first year of growth, however, thereafter plant survival is high even in the absence of weeding.

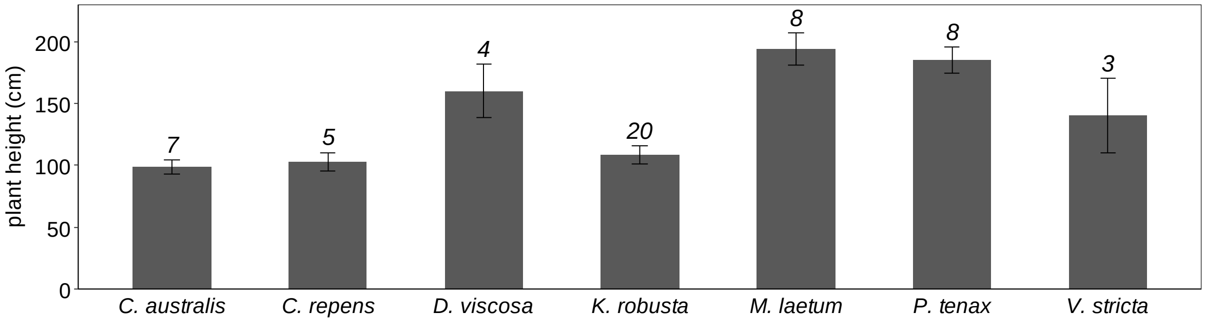

Figure 18 Plant height of native species recorded in transects at The Pot in May 2021, approx. three years after planting. All transects were taken in VegType3 (irrigated without weed management). Values above bars show the number of plants recorded (n).

Some species had significantly increased in height since 2019, for example taupata (53% height increase) and ngaio (107% height increase). In contrast, the average height of kānuka and koromiko only increased marginally (10% and 17%, respectively). Results contrast with those of Bergin and Kimberley (2011), who reported that kānuka had a height growth rate higher than other shrubs and small trees. In this study, this was only observed in the early stages of plant growth, when kānuka was one of the tallest plants measured in May 2019. Furthermore, kānuka was contributing to 36% of surviving plants. This indicates that this species performed relatively poorly compared to others, as it initially contributed 49% to all plants at the site. Similarly, mānuka was not present in any of the transects conducted in 2021, indicating that this species was not establishing well. This is consistent with results from the preliminary experiment (Section 4.1), whereby kānuka and mānuka did not benefit from TMW irrigation. It is possible that these species were therefore more susceptible to weed competition than others, resulting in high mortality. Furthermore, poor planting techniques may have impaired the initial growth and survival of these species, as they can be sensitive to root disturbance (Boffa Miskell, 2017).

In all transects combined, there was at least one plant for every 20m section of the transects (Figure 19). On average, there were 3.7 plants per 20 m, with a variance of 8.7. This indicates that the distribution of plants was moderately clumped (Fakhar Izadi & Keshtkar, 2020). This is also visible from the aerial view of The Pot (Figure 20). While regeneration of native vegetation will typically occur naturally given the proximity of the experimental plots to existing native vegetation (Sullivan et al., 2009), we did not observe any natural regeneration by 2022. This was likely due to the additional stressors in the form of weed growth and TMW irrigation. The speed of regeneration may be increased if these areas were interplanted with fast growing tree species such as ngaio, akeake, and koromiko, provided that the plants are weeded in the first year of growth. However, seedlings interplanted at the site in 2019 and 2020 also showed low survival rates.

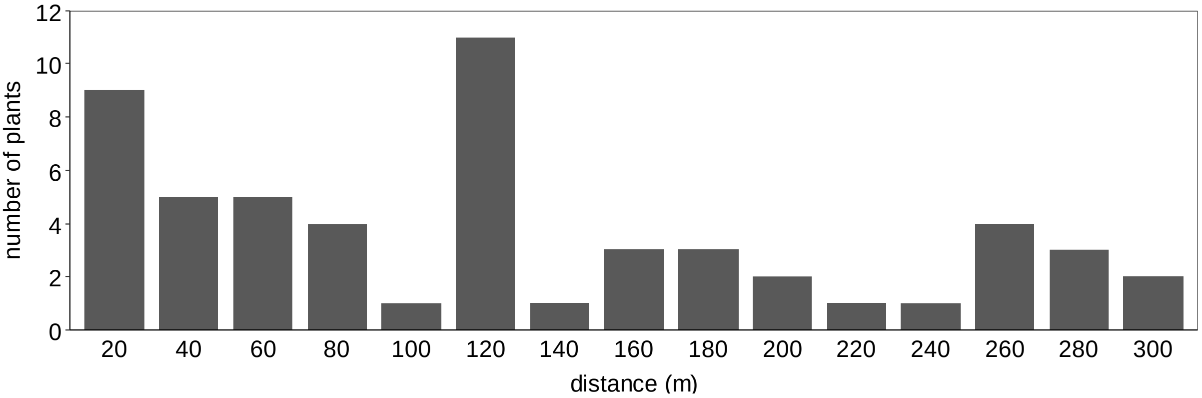

Figure 19 Distribution of native plants along all transects recorded at The Pot in May 2021, approx. three years after planting, in VegType3 (irrigated without weed management).

Figure 20 An aerial view of part of the experimental plot, showing the effect of the irrigation.

Throughout the site there was evidence of damage due to snails, browsing animals, and perhaps wayward herbicides used for weed control (Figure 21). The control of these factors will be crucial to minimise plant mortality. Early intervention will limit damage and reduce costs of lengthy management strategies and potential infill plantings that could otherwise become necessary.

Figure 21 Damage to native plants caused by snails (A & B); browsing animals (C); and suspected pesticide drift (D & E). Note that D & E were in non-irrigated areas and adjacent to areas where herbicide had been used.

4.3.3 Monitoring 2022

In May 2022, the plant density differed between the seven sampled areas (Figure 22). The ‘Top’ transect represented most of the ca. 10 ha of native plantings on the site. Here, the survival of planted NZ-native species was just 3%, with the remainder covered with inkweed or naturally-occurring NZ-native ferns. It should be noted that not all of the area was planted so the actual survival rate may be marginally higher than was measured. The survival in this area was 5.5% in 2021, indicating that some plant mortality occurred during the last year, likely due to higher irrigation rates.

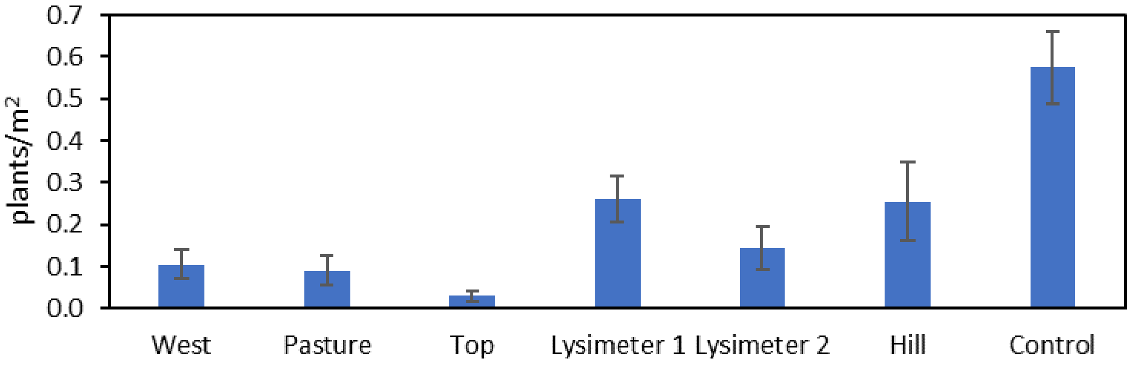

Figure 22 Density of NZ-native plants in the measured transects by plot. Mean ± standard error derived from 12.5 x 2 m transects (*n*=8, except for ‘Lysimeter 2’ *n*=13).

The ‘West’ site includes a former skid site, which had very low growth of any species. Plants on this site showed signs of nutrient deficiency and most of the site is not irrigated. Survival was ca. 10%. It is likely that neither NZ-natives nor pines will rapidly establish in this area (Hall, 1996). In this plot, the survival rate did not change since 2021, which is consistent with this site being more affected by another factor than irrigation.

‘Pasture’ was predominantly covered with Yorkshire fog. This site did not support pine growth before harvesting. Here again, survival was just 10% and it is unlikely that a canopy of NZ-native vegetation will establish without additional plantings and subsequent site management.

The two ‘Lysimeter’ plots had native plant densities of 0.26 and 0.15 plants/m^2, respectively. However, this is not transferable into survival rates due to fill-in plantings that occurred after the initial planting. It was noted that since 2021, large parts of these and other paddocks had become devoid of vegetation and covered in moss, indicating increasing irrigation rates. In the ‘Hill” plot, the plant density was similar to the lysimeter plots.

The Control plot had significantly higher survival (58%) compared to the TMW-irrigated plots and canopy closure has already occurred over much of the plot. This survival rate, however, is still lower than the >62% reported in other restoration plantings in New Zealand (Anton et al., 2015). Plants may experience water stress or nutrient deficits in the sandy soil at The Pot. Nevertheless, plant survival wasn’t lower than in the non-irrigated plot measured in 2019, supporting the finding that plant mortality is highest in the first year after planting. This is in contrast with other reports of high mortality even at ≥2 years after planting (Anton et al., 2015). It is possible that the TMW irrigation accelerated plant growth and therefore decreased the critical time during which native seedlings are too small to exceed the weed canopy.

In the TMW-irrigated area, most of the native species significantly increased in height since 2021 (Figure 23). However, koromiko showed signs of chemical toxicity and did not increase in height. Similarly, akeake had brown lesions on the leaves, which could potentially indicate toxicity from TMW irrigation or spray drift (Figure 24). Karamu showed signs of animal browsing, with many specimens being defoliated, and did also not increase in height. With the exception of kānuka, plant heights in the control plots were the same or lower than in the TMW-irrigated plots. Therefore, over the four-year growing period, there is evidence that the TMW increased plant growth. This is consistent with another site where TMW irrigation accelerated the growth of New Zealand native vegetation (Meister et al., 2022). The most successful native species were New Zealand flax, ngaio, and cabbage tree.

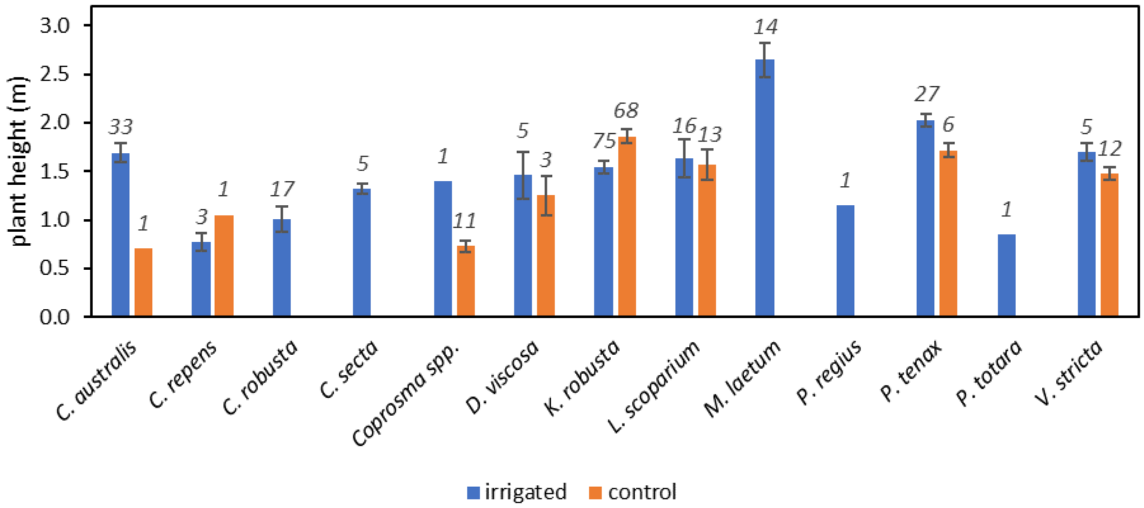

Figure 23 Plant height of NZ-native species in all irrigated transects combined, as well as in the non-irrigated control block next to the entrance. Mean ± standard error, with the italic number showing the number of plants recorded.

Figure 24 Evidence of toxicity in akeake.

4.4 Plant growth and contaminant fluxes in kānuka and mānuka *vs* pasture with different rates of TMW irrigation

4.4.1 Plant growth and chemical composition

Surprisingly, there was no significant correlation between the relative TMW irrigation rate and mānuka and kānuka plant height, nor between irrigation rate and pasture biomass (Table 5). It appears that TMW had neither a beneficial nor a detrimental effect on plant growth in these species. This is consistent with results from the preliminary experiment (Section 4.1). However, it is in contrast with other studies whereby TMW irrigation resulted in a positive growth response in kānuka (Meister et al., 2022) and pasture (Gutierrez-Gines et al., 2020). However, it is likely that the soil at The Pot already contained sufficient levels of nutrients for plant growth, because the site had been irrigated with TMW for >30 years prior to this experiment. This soil nutrient legacy meant that additional application of nutrients likely had no effect on plant growth. In the case of mānuka and kānuka, the lack of correlation may also be due to plant height potentially not correlating with plant biomass, which was not measured. Alternatively, the growth promoting properties of the TMW may be offset by some toxic factor in the effluent or elsewhere.

Table 5 Relative irrigation and soil chemistry at 0-10 cm depth under kānuka, mānuka and pasture.

0-10 cm	Kānuka	Mānuka	Pasture
Irrigation (m/day)	11 (2.5-50)	10 (2.4-43)	12 (2.6-81)
pH	4.7 (4.4 - 5.0)	4.7 (4.4 - 5.0)	4.8 (4.4 - 5.2) **[-S]**
EC (dS/m)	149 (83 - 265)	116 (54 - 250)	118 (73 - 235)
Total C (%)	5.5 (3.4 - 8.7)	4.9 (2.6 - 9.0)	5.4 (3.5 - 10)
Total N (%)	0.27 (0.17 - 0.33)	0.25 (0.13 - 0.49)	0.28 (0.18 - 0.58)
NO_3^--N	7.5 (2.5 - 23)	7.0 (1.9 - 26)	4.9 (1.8 - 16) **[+S*]**
NH_4^+-N	19 (11 - 33)	16 (9. 1 - 30)	16 (9.7 - 30)
Total P	579 (500 - 671)	577 (491 - 678)	535 (456 - 634)
Olsen P	131 (105 - 163) **[+S]**	121 (66 - 222) **[+S*]**	122 (91 - 214)
Total Na	734 (616 - 876) **[+S]**	803 (689 - 936)	708 (589 - 878) **[+S*]**
Total K	2584 (1999 - 3088)	2506 (2080 - 3019)	2278 (2008 - 2736)
Total Ca	7208 (6643-7822)	7476 (6988-7997)	7233 (6746-7834)
Total Mg	2570 (2325-2842)	2580 (2299-2896)	2409 (2265-2631)
Extractable Mg	129 (62-269) **[-S*]**	158 (87-287)	99 (37-235) **[-S]**
Total As	2.2 (1.9 - 2.6)	2.3 (2.0 - 2.5)	2.0 (1.9 - 2.3) **[+S*]**
Total Cd (µg/kg)	8.3 (5.6 - 12.3) **[-S*]**	6.5 (4.8 - 8.8) **[-S]**	5.5 (3.9 - 8.2) **[-S]**
Total Cu	5.0 (4.1 - 5.9)	4.7 (3.7 - 5.8) **[-S*]**	4.6 (3.7 - 5.8)
Total Pb	4.2 (3.4 - 5.3) **[-S]**	4.0 (3.6 - 4.5)	3.9 (3.5 - 4.8)

Values are geometric means and standard deviation ranges (*n*=17). Values are in mg/kg unless otherwise indicated. Variables that were significantly correlated with the relative irrigation are indicated in bold in square brackets; S: $p \leq 0.05$, S*: $p \leq 0.01$, S**: $p \leq 0.001$. Positive and negative correlations are indicated by + and -, respectively.

Figures 25A & B show that there were highly significant negative correlations between mānuka and kānuka heights and plant sodium concentrations. Sodium is non-essential for plant growth and is toxic at elevated concentrations (Bernstein, 1975). However, sodium concentrations in mānuka and kānuka were similar or lower than those reported in other studies (Esperschuetz, Anderson, et al., 2017; Reis et al., 2017). In contrast, pasture sodium concentrations were fourfold higher than the average concentrations in NZ pasturelands (Reiser et al., 2014), but they were not correlated with biomass. While sodium concentrations in the TMW were high (61 mg/L), it is possible that the proximity of The Pot to the sea also had an effect on plant sodium concentrations. It was shown that sea spray can increase Na concentrations (Jensen et al., 2019). The distance between the experimental area at The Pot and the sea is about 1 km and strong westerly winds are common in this area, increasing sea spray (KCDC, 1999). This is supported by results of the weed management trial (Section 4.2), where the mānuka planted farther from the sea were healthier than those planted closer.

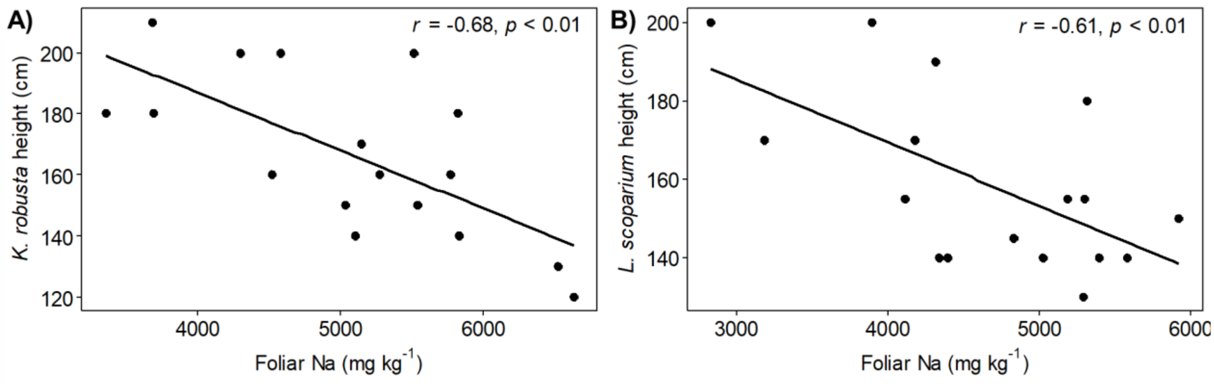

Figure 25 Foliar sodium (Na) concentration versus plant height of A) kānuka and B) mānuka.

The application rate of the major plant nutrients nitrogen, phosphorus, and potassium (Table 1) were three to eight times higher than at other land application sites (Meister, 2022; Sparling et al., 2006). Concentrations of these elements in pasture were higher than average values reported in pasturelands by Reiser et al. (2014). Similarly, in kānuka and mānuka their concentrations were higher than in other unamended soils (Dickinson et al., 2015) and soils with biosolids application (Esperschuetz, Anderson, et al., 2017; Gutierrez-Gines et al., 2019; Reis et al., 2017). In contrast to macronutrients, the concentrations of trace elements in pasture were similar (zinc, arsenic) or lower (cadmium, copper) than reported for NZ pasturelands (Reiser et al., 2014).

There were some positive correlations between relative irrigation rate and plant macronutrients, for example nitrogen in pasture and phosphorus in kānuka. Similarly, there were some positive correlations between trace elements and irrigation rate. Arsenic and lead correlated with TMW irrigation in kānuka, and copper and lead correlated with TMW irrigation in pasture. However, it is not clear if this was due to trace elements being applied with TMW, because their concentrations in TMW were below the detection limit (Table 1). Effects of TMW irrigation on the soil biogeochemistry may have resulted in higher uptake of trace elements already present in the soil.

There were significant differences in the chemical composition between pasture and the NZ-native plants mānuka and kānuka. This has been reported by other authors (Hahner et al., 2014). Figures 26A & B show the chemical separation of the plants as depicted by a principal component analysis. The pasture contained higher concentrations of macronutrients and lower concentrations of micronutrients than the myrtaceous species. There was no separation between mānuka and the kānuka.

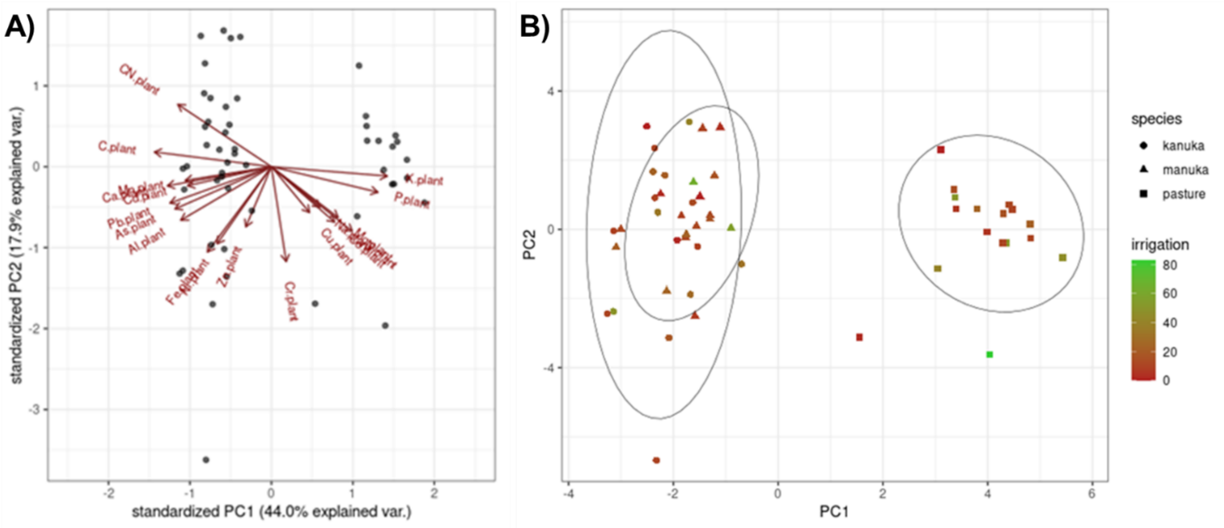

Figure 26 Principal component analysis of the plant chemistry showing the eigenvectors (A) and Principal Component 1 vs Principal Component 2 (B).

4.4.2 Soil chemistry

Tables 6 and 7 show the chemical composition of the topsoil (0-10 cm depth) and subsoil (30-45 cm depth), respectively, under mānuka, kānuka, and pasture. The topsoil can be classified as "acidic". Under pasture, the relative TMW irrigation rate was negatively correlated with soil pH in both the top- and subsoil. This was not observed under kānuka and mānuka. The negative correlation is in contrast to other studies reporting pH increases in TMW irrigation systems (Sparling et al., 2006; Walker & Lin, 2008). The low soil pH was likely a result of leaching of basic cations (calcium, magnesium, potassium) from the soil and the associated decrease in the soil's acid buffering capacity (Chahal et al., 2011; Werner et al., 2019), due to the high application of sodium. Sodium concentrations were 2-3 times higher than those measured in TMW irrigated soil elsewhere in NZ (Meister et al., 2022), which can explain the impaired growth observed in mānuka and kānuka with increasing TMW irrigation rates.

Table 6 Relative irrigation and soil chemistry at 0-10 cm depth under kānuka, mānuka and pasture.

0-10 cm	**Kānuka**	**Mānuka**	**Pasture**
Irrigation (mm/day)	11 (2.5-50)	10 (2.4-43)	12 (2.6-81)
pH	4.7 (4.4 - 5.0)	4.7 (4.4 - 5.0)	4.8 (4.4 - 5.2) **[-S]**
EC (dS/m)	149 (83 - 265)	116 (54 - 250)	118 (73 - 235)
Total C (%)	5.5 (3.4 - 8.7)	4.9 (2.6 - 9.0)	5.4 (3.5 - 10)
Total N (%)	0.27 (0.17 - 0.33)	0.25 (0.13 - 0.49)	0.28 (0.18 - 0.58)
NO_3^--N	7.5 (2.5 - 23)	7.0 (1.9 - 26)	4.9 (1.8 - 16) **[+S*]**
NH_4^+-N	19 (11 - 33)	16 (9. 1 - 30)	16 (9.7 - 30)
Total P	579 (500 - 671)	577 (491 - 678)	535 (456 - 634)
Olsen P	131 (105 - 163) **[+S]**	121 (66 - 222) **[+S*]**	122 (91 - 214)
Total Na	734 (616 - 876) **[+S]**	803 (689 - 936)	708 (589 - 878) **[+S*]**
Total K	2584 (1999 - 3088)	2506 (2080 - 3019)	2278 (2008 - 2736)

Total Ca	7208 (6643-7822)	7476 (6988-7997)	7233 (6746-7834)
Total Mg	2570 (2325-2842)	2580 (2299-2896)	2409 (2265-2631)
Total As	2.2 (1.9 - 2.6)	2.3 (2.0 - 2.5)	2.0 (1.9 - 2.3) **[+S*]**
Total Cd (µg/kg)	8.3 (5.6 - 12.3) **[-S*]**	6.5 (4.8 - 8.8) **[-S]**	5.5 (3.9 - 8.2) **[-S]**
Total Cu	5.0 (4.1 - 5.9)	4.7 (3.7 - 5.8) **[-S*]**	4.6 (3.7 - 5.8)
Total Pb	4.2 (3.4 - 5.3) **[-S]**	4.0 (3.6 - 4.5)	3.9 (3.5 - 4.8)

Values are geometric means and standard deviation ranges (n=17). Values are in mg kg^{-1} unless otherwise indicated. Variables that were significantly correlated with the relative irrigation are indicated in bold in square brackets; S: $p \leq 0.05$, S*: $p \leq 0.01$, S**: $p \leq 0.001$. Positive and negative correlations are indicated by + and -, respectively.

Table 7 Soil chemistry at 30-45 cm depth under kānuka, mānuka, and pasture.

30-45 cm	**Kānuka**	**Mānuka**	**Pasture**
pH	5.3 (4.9 - 5.7)	5.5 (5.0 - 6.1)	5.3 (4.8 - 5.8) **[-S]**
EC (dS/m)	30 (20 - 47)	27 (19 - 39)	22 (17 - 32) **[+S]**
Total C (%)	0.7 (0.5 - 1.0)	0.6 (0.5- 0.8)	0.7 (0.5 - 0.9)
Total N (%)	<0.05	<0.05	<0.05
NO_3^--N	2.0 (0.6 - 6.4)	1.9 (0.6 - 5.9)	1.1 (0.3 - 3.9)
NH_4^+-N	4.6 (2.5 - 8.5)	4.2 (2.3 - 7.5)	4.0 (2.0 - 7.2)
Total P	388 (307 - 490)	372 (299 - 464)	417 (325 - 524)
Olsen P	39 (22 - 66)	28 (12 - 62)	50 (27 - 110)
Total Na	734 (658 - 818)	712 (586 - 866)	680 (570 - 817)
Total K	2121 (1683 - 2676)	2416 (2163 - 2700)	2118 (1640 - 2423)
Total Ca	7418 (6771-8126)	7726 (7296-8182)	7562 (6487-8277)
Total Mg	2880 (2584-3209)	3058 (2821-3315)	2882 (2407-3198)
Total As	2.5 (2.2 - 2.9) **[+S]**	2.6 (2.4 - 2.9)	2.6 (2.2 - 3.0)
Total Cd (µg/kg)	5.2 (3.5 - 7.9)	6.5 (5.3 - 4.1)	5.1 (3.5 - 7.7)
Total Cu	3.7 (3.4 - 3.9)	3.7 (3.3 - 4.1)	3.7 (3.2 - 4.0)
Total Pb	3.7 (3.4 - 4.2)	3.8 (3.6 - 4.1)	3.8 (3.4 - 4.2)

Values are geometric means and standard deviation ranges (n=17). Values are in mg kg^{-1} unless otherwise indicated. Variables that were significantly correlated with the relative irrigation (Table 4-1) are indicated in bold in square brackets; S: $p \leq 0.05$, S*: $p \leq 0.01$, S**: $p \leq 0.001$. Positive and negative correlations are indicated by + and -, respectively.

Total C and N concentrations were ca. 10-fold lower than those found in pastoral soils (Reiser et al., 2014). This is typical for a sandy soil as its ability to store organic matter is low due to the low specific surface area of sand (McLaren & Cameron, 1996). There was no correlation between soil total carbon and nitrogen concentrations and relative TMW irrigation rate. However, there were strong positive correlations between total carbon and nitrogen in the topsoil under all species (r=0.97, $p \leq 0.01$), which is consistent with most of the soil nitrogen being present as organic nitrogen. About 45% of the nitrogen applied with TMW was applied as organic nitrogen (Table 1). Organic nitrogen can readily leach from Recent soils (Barton et al., 2005) and would therefore not have accumulated in the soil. Concentrations of mineral nitrogen, namely ammonium and nitrate, were relatively high, indicating there was sufficient available nitrogen for plant growth. This is consistent with the high nitrogen concentrations in the plant foliage (Table 5). Soil nitrate and ammonium concentrations were similar to those found elsewhere after only 1-3 years of TMW irrigation (Barton et al., 1999; Meister et al., 2022). Given the high mobility of nitrate in soil (Di & Cameron, 2002), its concentration likely rose with the onset of TMW irrigation but did not continue to increase over time due to leaching.

As with nitrogen, total phosphorus concentrations were just 50% of what is typically found in NZ pastoral soils (McDowell & Condron, 2004; Reiser et al., 2014), yet plant-available phosphorus, as indicate by Olsen P (~125 mg/kg), was manifold higher than what is required for plant growth (10 - 40 mg/kg) and comparable with values reported in market gardens, which is considered "excessive", i.e. likely to lead to environmental degradation (Drewry et al., 2021; Taylor et al., 2016). Olsen P in the topsoil was positively correlated with relative irrigation under kānuka (r=0.60, p≤0.05) and mānuka (r=0.64, p≤0.01). While phosphorus is mostly entering streams through surface runoff (Pionke et al., 2000), leaching losses of phosphorus can be high with TMW irrigation (Sparling et al., 2006). Given the high Olsen P content at The Pot and the relatively high hydraulic conductivity of sandy soils (LEI, 2017; McLaren & Cameron, 1996), subsurface flow can be expected to contribute to phosphorus fluxes into groundwater and the Waiwiri Stream (Mittelstet et al., 2011).

Concentrations of the trace elements arsenic, cadmium, chromium, copper, lead, and nickel in the TMW were below detection limit (<0.01 mg/L) and within the recommended limits for continuous TMW irrigation (FAO, 2003). They are not expected to accumulate in the soil, and measured concentrations were similar or lower than in NZ pastoral soils (Reiser et al., 2014). However, there was a positive correlation between TMW irrigation rate and arsenic in the topsoil under pasture, and in the subsoil under kānuka. In the topsoil, cadmium was negatively correlated with TMW irrigation under all species, and the same was true for copper under mānuka and lead under kānuka. Soil pH is the major factor controlling the solubility of trace elements in soil (Bradl, 2004). The low pH at The Pot likely resulted in high solubility of trace elements, and therefore a reduction in the topsoil with high TMW irrigation. Therefore, changes in trace element concentrations and leaching likely derive from changes in the geochemistry of the soil, rather than from inputs through TMW.

4.4.3 Species potential to manage nutrients and contaminants

The uptake of N by pasture was equivalent to 204 kg/ha, which represents just 13% of the annually applied N (Table 1). This indicates that pasture could only remove a small fraction of the applied N if it were harvested regularly. Similarly, the concentration of P in the pasture was equivalent to a plant uptake of 32 kg/ha, which represents 10% of annually applied P. This is not consistent with other studies, whereby cut-and-carry pasture can significantly uptake large proportions of the nutrients applied to land with wastewater (Gutierrez-Gines et al., 2020; Luo et al., 2004). Marden and Lambie (2016) found that mānuka annual rates of biomass production ranged from 27 to 785 kg/ha/yr at a plant density equivalent to 8-12% survival rate of plantings at The Pot. At such biomass production rates, and assuming that the measured foliage nitrogen and phosphorus concentrations are representative for all of the aboveground biomass, this would be equivalent to accumulation rates of 0.6 to 17 kg N/ha/yr and 0.06 to 1.8 kg P/ha/yr, respectively. For both elements, these uptake rates are manifold lower than the amount of nitrogen and phosphorus applied with TMW (Table 1). The N uptake aligns with that reported in 25-year old stands of mānuka and kānuka of 104 and 22 kg N/ha, respectively (Scott et al., 2000). If native plant survival rates were as high as 80% reported at another TMW irrigation site (Meister et al., 2022), nitrogen and phosphorus accumulation rates may be up to 170 kg N/ha/yr and 180 kg P/ha/yr, respectively. If all the plants were harvested and removed from the site, this would remove 11% of the applied nitrogen and 58% of the applied phosphorus at the current TMW irrigation rate.

Soil N concentrations did not differ between species, indicating that excess N that is not taken up by plants will be leached from the soil or lost via denitrification. Despite the difference in nutrient uptake between the tested species, there were no differences in soil N and P between the myrtaceous species and pasture (Tables 2 and 3). While previous studies showed different effects of kānuka and mānuka on soil nitrogen concentrations and losses compared to other species (Chahal et al., 2011; Werner et al., 2019), any such effects were likely outweighed by high nitrogen application rates at the study site. Therefore, it is expected that immobile nutrients such as phosphorus will continue to accumulate in the soil until saturation and eventually leach, while more mobile ones such as nitrate will readily leach from the soil into groundwater as well as the nearby Waiwiri Stream. Further losses of nitrogen are by denitrification, and plant species can distinctively affect soil conditions and the rate of denitrification (Alldred & Baines, 2016), although such effects may be similarly outweighed by irrigation and nitrogen application at the high TMW application rates at The Pot.

4.5 Water flux meters

The irrigation onto the lysimeters was fluctuating throughout the year due to differences in the water levels in the pond. We measured relative rates of irrigation onto the eight lysimeters and found that there were no significant differences between them.

The recorded irrigation of TMW during the three days of monitoring in May 2021 was 14 ± 2.3 mm/day. There was no significant difference in irrigation between lysimeters with kānuka and pasture. The average drainage in the kānuka and pasture lysimeters was 1.0 mm/day and 1.4 mm/day, respectively (Table 8). As irrigation was not measured underneath the canopy, the lower leaching under kānuka was likely affected by the “umbrella effect” (Mertens et al., 2005) whereby the irrigated TMW directly re-evaporated from the kānuka canopy.

Table 8 Drainage and nitrate leaching in the lysimeters planted with kānuka and pasture.

	Kānuka	Pasture
Drainage (mm/day)	1.0 ± 0.25	1.4 ± 0.35
Nitrate leaching (mg NO_3^--N/day)	2.0 ± 0.78	2.7 ± 1.4

Mean ± standard error (*n*=6).

There was no significant difference in nitrate leaching between kānuka and pasture. The results are not consistent with those of (Esperschuetz, Balaine, et al., 2017), who reported that kānuka may inhibit nitrification and reduce nitrate leaching more than other species. However, potential inhibiting effects of kānuka on nitrification may have been offset by the high TMW irrigation rate, which limits any potential plant effect on N cycling. Nitrate leaching was equivalent to 28% and 38% of the applied nitrogen under kānuka and pasture, respectively. In a study by Barton et al. (2005), 22% of applied N was lost through leaching, although 87% thereof was leaching as organic nitrogen. With approximately 45% of N at The Pot applied as organic nitrogen (Table 1), it can be expected that organic nitrogen leaching significantly contributes to total nitrogen leaching.

Samples from the sampling campaign conducted between November 2021 and January 2022 were sent for analysis of nitrate and ammonium. Generally, the mass of nitrate leached was small, representing about 2-20% of the mass of nitrogen applied. This was most likely due to groundwater ingression that led to a dilution of the leachate within the lysimeter, and possibly due to some denitrification. However, denitrification in TMW-irrigated soils was reported to contribute just 1% to N losses from TMW-irrigated soils (Van der Weerden et al., 2016). It was evident that the lysimeters had become flooded due to nearby surface ponding. There were no surviving kānuka on two of the lysimeters (Figure 27), and consequently no roots to impede infiltration. All higher plants at these sites were dead, presumably due to chemical toxicity arising from excessive TMW irrigation.

Figure 27: All kānuka and other higher plants on two of the lysimeters had died, leaving a cover of moss.

Escherichia coli analysed in the leachates from the WFM between February and April 2022 did not show differences between kānuka and pasture. Of the 18 analysed samples (6 WFMs x 3 dates), 10 samples did not recover any *E. coli* counts. Five samples from WFMs under kānuka had *E. coli* levels between 1 and 39 MPN/100 mL, while three samples from the same WFMs under pasture had levels of 580 to >2400 MPN/100 mL. This indicates that under certain conditions, most likely due to high irrigation rates and high leachate rates under pasture (as demonstrated previously), the concentration of *E. coli* in water that can potentially leach into groundwater is higher than the limits considered safe for recreational water (<130 MPN/100 mL, MfE (2022)).

4.6 General observations

4.6.1 Apparent increase in irrigation rates

In May 2022, we observed a change in the weed flora at the site. Ferns, particularly bead ferns (*Hypolepis* spp.), bracken (*Pteridium aquilinum*), and water-fern (*Histiopteris incisa*) were widespread (Figure 28A). These species were outcompeting the inkweed and nightshade, which were the predominant weed species at The Pot in 2021, at some locations. In other areas, pampas grass (*Cortaderia selloana*) has become dominant (Figure 28B). Pampas grasses are an invasive weed and require control (Gosling et al., 2000).

Figure 28 Weeds observed in May 2022**.** A) Ferns were the predominant species in many TMW-irrigated plots; B) pampas grass was widespread.

The changes in the weed flora are consistent with observations of extremely wet conditions at the site. The fern species and pampas grasses mostly occur in wet conditions (Gosling et al., 2000; Lehmann et al., 2002). Standing water was present in various locations across the experimental plots at The Pot (Figure 29A & B). In many of these areas, all higher plants had died, including both weeds and NZ-native plants, which was a likely a consequence of either the waterlogged conditions which plants were not selected for, or chemical toxicity arising from high application rates of TMW (Figure 30A). Toxicity can derive from excess nutrients or increased sodicity and salinity, for example (Bernstein, 1975; Chaney, 1989). Some areas around the sprinklers were only covered in pasture and could not sustain other plant species (Figure 30B). In contrast, native plants were more present outside of the irrigated areas. In order to avoid further plant death, a reduction in TMW application will likely be required. It was demonstrated elsewhere that native vegetation can be established successfully with TMW irrigation of 1000 mm/yr (Meister et al., 2022). If this was achieved, native plantings at The Pot would be highly valuable as they provide ecosystem services, for example carbon sequestration and erosion control, provide a habitat for native insects and birds, and may be utilised for the production of fibre and timber (Gutierrez-Gines et al., 2022).

Figure 29 A) Standing water in the TMW-irrigated plots; B) cabbage trees starting to die off in May 2022.

Figure 30 A) TMW-irrigated area where the death of all higher plants occurred; B) area where only pasture species can be found surrounding a sprinkler in May 2022.

In some areas that were not water-logged and received little or no irrigation, NZ-native plants were alive but appeared to have not grown and their size was lower than what would be expected for the plants' age (Figure 31). This indicates that it is unlikely a closed canopy of native plants will establish there. It should be noted that in some of these areas there were no pines (before harvesting) and scant weed cover. In these areas, another growth limiting factor is evident. It is possible that these areas were previously used for skid sites. Tree growth is often impaired at skid sites due to the area being stripped of topsoil and compacted (Hall, 2013). This shows that historical land use needs to be considered when land treatment sites are established, independent of the intended vegetation type.

Figure 31 Non-irrigated areas where native plants are not growing well in May 2022.

4.6.2 Pests

Throughout the site, there was evidence of animals impairing plant growth in May 2022. Droppings of deer and cows were distributed throughout the plots, and a cow was spotted on site (Figure 32). In addition, snails were present at the site, which were also observed in 2021. We observed plant damage that was consistent with animal browsing and scratching, including defoliation and broken branches (Figure 33). Fencing and lethal methods of pest control, including shooting and poisoning, may be required to control pests at the site. Where large populations of mammal pests are present, this can lead to the disappearance of palatable, typically large-leaved, species from native plantings (Bee et al., 2007; Smale et al., 1995). This is supported by observations at The Pot, where many *Coprosma* spp. appeared to be defoliated due to browsing (Figure 33).

Figure 32 Evidence of animals browsing and damaging plants at The Pot.

5. Conclusions and recommendations

Over most of the 10 ha, permanent native vegetation cover could not be established in this project. Yet, the results provided evidence that wastewater can increase the growth of native plants. We were able to identify critical success factors for the establishment of native plantings irrigated with TMW.

Irrigation rates are critical for a number of reasons. During early plant establishment, TMW irrigation at rates of ca. 4,000 mm/yr did not directly impair plant health and even increased plant growth in some species. However, this application rate of TMW accelerated the growth of exotic weeds more than that of native seedlings. As a consequence of the dense weed canopy and high irrigation rate, native seedlings were dying in dark and humid conditions created. In the later stages of the project, it appeared that TMW irrigation rates had increased, possibly to >5,000 mm/yr. This led to a change in weed flora and standing water being present in many areas of the pot. Therefore, native plant growth and survival was impaired, either due to them not tolerating water saturated conditions, or due to toxicity deriving from the high application of nutrients and contaminants through TMW. To mitigate these issues, a reduction of TMW irrigation rates is necessary, although this is currently not feasible at The Pot.

Weeds were identified to be most detrimental for native plant establishment. This requires adequate planning and resourcing. Intensive weed management is necessary for at least the first 1-2 years, after which the intensity can be reduced if the native canopy is taller than the weeds. However, some weed control and close monitoring will still be required, in case new weed species appear on site, such as pampas grass, which appeared later than other problematic species such as inkweed and nightshades. Similarly, pests need to be controlled to increase survival rates of native seedlings. Even species that are not considered palatable for mammals were strongly affected by damage from tramping and scratching. Fencing, shooting, and poisoning may need to be considered depending on the prevalent pest species. Overall, results from The Pot have demonstrated that stepwise planting of large areas is advisable so that the plots can be adequately managed and unexpected factors that may present during the critical years of plant establishment, such as weeds and pests, can be rigorously controlled.

There was evidence that sea spray was likely an additional input of sodium, which was found to impair plant growth. This shows that the effect of local environmental conditions and potential microclimates can be significant and were underestimated at The Pot. Although the species selected for the planting at The Pot were considered appropriate for the local dune environment, many could not tolerate a combination of these factors. One way to manage this would be to select a wider range of species and plant them at equal percentages, rather than dominated by one or two species. This will allow for better overall growth, even if individual species may not tolerate local conditions.

There was no evidence of kānuka and mānuka performing better than pasture in regards to decreasing export of pollutants. The only exception was a reduction of leaching under kānuka due to the umbrella effect, whereby irrigation and precipitation evaporates from the foliage of the trees. Furthermore, there was no evidence of different concentrations of nitrogen and phosphorus in the soil underneath kānuka and mānuka vs pasture. Similarly, leaching of *E. coli* did not differ between kānuka and pasture and the high irrigation rate likely resulted in preferential flow and increased leaching. With the low survival of kānuka and groundwater ingression into the WFMs, leaching results are based on very limited sample points and further research is needed. Nevertheless, we can conclude that at high irrigation rates any potential benefits of kānuka and mānuka were outweighed by the application of large amounts of nutrients and contaminants, beyond what any species could manage. Plant uptake only accounted for a small proportion (<20%) of the applied nitrogen and phosphorus. In addition, all nutrients will eventually re-enter the soil through litter inputs and plant senescence. Occasional harvesting of plants, such as for fibre or timber, would be required to allow export of nutrients and contaminants from the site. Ultimately, a decrease in irrigation rate to levels where plants can manage the applied water, nutrients, and contaminants will be most efficient to reduce contaminants losses and improve the water quality in the nearby Waiwiri Stream.

References

Alldred, M., & Baines, S. B. (2016). Effects of wetland plants on denitrification rates: a meta-analysis. *Ecological Applications*, *26*(3), 676-685. https://doi.org/10.1890/14-1525

Allen, C., Sinner, J., Banks, J., & Doehring, K. (2012). *Waiwiri Stream: Sources of Poor Water Quality and Impacts on the Coastal Environment. Manaaki Taha Moana Research Report No. 9* (Cawthron Report No. 2240, Issue.

Barton, L., McLay, C. D. A., Schipper, L. A., & Smith, C. T. (1999). Denitrification rates in a wastewater-irrigated forest soil in New Zealand. *Journal of Environmental Quality*, *28*(6), 2008-2014. https://doi.org/10.2134/jeq1999.00472425002800060042x

Barton, L., Schipper, L. A., Barkle, G. F., McLeod, M., Speir, T. W., Taylor, M. D., McGill, A. C., van Schaik, A. P., Fitzgerald, N. B., & Pandey, S. P. (2005). Land Application of Domestic Effluent onto Four Soil Types: Plant Uptake and Nutrient Leaching. *Journal of Environmental Quality*, *34*, 635-643. https://doi.org/10.2134/jeq2005.0635

Bee, J. N., Kunstler, G., & Coomes, D. A. (2007). Resistance and resilience of New Zealadn tree species to browsing. *Journal of Ecology*, *95*, 1014-1026. https://doi.org/10.1111/j.1365-2745.2007.01261.x

Bernstein, L. (1975). Effects of salinity and sodicity on plant growth. *Annual Review of Phytopathology*, *13*, 295-312. https://doi.org/10.1146/annurev.py.13.090175.001455

Blakemore, L. C., Searle, P. L., & Daly, B. K. (1987). Methods for chemical analysis of soils. *NZ Soil Bureau Scientific Report*, *80*.

Boffa Miskell. (2017). *The Manuka & Kanuka Plantation Guide*.

Boffa Miskell. (2018). *Levin wastewater discharge: The Pot: Assessment of ecological effects*.

Bradl, H. B. (2004). Adsorption of heavy metal ions on soils and soils constituents. *Journal of Colloid and Interface Science*, *277*(1), 1-18. https://doi.org/10.1016/j.jcis.2004.04.005

Chahal, M. K., Toor, G. S., Nkedi-Kizza, P., & Santos, B. M. (2011). Effect of tomato packinghouse wastewater properties on phosphorus and cation leaching in a Spodosol. *Journal of Environmental Quality*, *40*(3), 999-1009. https://doi.org/doi.org/10.2134/jeq2010.0369

Chaney, R. L. (1989). Toxic element accumulation in soils and crops: Protecting soil fertility and agricultural food-chains. In B. Bar-Yosef, N. J. Barrow, & J. Goldshmid (Eds.), *Inorganic Contaminants in the Vadose Zone* (pp. 140-158). Springer. https://doi.org/10.1007/978-3-642-74451-8_10

Chappell, P. R. (2015). *The climate and weather of Manawatu-Wanganui. 2nd edition* (NIWA Science and Technology Series Number 66, Issue.

Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, *46*, 237-256. https://doi.org/10.1023/a:1021471531188

Dickinson, N., Marmiroli, M., Das, B., McLaughlin, D., Leung, D., & Robinson, B. (2015). Endemic Plants as Browse Crops in Agricultural Landscapes of New Zealand. *Agroecology and Sustainable Food Systems*, *39*(2), 224-242. https://doi.org/10.1080/21683565.2014.967438

Dollery, R., Bowie, M. H., & Dickinson, N. M. (2018). Tree guards and weed mats in a dry shrubland restoration in New Zealand. *Ecological Management & Restoration*, *19*(3), 259-263. https://doi.org/10.1111/emr.12341

Drewry, J. J., Cavanagh, J.-A. E., McNeill, S. J., Stevenson, B. A., Gordon, D. A., & Taylor, M. D. (2021). Long-term monitoring of soil quality and trace elements to evaluate landuse effects and temporal change in the Wellington region, New Zealand. *Geoderma Regional*, *25*, e00383. https://doi.org/10.1016/j.geodrs.2021.e00383

Esperschuetz, J., Anderson, C., Bulman, S., Katamian, O., Horswell, J., Dickinson, N. M., & Robinson, B. H. (2017). Response of Leptospermum scoparium, Kunzea robusta and Pinus radiata to contrasting biowastes. *Science of The Total Environment*, *587-588*, 258-265. https://doi.org/10.1016/j.scitotenv.2017.02.134

Esperschuetz, J., Balaine, N., Clough, T., Bulman, S., Dickinson, N. M., Horswell, J., & Robinson, B. H. (2017). The potential of L. scoparium, K. robusta and P. radiata to mitigate N-losses in silvopastural systems. *Environmental Pollution*, *225*, 12-19. https://doi.org/10.1016/j.envpol.2017.03.042

Evans, B. (1983). *Revegetation manual. A guide to revegetation using New Zealand native plants*. Queen Elizabeth the Second National Trust.

FAO. (2003). *User manual for irrigation with treated wastewater*.

Franklin, H. M. (2014). *The interaction of New Zealand native plants with nitrogen in Canterbury's agricultural landscapes* [Doctoral thesis, Lincoln University]. Lincoln. https://hdl.handle.net/10182/6482

Franklin, H. M., Robinson, B. H., & Dickinson, N. M. (2019). Plants for nitrogen management in riparian zones: A proposed trait-based framework to select effective species. *Ecological Management & Restoration*, *20*(3), 202-213. https://doi.org/10.1111/emr.12380

Franklin, H. M., Woods, R. R., Robinson, B., & Dickinson, N. (2017). Nitrous oxide emissions following dairy shed effluent application beneath Kunzea robusta (Myrtaceae) trees. *Ecological Engineering*, *99*, 473-478. https://doi.org/10.1016/j.ecoleng.2016.11.064

Gosling, D. S., Shaw, S. B., & Beadel, S. M. (2000). *Review of control methods for pampas grasses in New Zealand*. D. o. Conservation. https://www.doc.govt.nz/documents/science-and-technical/sfc165.pdf

Gray, C. W., McLaren, R. G., Roberts, A. H. C., & Condron, L. M. (1999). Effect of soil pH on cadmium phytoavailability in some New Zealand soils. *New Zealand Journal of Crop and Horticultural Science*, *27*(2), 169-179. https://doi.org/10.1080/01140671.1999.9514093

Gutierrez-Gines, M. J., Alizadeh, H., Alderton, E., Ambrose, V., Meister, A., Robinson, B. H., Halford, S., Prosser, J. A., & Horswell, J. (2021). Phytoremediation of microbial contamination in soil by New Zealand native plants. *Applied Soil Ecology*, *167*, 104040. https://doi.org/10.1016/j.apsoil.2021.104040

Gutierrez-Gines, M. J., Bisht, A., Meister, A., Robinson, B. H., Clarke, D., Tupuhi, G., Alderton, I., Horswell, J., I-Kai Wang, K., Bohm, K., Taylor, M., Adamson, O. M., Simcock, R., O'Neill, T. A., Nikau, T., & Ambrose, V. (2022). *Maanuka dominated ecosystems to improve water and soil quality in Lake Waikare catchment*. I. o. E. S. a. Research.

Gutierrez-Gines, M. J., Madejon, E., Lehto, N. J., McLenaghen, R. D., Horswell, J., Dickinson, N., & Robinson, B. H. (2019). Response of a pioneering species (Leptospermum scoparium J.R.Forst. & G.Forst.) to heterogeneity in a low-fertility soil. *Frontiers in Plant Science*, *10*, 93. https://doi.org/10.3389/fpls.2019.00093

Gutierrez-Gines, M. J., Mishra, M., McIntyre, C., Chau, H. W., Esperschuetz, J., McLenaghen, R., Bourke, M. P., & Robinson, B. H. (2020). Risks and benefits of pasture irrigation using treated municipal effluent : a lysimeter case study, Canterbury, New Zealand. *Environmental Science and Pollution Research*, *27*(11), 11830-11841. https://doi.org/10.1007/s11356-020-07759-8

Hahner, J. L., Robinson, B. H., Hong-Tao, Z., & Dickinson, N. M. (2014). The phytoremediation potential of native plants on New Zealand dairy farms. *International Journal of Phytoremediation*, *16*(7-12), 719-734. https://doi.org/10.1080/15226514.2013.856845

Hall, P. (2013). Bioenergy options for New Zealand: key findings from five studies. *Wiley Interdisciplinary Reviews: Energy and Environment*, *2*(6), 587-601. https://doi.org/10.1002/wene.60

Horowhenua District Council. (2011). *Outstanding natural landscapes & features review*.

Horowhenua District Council. (2018). *Levin Wastewater Discharge at The Pot - Resource Consent Application and AEE*.

Jensen, H., Orth, B., Reiser, R., Bürge, D., Lehto, N. J., Almond, P., Gaw, S., Thomson, B., Lilburne, L., & Robinson, B. (2019). Environmental parameters affecting the concentration of iodine in New Zealand pasture. *Journal of Environmental Quality*, *48*, 1517-1523. https://doi.org/10.2134/jeq2019.03.0128

KCDC. (1999). *A guide to growing native plants in Kapiti*.

Lai, P. C. C., & Wong, B. S. F. (2005). Effects of Tree Guards and Weed Mats on the Establishment of Native Tree Seedlings: Implications for Forest Restoration in Hong Kong, China. *Restoration Ecology*, *13*(1), 138-143. https://doi.org/10.1111/j.1526-100X.2005.00016.x

Lehmann, A., Leathwick, J. R., & Overton, J. M. (2002). Assessing New Zealand fern diversity from spatial predictions of species assemblages. *Biodiversity & Conservation*, *11*(12), 2217-2238. https://doi.org/10.1023/A:1021398729516

LEI. (2017). *Levin wastewater land application re-consenting: The Pot site characterisation*.

Luo, J., Lindsey, S., & Xue, J. (2004). Irrigation of meat processing wastewater onto land. *Agriculture, Ecosystems & Environment*, *103*(1), 123-148. https://doi.org/https://doi.org/10.1016/j.agee.2003.10.008

Marden, M., & Lambie, S. (2016). *Plot-based, growth performance of space-planted mānuka (Leptospermum scoparium) on marginal land, and vulnerability to erosion*. M. f. P. Industries.

McDowell, R. W., & Condron, L. M. (2004). Estimating phosphorus loss from New Zealand grassland soils. *New Zealand Journal of Agricultural Research*, *47*(2), 137-145. https://doi.org/10.1080/00288233.2004.9513581

McLaren, R. G., & Cameron, K. C. (1996). *Soil Science: Sustainable Production and Environmental Protection*. Oxford University Press.

McLeod, M. (2018). *Soils of "The Pot" and "Tucker Block" - Levin*.

Meister, A. (2022). *Soil-plant interactions of New Zealand native vegetation irrigated with treated municipal wastewater* [PhD thesis, University of Canterbury]. https://ir.canterbury.ac.nz/handle/10092/103727

Meister, A., Li, F., Gutierrez-Gines, M. J., Dickinson, N., Gaw, S., Bourke, M., & Robinson, B. (2022). Interactions of treated municipal wastewater with native plant species. *Ecological Engineering*, *183*, 106741. https://doi.org/10.1016/j.ecoleng.2022.106741

Mertens, J., Barkle, G. F., & Stenger, R. (2005). Numerical analysis to investigate the effects of the design and installation of equilibrium tension plate lysimeters on leachate volume. *Vadose Zone Journal*, *4*(3), 488-499. https://doi.org/10.2136/vzj2004.0161

MfE (Ministry for the Environment). (2022). *National Policy Statement for Freshwater Management 2020*. https://environment.govt.nz/assets/publications/National-Policy-Statement-for-Freshwater-Management-2020.pdf

Miranda, K. M., Espey, M. G., & Wink, D. A. (2001). A rapid, simple spectrophotometric method for simultaneous detection of nitrate and nitrite. *Nitric Oxide*, *5*(1), 62-71. https://doi.org/10.1006/niox.2000.0319

Mittelstet, A. R., Heeren, D. M., Fox, G. A., Storm, D. E., & White, M. J. (2011). Comparison of subsurface and surface runoff phosphorus transport rates in alluvial floodplains. *Agriculture, Ecosystems & Environment*, *141*, 417-425. https://doi.org/10.1016/j.agee.2011.04.006

Mulvaney, R. L. (1996). Nitrogen–Inorganic Forms. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Leoppert, P. Soltanpour, N. Tabatabai, M. A. Johnston, & M. E. Summer (Eds.), *Methods of Soil Analysis. Part 3. Chemical Methods–SSSA Book Series no. 5*. Soil Science Society of America and American Society of Agronomy.

NIWA. (2021). *NZ Freshwater Fish Database*. Retrieved 07 October 2021 from https://nzffdms.niwa.co.nz/search

Pionke, H. B., Gburek, W. J., & Sharpley, A. N. (2000). Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. *Ecological Engineering*, *14*, 325-335. https://doi.org/10.1016/s0925-8574(99)00059-2

Prosser, J. A., Woods, R. R., Horswell, J., & Robinson, B. H. (2016). The potential in-situ antimicrobial ability of Myrtaceae plant species on pathogens in soil. *Soil Biology and Biochemistry*, *96*, 1-3. https://doi.org/10.1016/j.soilbio.2015.12.007

Reis, F. V. P., Gutiérrez-Ginés, M. J., Smith, C. M. S., Lehto, N. J., & Robinson, B. H. (2017). Mānuka (*Leptospermum scoparium*) roots forage biosolids in low fertility soil. *Environmental and Experimental Botany*, *133*, 151-158. https://doi.org/10.1016/j.envexpbot.2016.10.012

Reiser, R., Simmler, M., Portmann, D., Clucas, L., Schulin, R., & Robinson, B. (2014). Cadmium concentrations in New Zealand pastures: Relationships to soil and climate variables. *Journal of Environmental Quality*, *43*(3), 917-925. https://doi.org/10.2134/jeq2013.09.0367

Scott, N. A., White, J. D., Townsend, J. A., Whitehead, D., Leathwick, J. R., Hall, G. M. J., Marden, M., Rogers, G. N. D., Watson, A. J., & Whaley, P. T. (2000). Carbon and nitrogen distribution and accumulation in a New Zealand scrubland ecosystem. *Canadian Journal of Forest Research*, *30*(8), 1246-1255. https://doi.org/10.1139/x00-048

Seyedalikhani, S., Esperschuetz, J., Dickinson, N. M., Hofmann, R., Breitmeyer, J., Horswell, J., & Robinson, B. H. (2019). Biowastes to augment the essential oil production of Leptospermum scoparium and Kunzea robusta in low-fertility soil. *Plant Physiology and Biochemistry*, *137*, 213-221. https://doi.org/10.1016/j.plaphy.2019.02.008

Smale, M. C., Hall, G. M. J., & Gardner, R. O. (1995). Dynamics of kanuka (Kunzea ericoides) forest on South Kaipara spit, New Zealand, and the impact of fallow deer (Dama dama). *New Zealand Journal of Ecology*, *19*(2), 131-141. https://www.jstor.org/stable/24054431

Sparling, G. P., Barton, L., Duncan, L., McGill, A., Speir, T. W., Schipper, L. A., Arnold, G., & Van Schaik, A. (2006). Nutrient leaching and changes in soil characteristics of four contrasting soils irrigated with secondary-treated municipal wastewater for four years. *Australian Journal of Soil Research*, *44*, 104-116. https://doi.org/10.1071/sr05084

Stephens, J. M. C., Molan, P. C., & Clarkson, B. D. (2005). A review of Leptospermum scoparium (Myrtaceae) in New Zealand. *New Zealand Journal of Botany*, *43*(2), 431-449. https://doi.org/10.1080/0028825x.2005.9512966

Sullivan, J. J., Meurk, C., Whaley, K., & Simcock, R. (2009). Restoring native ecosystems in urban Auckland: urban soils, isolation, and weeds as impediments to forest establishment. *New Zealand Journal of Ecology*, *33*(1), 60-71. https://www.jstor.org/stable/24060863

Taylor, M., Drewry, J., F., C.-C., Pearson, L., McDowell, R., & Lynch, B. (2016). Soil quality targets for Olsen P for the protection of environmental values. In L. D. Currie & R. Singh (Eds.), *Integrated nutrient and water management for sustainable farming. Occasional Report No. 29* (pp. 12). Fertilizer and Lime Research Centre, Massey University.

Tzanakakis, V. A., Paranychianakis, N. V., & Angelakis, A. N. (2009). Nutrient removal and biomass production in land treatment systems receiving domestic effluent. *Ecological Engineering*, *35*(10), 1485-1492. https://doi.org/10.1016/j.ecoleng.2009.06.009

Van der Weerden, T., Cox, N., Luo, J., Di, H. J., Podolyan, A., Phillips, R., Saggar, S., de Klein, C., Ettema, P., & Rys, G. (2016). Refining the New Zealand nitrous oxide emission factor for urea fertiliser and farm dairy effluent. *Agriculture, Ecosystems & Environment*, *222*, 133-137. https://doi.org/https://doi.org/10.1016/j.agee.2016.02.007

Walker, C., & Lin, H. S. (2008). Soil property changes after four decades of wastewater irrigation: A landscape perspective. *CATENA*, *73*, 63-74. https://doi.org/10.1016/j.catena.2007.09.002

Werner, S., Akoto-Danso, E. K., Manka’abusi, D., Steiner, C., Haering, V., Nyarko, G., Buerkert, A., & Marschner, B. (2019). Nutrient balances with wastewater irrigation and biochar application in urban agriculture of Northern Ghana. *Nutrient Cycling in Agroecosystems*, *115*(2), 249-262. https://doi.org/10.1007/s10705-019-09989-w

Wilson, H. D. (1994). Regeneration of native forest on Hinewai Reserve, Banks Peninsula. *New Zealand Journal of Botany*, *32*(2), 373-383. https://doi.org/10.1080/0028825x.1994.10410480