A field trial to determine the effect of the land application of treated municipal wastewater onto selected NZ-native plants on Banks Peninsula

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Executive Summary

- The application of Treated Municipal Wastewater (TMW) on NZ-native vegetation is a management option under consideration for towns on Banks Peninsula and elsewhere. There is little information on the effect of TMW on the growth of NZ-native plants or the fluxes of nutrients or contaminants in the underlying soil.

- In July 2015, 1350 native species were planted onto a 20 m x 55 m plot on Piper's Valley Road, Duvauchelle, Banks Peninsula. The plants were arranged into 27 blocks (4.5 m x 4 m), with 12 of the blocks receiving TMW. There were three NZ-native vegetation types tested: Type 1 (*Phormium tenax, Phormium colensoi, Cordyline australis, Griselinia littoralis, Pittosporum eugenioides),* Type 2 (*Leptospermum scoparium*, *Kunzea robusta*) and Type 3 (*Coprosma robusta, Pseudopanax arboreus, Podocarpus laetus, Olearia paniculata*). Irrigation with TMW at a rate of 1000 mm/yr started in January 2016.

- In October/November 2018 forty soil pits were opened and samples taken from five depths (0-5, 15, 30, 45 and 60 cm). From January 2016 to the time of sampling, the soils received a total of 3400 mm of TMW. Soils were analysed for pH, total elements, and soluble ('phytoavailable') fractions of key nutrients and contaminants (ammonium, nitrate, Olsen phosphorus, heavy metals).

- There was no visible evidence of changes in soil structure as a result of TMW application that have been reported to occur in other soils receiving TMW due to the accumulation of sodium. Nor was there any visible evidence of runoff.

- On average the Na concentrations in the topsoil (0-5 cm) was significantly higher in the TMW-irrigated plots compared to the control plots. This is only a 25% increase, despite a disproportionately large mass of Na that was added with the effluent. This indicates that Na is moving down the soil profile and not accumulating in the root-zone, where it may cause degradation of the soil structure.

- There was a significant (6%) increase in the total nitrogen concentration in the topsoil (0-5 cm) but at greater soil depths, the total nitrogen in the TMW-treated plots was not significantly greater than the control plots. There were no significant differences in ammonium in any of the soils. Nitrate was significantly higher in the surface soil but not deeper in the soil profiles. It is likely that most excess nitrogen added to the soil (200 kg/ha/yr) is either taken up into the vegetation, denitrified into N_2 and N_2O or leached.

- There was no evidence of phosphorus accumulation in the soil, probably because the amount of phosphorus added in the TMW (110 kg/ha/yr, total of 312 kg/ha) was small compared to the mass of P in the soil profile (7606 kg/ha). This is consistent with the findings of our previous report, modelling the accumulation of P in these soils. Available phosphorus (Olsen-P) was within the range (10 - 30 mg/kg) typically found on extensive farming systems, and well below concentrations reported on soils irrigated with high-P effluent.

- Soil concentrations of potentially toxic heavy metals, including copper, cadmium, lead, and zinc, were not affected by TMW application. The concentrations of these elements were similar to background values reported for Canterbury Soils.

- Plant survival and growth was monitored throughout the trial. Growth (biomass) was assessed initially by canopy volume, and following canopy closure, by plant height. Harvested biomass will be determined at the conclusion of the trial. Plant suitability for effluent application on Banks Peninsula was determined by survival and growth.

- The effluent had a negligible effect on the concentrations of nutrients and contaminants in the plant tissues. While the growth of all species was accelerated by the effluent, there was no indication of luxury uptake of plant nutrients or increased concentrations of elements that may be harmful. This indicates that TMW is unlikely to affect ecological food chains.

- This trial demonstrated the feasibility of establishing NZ-native vegetation using TMW. We recommend irrigation rates of 500 - 800 mm/yr. Further experimental plantings should be conducted with these species to explore the possibility of using TMW to re-establish rare or endangered plants that may significantly enhance the ecological value of the area. A critical success factor for the establishment of New Zealand native vegetation on Banks Peninsula that are to receive TMW is the control of exotic weeds. It is likely that some weeds will have a greater growth response to TMW than the native species. It is therefore critical that these weeds be suppressed as the native vegetation becomes established.

Contents

Introduction

In 2014, the Christchurch City Council (CCC) commissioned an investigation to determine whether Treated Municipal Wastewater (TMW) from the township of Duvauchelle could be irrigated onto the local golf course or surrounding grazed pasture. Subsequent engagement with the community during public open days in 2015 and 2016, this brief was expanded to include cut-and-carry pasture as well as New Zealand (NZ) native vegetation. The feasibility of irrigating TMW onto pasture was demonstrated for two soil types, Barry's soil and the Pawson Silt Loam, from Duvauchelle and the Takamatua Peninsula in lysimeter experiments (Gutierrez-Gines et al., 2017, 2020).

Potentially, TMW from the town of Akaroa, Banks Peninsula, could be irrigated onto NZ-native vegetation, instead of being discharged into Akaroa harbour. Such an approach is consistent with land application being the preferred option over discharge into waterways or the ocean (Sparling et al., 2006), where it can exacerbate eutrophication and/or toxic algal blooms (Sonune and Ghate, 2004). The Irrigation of TMW onto land reduces the contaminants that enter waterways and therefore has positive effects on the water quality (Herath, 1997). While there is significant interspecific variation, the root-zones of plants remove nutrients contained in the TMW, mitigate pathogens (Mandal et al., 2007), and break down or immobilise contaminants (Chaudhry et al., 2005) that would otherwise degrade water bodies. The application of TMW can accelerate the growth of some plants by providing water and nutrients (Overman and Nguy, 1975).

The rate that TMW can be applied to soil depends on the soil type and quality of the TMW (Gutiérrez-Ginés et al., 2020). There are numerous examples of where land application of TMW has been discontinued because of excessive nutrient leaching (Houlbrooke et al., 2003), or degradation of soil quality to the point TMW runoff degraded surface waters (Cameron et al., 1997). Elevated concentrations of monovalent cations, especially sodium and potassium, can degrade soil structure through the dispersion of clays (Mojid and Wyseure, 2013), and reduce plant growth through salinity and sodicity (Bernstein, 1975). The successful application of TMW to land on Banks Peninsula requires particular attention to soil quality. Soils of the lowland areas of the peninsula where TMW could potentially be applied are mostly derived from loess with a relatively high clay content (Griffiths, 1973). They are often imperfectly drained and may contain a fragipan (a layer of impermeable soil). These soils present a higher risk of infiltration problems compared to free-draining soils and consequently an improperly designed TMW application system may be susceptible to surface runoff and erosion. Gutierrez-Gines et al. (2017) demonstrated the feasibility of irrigating TMW at rates up to 1500 mm/yr onto Barry's soil and the Pawson Silt Loam, with a recommended irrigation rate of 500-800 mm/yr. An infiltration study on the Pawson Silt Loam showed that infiltration of up to 1500 mm of TMW irrigation was unimpeded, even when the TMW was spiked with additional Na up to 325 mg/L (McIntyre, 2018).

The irrigation of TMW from the towns of Duvauchelle or Akaroa onto NZ-native vegetation could potentially increase the production of valuable native products and create zones of ecological value (Meurk, 2008; Franklin et al., 2015). *Leptospermum scoparium* (mānuka) is an obvious candidate species because of its associated high-value honey and essential oils (Seyedalikhani et al., 2019). Moreover, *L. scoparium* has been shown to kill soil-borne pathogens (Prosser et al., 2016) and reduce nitrate leaching (Esperschuetz et al., 2017b). Other potential valuable native species are *Kunzea robusta* (kānuka) for essential oil production, P*hormium tenax* (harakeke) for fibre production, and a whole suite of species, including *Griselinia littoralis* (kapuka) that may be a nutritious supplement due to tannins and trace elements (Dickinson et al., 2015).

In many countries, including NZ, TMW is used to irrigate forestry (Capra and Scicolone, 2004; Barton et al., 2005), however, there is as yet a lacuna of data on the effects of TMW irrigation onto soils supporting NZ-native vegetation. There is demonstrable evidence that some NZ-native species, such as *L. scoparium*, *K. robusta*, *P. tenax*, *Cordyline australis* (tī kouka), *Myoporum laetum* (ngaio) and *Austroderia australi*s (toetoe) thrive in high-nutrient environments, even if some of these species (*L. scoparium* and *K. robusta*) are adapted to low-fertility soils (Gutiérrez-Ginés et al., 2017; Esperschuetz et al., 2017a). However, Gutierrez-Gines et al. (2017) showed that some other species, such as *Hebe salicifolia* (koromiko) and *Coprosma acerosa* (sand coprosma) had a limited or negative response to increased nutrients. Therefore, selection of NZ-native species that will tolerate TMW irrigation is critical for a successful operation.

When establishing an ecosystem of NZ-native plants that is receiving TMW, the response of exotic weeds to the TMW also needs to be considered. Species such as *Rubus fruticosus* (blackberry), *Solanum mauritianum* (wooly nightshade), *Solanum dulcamara* (woody nightshade), *Phytolacca octandra (*inkweed), and C*lematis vitalba* (old-man's beard) may have a greater growth response to TMW than the NZ-native species, thereby making their control more difficult.

Transitioning grazed pasture to TMW irrigated native plants will eliminate the application of mineral fertilisers such as superphosphate, which contain elevated concentrations of toxic cadmium, fluorine and uranium that can accumulate in soil (Kim and Robinson, 2015). Irrigation with UV-sterilized TMW, such as that resulting from treatment at Duvauchelle or Akaroa, will also result in a lower environmental pathogen load than grazed pasture. A native ecosystem receiving TMW would likely remain unharvested or have only a small fraction of the biomass removed. Therefore, unlike a cut-and-carry pasture receiving TMW, there would lower-rates of nutrient removal from the system. Therefore, it is likely that nitrate leaching and phosphorus accumulation in the soil would be greater than in a grazed pasture.

Aims

We aimed to determine whether NZ-native vegetation on Banks Peninsula could be established while receiving TMW irrigation at a rate of 1000 mm per year. Specifically, we sought to determine, whether this rate of irrigation would result in ponding, excess nitrate leaching, accumulation or depletion of elements in soil, changes in the survival and growth of individual NZ-native plant species.

Methods

Field trial

In June 2015 a field trial was established at Piper's Valley Road, Duvauchelle, Banks Peninsula (Figure 1). The area of ca. 20 m x 55 m was fenced off from an adjacent paddock under sheep grazing. The soil was a Pawson Silt Loam (Table 1) supporting a pasture dominated by *Dactylis spp.* (cocksfoot) with some *Holcus lanatus* (Yorkshire fog).

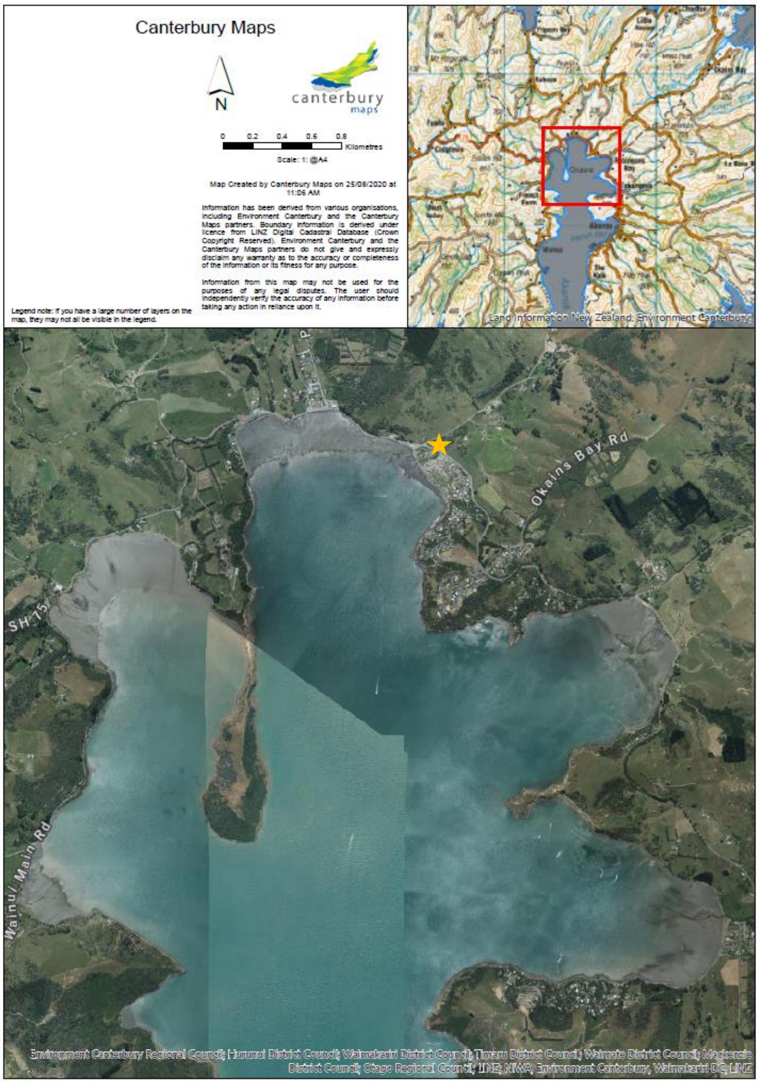
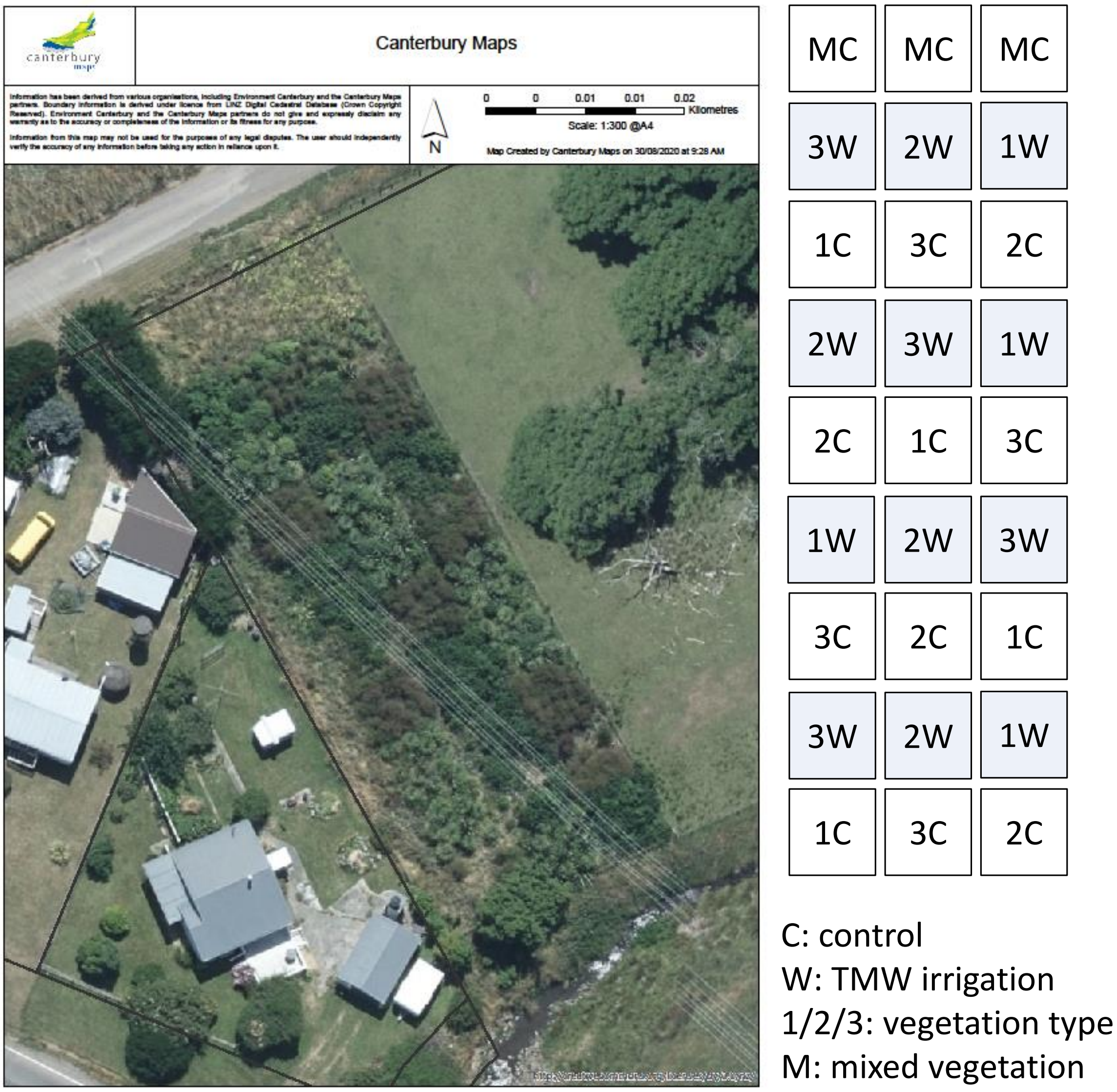


Figure 1: Location of the field site in Duvauchelle (yellow star).

Table 1: Physical properties of the Pawson Silt Loam from the field site at Duvauchelle. Values in brackets represent the standard error of the mean, n=5. (Griffiths 1973; McIntyre 2018).

Horizon	A	Bw	Bg
Depth (m)	0.20-0.28	0.28-0.39	0.39-0.60
Clay (%)	8 (1.3)	9.8 (0.9)	8.3 (0.7)
Silt (%)	22.5 (2.5)	25.4 (1.8)	23.5 (1.6)
Sand (%)	68.5 (3.5)	64.8 (2.8)	68.3 (2.2)

In July 2015, 1350 native trees were planted. The trees were divided into 27 blocks of 4 m x 4.5 m (Figure 2). Eleven native New Zealand species were split into three different vegetation types: monocot dominated, Myrtaceae and broadleaves (Table 2). Twelve of the 27 blocks received TMW irrigation at a rate of 1000 mm per annum (Table 3). Irrigation started in January 2016. Weed control was conducted by lawnmower from 2015 to 2017. In June 2017, all areas within the plot that were not under native vegetation were planted with silver tussock (*Poa cita*) to minimise the need for further weed control. Thereafter, weeds were occasionally removed using a weedeater.



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MC	MC	MC
3W	2W	1W
1C	3C	2C
2W	3W	1W
2C	1C	3C
1W	2W	3W
3C	2C	1C
3W	2W	1W
1C	3C	2C

C: control
W: TMW irrigation
1/2/3: vegetation type
M: mixed vegetation

Figure 2: Recent satellite photo of the field site with visible treatment blocks (left) and schematic overview of the trial (right).

Table 2: Vegetation types at the field site.

Vegetation	Species	Botanical reference	Māori name	Common name
Type 1 (Myrtaceae)	*Leptospermum scoparium*	J.R. Forst. & G. Forst.	mānuka	tea tree
	Kunzea robusta	De Lange & Toelken	kānuka	tea tree
Type 2 (Broadleaves)	*Coprosma robusta*	Raoul	karamu	-
	Olearia paniculata	Druce	akiraho	-
	Pseudopanax arboreus	Philipson	puahou	five finger
	*Podocarpus laetus**	Hooibr. ex. Endl.	tōtara	Hall's tōtara
Type 3 (Monocot dominated)	*Phormium tenax*	J.R. Forst. & G. Forst.	harakeke	flax
	Phormium colensoi	Hook.f.	wharariki	mountain flax
	Cordyline australis	Hook.f.	tī kōuka	cabbage tree
	Pittosporum eugenioides	A.Cunn.	tarata	lemonwood
	Griselinia littoralis	Raoul	kapuka	broadleaf

* Referred to as *Podocarpus cunninghamii* in previous reports.

Table 3: Characteristics of irrigated TMW from the Duvauchelle wastewater treatment plant. Mean and standard deviation, n=54. Total applied refers to a 34-month period from the start of the irrigation in January 2016 to soil sampling in October/November 2018.

Compound	TMW		Amount applied kg/ha/yr	Total applied kg/ha
pH	7.5			
Electric Conductivity	423 (40)	uS/cm		
Total suspended solids	32	g/m^3		
Ammonium-nitrogen	0.49 (0.15 – 0.80)*	mg/L	4.9	13.9
Nitrate-nitrogen	18 (7.5)	mg/L	180	510
Nitrite-nitrogen	0.86 (0.09)	mg/L	8.6	24.4
Total nitrogen	<25	mg/L	<250	<708
Aluminium	0.43 (0.11 – 1.7)*	mg/L	4.3	12.2
Boron	0.10 (0.04)	mg/L	1	2.8
Calcium	59 (12)	mg/L	59	1672
Cadmium	<0.001	mg/L	<0.01	0.03
Copper	0.04 (0.03)	mg/L	0.4	1.13
Iron	0.96 (0.25 – 3.6)*	mg/L	9.6	26.9
Potassium	22 (5.0)	mg/L	220	623
Magnesium	19 (5.5)	mg/L	190	538
Manganese	0.06 (0.03)	mg/L	0.6	2.7
Sodium	95 (21)	mg/L	950	2692
Phosphorus	11 (5.0)	mg/L	110	312
Sulphur	25 (11)	mg/L	250	708
Zinc	0.17 (0.11)	mg/L	1.7	4.8
Sodium Accumulation Ratio	15 (2.6)			

*Geometric mean and standard error range.

Sample collection

Soil samples were collected between 25.10.2018 and 08.11.2018. The soil was sampled under 5 species; *Phormium tenax*, *Cordyline australis*, *Leptospermum scoparium*, *Kunzea robusta* and *Coprosma robusta*. Four soil pits were opened per species and treatment (TMW/control) combination, resulting in a total of forty pits. A spade was used to open soil pits of 0.6 m x 0.6 m x 0.6 m next to the plant base. This ensured that the collected soil sample originated from the root zone of the plant. Following removal of the surface litter, a trowel was used to sample soil at 0-5 (referred to as 0 in Figures), 15, 30, 45, and 60 cm, resulting in a total of 200 samples (Figure 3).

Figure 3: Sample collection from a soil pit.

Plant growth was assessed in July 2019. At that time plant canopy had closed and the estimation of the biomass was made by measuring plant height. Each of the 1350 plants at the site was measured with a measurement tape. Plant samples were taken from the forty plants that had soil pits dug at their base in 2018. For each plant, 10 branches/leaves from different heights were cut by secateurs and combined to generate a representative sample.

Chemical analyses

Soil nitrate and exchangeable ammonium were extracted from the soil with 2 M KCl (Blakemore, 1987). 40 mL of 2M KCl was added to 4 g of fresh soil, shaken for 1 hour at 120 cycles/min in a horizontal shaker, and filtered through Whatman No. 42 filter paper. Colorimetric methods were used to determine nitrate (Miranda et al., 2011) and ammonium (Mulvaney, 1996) in the extract, using a Cary 100 Bio (Agilent Technologies) UV-visible spectrophotometer.

Soils were spread on aluminium trays, dried at 40 °C for 4 days and sieved to <2mm. Plants were washed with deionised water before being dried at 60 °C for 4 days. Leaves were separated from the stems. Plant leaves and subsamples of soils were ground with a Rocklabs ring mill.

Soil moisture content was determined by drying 10-20 g of moist soil at 105 °C for 24 hours. Soil weight was recorded before and after drying and the difference used to determine the moisture factor (Blakemore et al., 1987).

A Vario-Max CN Elemental Analyser (Elementar, Germany) was used to determine total carbon and nitrogen contents in the ground soil samples. A LECO CN828 Carbon/Nitrogen analyser (LECO, U.S.) was used to determine total carbon and nitrogen contents in the ground plant samples.

Soil pH was determined in deionised water using a 1: 2.5 g soil: water ratio. The extracts were shaken vigorously and left to equilibrate overnight. The pH was determined using a HQ 440d Multi-Parameter Meter (HACH, U.S.) with pH probe PHC735 (HACH, U.S.).

Soil and plant samples were digested to determine total element concentrations. 1.0 g of ground soil was digested with 4 mL HNO_3 and 10 mL HCl. Samples were left to pre-digest overnight and were then digested on an aluminium heating block at 90 °C for 1 hr. Samples were left to cool down, diluted to 20 mL with ultrapure water (18.2 MΩ cm) and filtered through Whatman No. 42 filter paper. 0.2 g of ground plant sample was digested with 15 mL ultrapure conc. HNO_3 on an aluminium block at 120 °C for 1 hr. Digests were diluted to 25 mL with ultrapure water. Certified reference material was included for soil and plant digestions (SRM 2710a – Montana I Soil and SRM1573a – Tomato Leaves, National Institute of Standards and Technology, U.S. Department of Commerce). Element concentrations in the digests were determined by Microwave Plasma-Atomic Emission Spectrometer (MP-AES) Agilent 4200 (Agilent Technologies, U.S.)

$Ca(NO_3)_2$ was used to extract phytoavailable metals from the soil (Gray et al., 1999). 5.0 g of soil (air-dried, sieved to <2mm) was shaken with 30 mL of 0.05 M $Ca(NO_3)_2$ for 120 min at 15 rpm in an end-over-end shaker, followed by centrifugation at 10,000 rpm for 10 min. Extracts were filtered through Whatman No. 42 filter paper. Extracts were diluted 21 times with 2% ultrapure HNO_3 and element concentrations analysed by Inductively coupled plasma mass spectrometry (ICP-MS) Agilent 7500 CX (Agilent Technologies, U.S.)

To determine plant-available phosphorus (Olsen P), 1.0 g of soil (air dried, <2mm) was extracted with 20 mL 0.5 M $NaHCO_3$ extractant (Blakemore et al., 1987). Samples were shaken for 30 min in an end-over-end shaker at 50 rpm and centrifuged at 2,000 rpm for 10 min. The extract was filtered through Whatman No. 42 filter paper. The P concentration in the extract was determined colorimetric (Olsen, 1954), using a Cary 100 Bio UV-visible spectrophotometer (Agilent Technologies, U.S.).

Calculation of nitrate leaching

Nitrate leaching was calculated using the drainage and the concentration of nitrate measured at 60 cm depth, a zone that is depauperate in organic matter and NZ-native plant roots (Franklin, 2014). Assuming an average annual precipitation is 1000 mm (ClimateData.org, 2020) and the average annual evapotranspiration is 500 mm (Stats, 2020), the drainage from the site will be:

Drainage = 1000 mm irrigation + 1000 mm rainfall - 500 mm = 1500 mm (15000 m^3/ ha)

Nitrate leaching (kg/ha) was calculated using nitrate-nitrogen concentrations at 0.6 m depth, which was below all but the deepest roots. Nitrate at this depth is assumed to leach into groundwater.

Statistical analysis

Data was analysed, graphed and tabulated in Microsoft Excel 2016. A one-way t-test was used to compare treatments at different soil depths. The significance level was $p<0.05$.

Results and discussion

Infiltration and accumulation of sodium and other basic cations

No evidence of ponding or runoff throughout the trial indicating that infiltration was adequate and not significantly perturbed by the application of TMW. This is consistent with the findings of other studies investigating infiltration of similar rates of TMW into Banks Peninsula soils (McIntyre, 2018; Gutiérrez-Ginés et al., 2020). The effluent in Duvauchelle has Sodium Accumulation Ratio (SAR) of 15 (Table 3), below this threshold. In some of the plots, irrigation with TMW significantly increased soil sodium concentrations. While sodium in the topsoil increased by 25% (Table 4), we have strong evidence that sodium is not continuing to accumulate in this system. Over the three-year irrigation period, some 2700 kg/ha sodium equivalent was added to the soil. However, the measured increase in sodium in the soil profile was only 735 kg/hg. This indicates that excess sodium was leaching through the soil profile and not accumulating in the top 0.6 m. These findings are consistent with (Gutiérrez-Ginés et al., 2020), who demonstrated that while TMW increased soil Na concentrations in Barry Silt Loam (Duvauchelle), there was no long-term accumulation of sodium in a lysimeter trial.

Figure 4 shows the concentrations of sodium in the soil profile[1]. Accumulation of sodium can also change soil pH (Figure 5). Our results indicate soil pH was significantly increased on the *L. scoparium* and *K. robusta* plots. This pH value of the TMW soils and the magnitude of change is similar to what may be achieved in agriculture by adding lime to the soils (McLaren and Cameron, 1996). The pH of all the plots was within the optimal range for most plants (Rengel, 2002).

Total sodium was not significantly increased on average (all species). However, some species showed significant increases. Using e.g. *P. tenax* as an example, the topsoil (0-5 cm) contained 174 mg/kg more sodium in the treatment compared to the control (a 25% increase). On a per-hectare basis, this equates to 120 kg extra sodium per ha. In contrast, some 2700 kg of sodium were added - indicating that 2580 kg have leached to deeper horizons. This indicates that sodium is only accumulating to a certain level in the topsoil - consistent with the findings of Gutiérrez-Ginés et al. (2020).

Continual application of sodium can result in the increased leaching of other basic cations, especially potassium, magnesium and calcium (K^+, Mg^{2+} and Ca^{2+}) (FAO, 2020). The results at Duvauchelle indicate that all three of these elements significantly increased in the topsoil (Table 4). Calcium and magnesium increased by 7% and 37% respectively, thereby offsetting the increase in sodium. Unlike sodium, the increase in soil calcium was proportional to the calcium added in the effluent, indicating that there will be a long-term accumulation of calcium. This is beneficial for the system, because calcium improves soil structure (McLaren and Cameron, 1996) and plants can thrive in soils containing several percent calcium (Valentinuzzi et al., 2015).

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[1] Provisional results. These results are precise (i.e. relatively correct. Relative Standard Error <4%), however, accuracy (i.e. absolute value) to be revised.

Table 4: Soil properties of the irrigated and non-irrigated plots for the Duvauchelle field trial at 0-5 cm. Mean and standard error of the mean in brackets (n=20). The chemical parameters of the deeper profiles are given in Tables A-1 to A-4 (Appendix 1).

	Total		$Ca(NO_3)_2$-extractable	
	Control	TMW application	Control	TMW application
pH	5.54 (0.04)	5.66 (0.05)*	na	na
Carbon (%)	3.32 (0.10)	3.48 (0.10)	na	na
Plant nutrients				
Nitrogen (%) Ammonium (mg/kg) Nitrate (mg/kg)	0.33 (0.01) 17.6 (1.70) 5.9 (0.86)	0.35 (0.01)* 19.2 (1.69) 11.5 (1.51)*	na	na
Phosphorus (mg/kg) Olsen-P	1133 (36.3) 14.0 (1.17)	1261 (58.0)* 17.3 (2.71)	na	na
Potassium (mg/kg)	2340 (138)	2410 (124)	nd	nd
Sulphur (mg/kg)	<816 (75.7)	947 (66.5)	nd	nd
Calcium (mg/kg)	7145 (257)	7653 (355)	nd	nd
Magnesium (mg/kg)	7232 (910)	9941 (1577)	nd	nd
Copper (mg/kg)	16.0 (0.55)	19.3 (2.13)	<0.012 (0.004)	<0.046 (0.019)*
Manganese (mg/kg)	1159 (53.2)	1322 (115)	1.91 (0.16)	1.86 (0.41)
Zinc (mg/kg)	88.9 (3.30)	89.0 (3.37)	0.096 (0.012)	0.106 (0.017)
Contaminants				
Sodium (mg/kg)	705 (34.2)	>879 (52.6)*	nd	nd
Cadmium (ug/kg)	nd	nd	0.67 (0.05)	0.50 (0.05)*
Lead (ug/kg)	nd	nd	0.57 (0.17)	<1.21 (0.43)

na=not applicable

nd=not determined

* significant difference between treatments ($p<0.05$)

< actual mean is lower due to sample concentrations being below detection limit

> actual mean is higher due to samples concentrations being above measurement range

Sodium

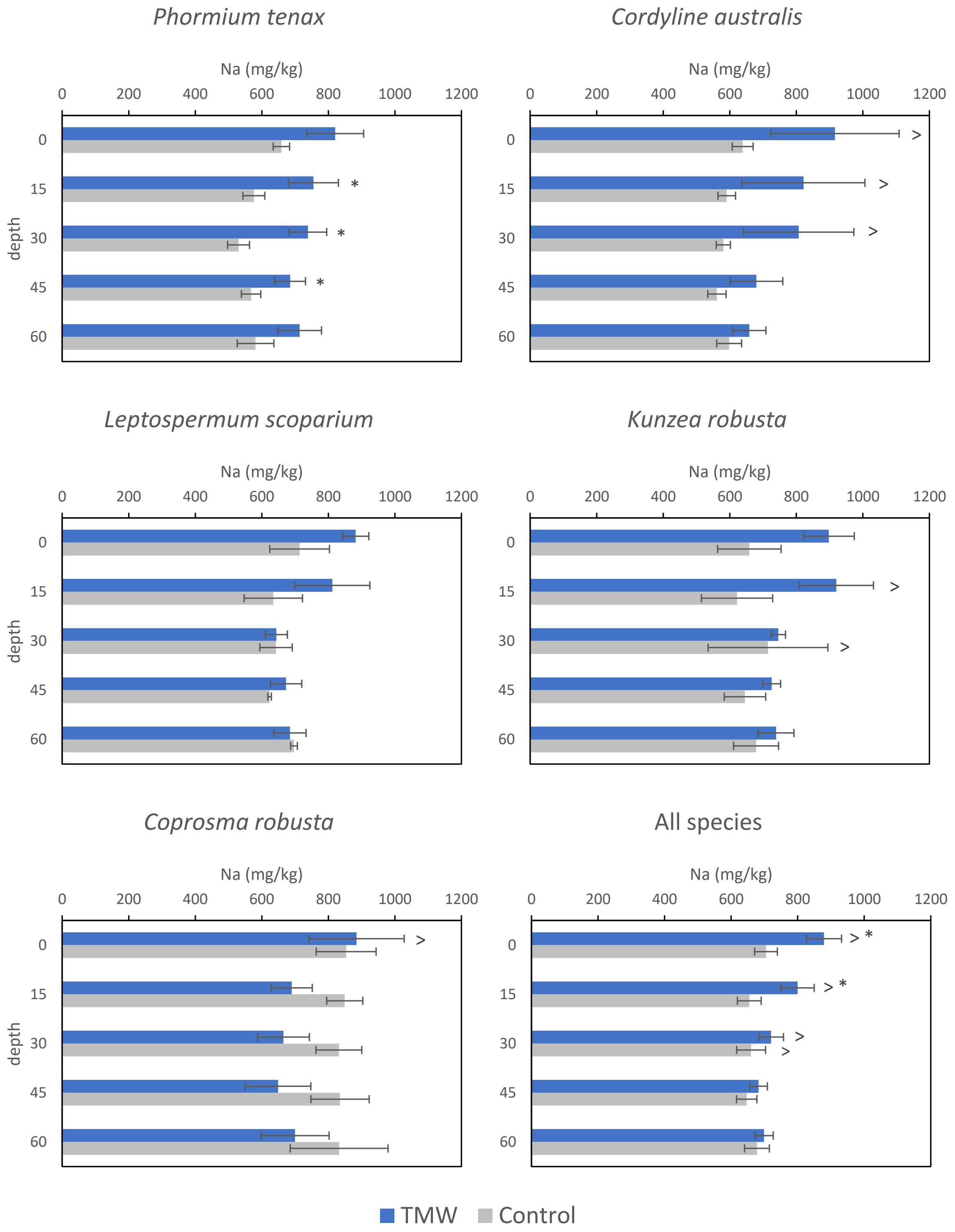

Figure 4: Soil sodium concentration (mg/kg) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at p<0.05 indicated by (*).

pH

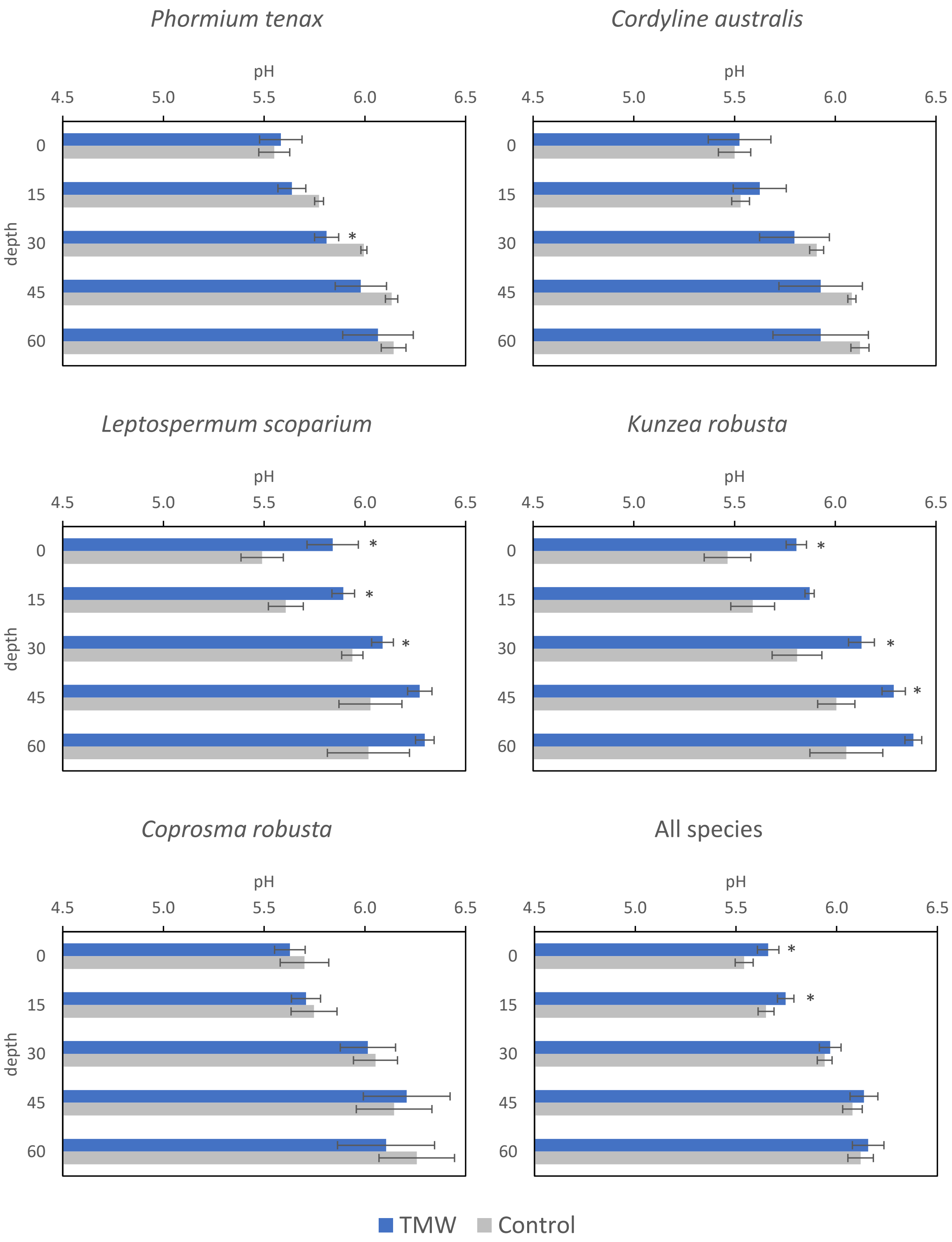

Figure 5: Soil pH under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at $p<0.05$ indicated by (*).

Carbon and Nitrogen

Across all the plots, the application of TMW did not significantly change soil carbon (Table 4). In the *P. tenax* and *K. robusta* plots, there was a significant increase in soil carbon in the topsoil (Figure 6). This indicates that TMW application is not reducing soil organic matter, despite the potential for elevated nitrogen and phosphorus, applied with the TMW, to increase the oxidation of soil organic matter (McLaren and Cameron, 1996). We would expect there to be a decrease of soil carbon as grazed pasture is converted into forest (Scott et al., 2006). Such a decrease would occur with or without TMW application.

Irrigation with TMW increased soil nitrogen by just 6%, despite an application rate of 250 kg N/ha/yr equivalent (Figure 7). This may be due to increased plant uptake, and increased leaching, and increased denitrification due to increased soil moisture content (Clough et al., 2004) and high pH (SImek and Cooper, 2002) in the TMW irrigated plots. Overseas studies have shown that 25 - 150 kg/ha of applied nitrogen can be lost through denitrification (Paul and Zebarth, 1997; Mahmood et al., 1998). In New Zealand, studies with Dairy Shed Effluent reported that some 60 kg/ha/yr were lost through denitrification (Di and Cameron, 2000).

Soil ammonium concentrations were not significantly different in the TMW and control plots (Figure 8). However, TMW significantly increased soil nitrate concentrations (Table 4, Figure 9) in many of the soils. Higher nitrate is consistent with higher application rates of nitrogen through TMW and higher rates of nitrification caused by higher pH (Ste-Marie and Paré, 1999; Sahrawat, 2008). Nitrate concentration in the irrigated plots is highest in *K. robusta*, followed by *L. scoparium*. Any nitrogen that is added to the soil in the TMW will either be taken up by plants, denitrified into nitrogen gas or nitrous oxide (N_2O), or leached down through the soil profile as nitrate (Figure 10 and Appendix 2).

Just 1% of the applied nitrogen is expected to be emitted as nitrous oxide following TMW irrigation, indicating that 2.5 kg N_2O-N/ha/yr is emitted from the irrigated plots in Duvauchelle (van der Weerden et al., 2016). This is lower than nitrous oxide emissions from grazed pasture, which can be as high as 11.7 kg N_2O-N/ha/yr (Saggar et al., 2007).

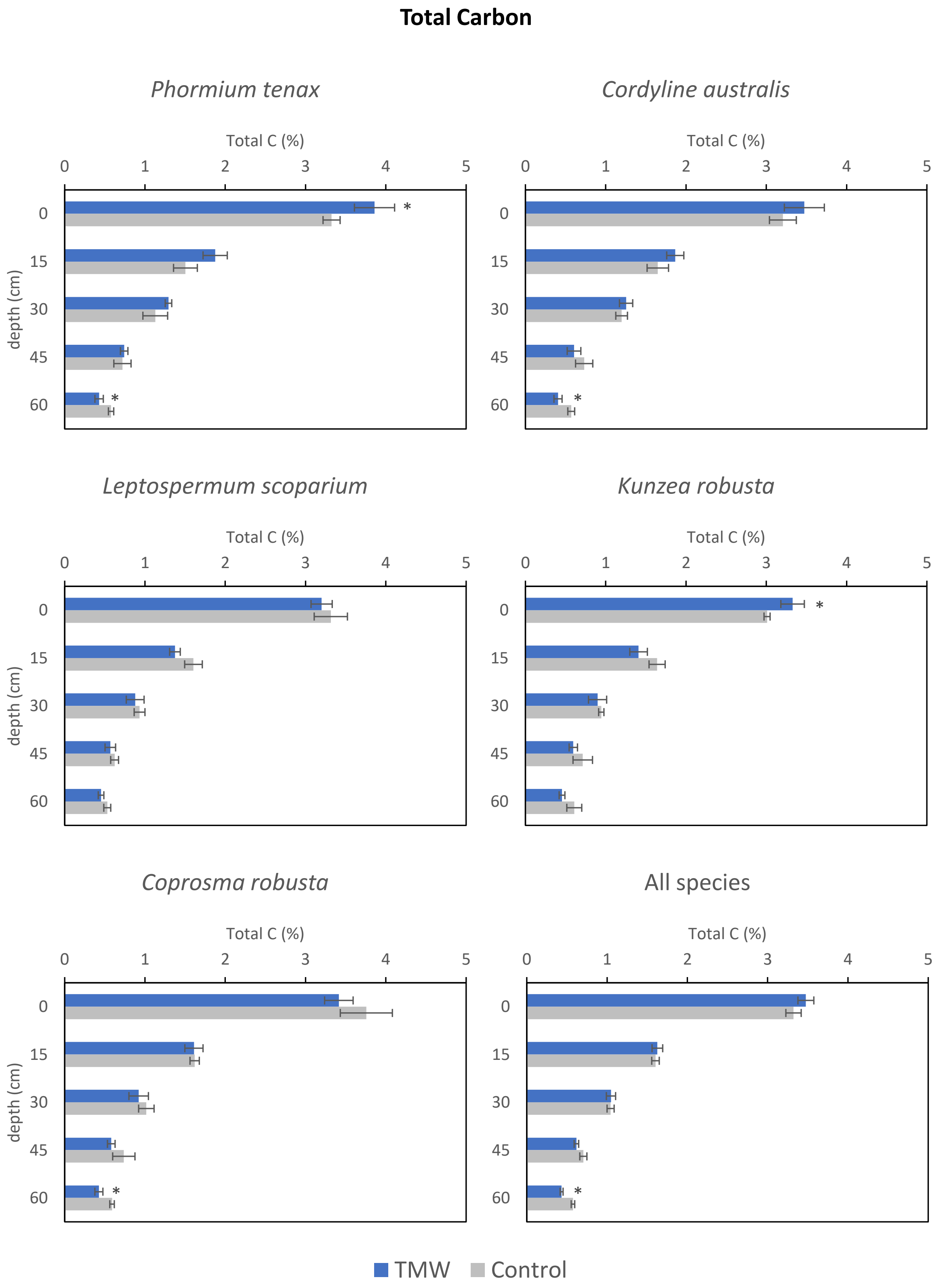

Figure 6: Soil total carbon concentration (%) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at $p<0.05$ indicated by (*).

Total Nitrogen

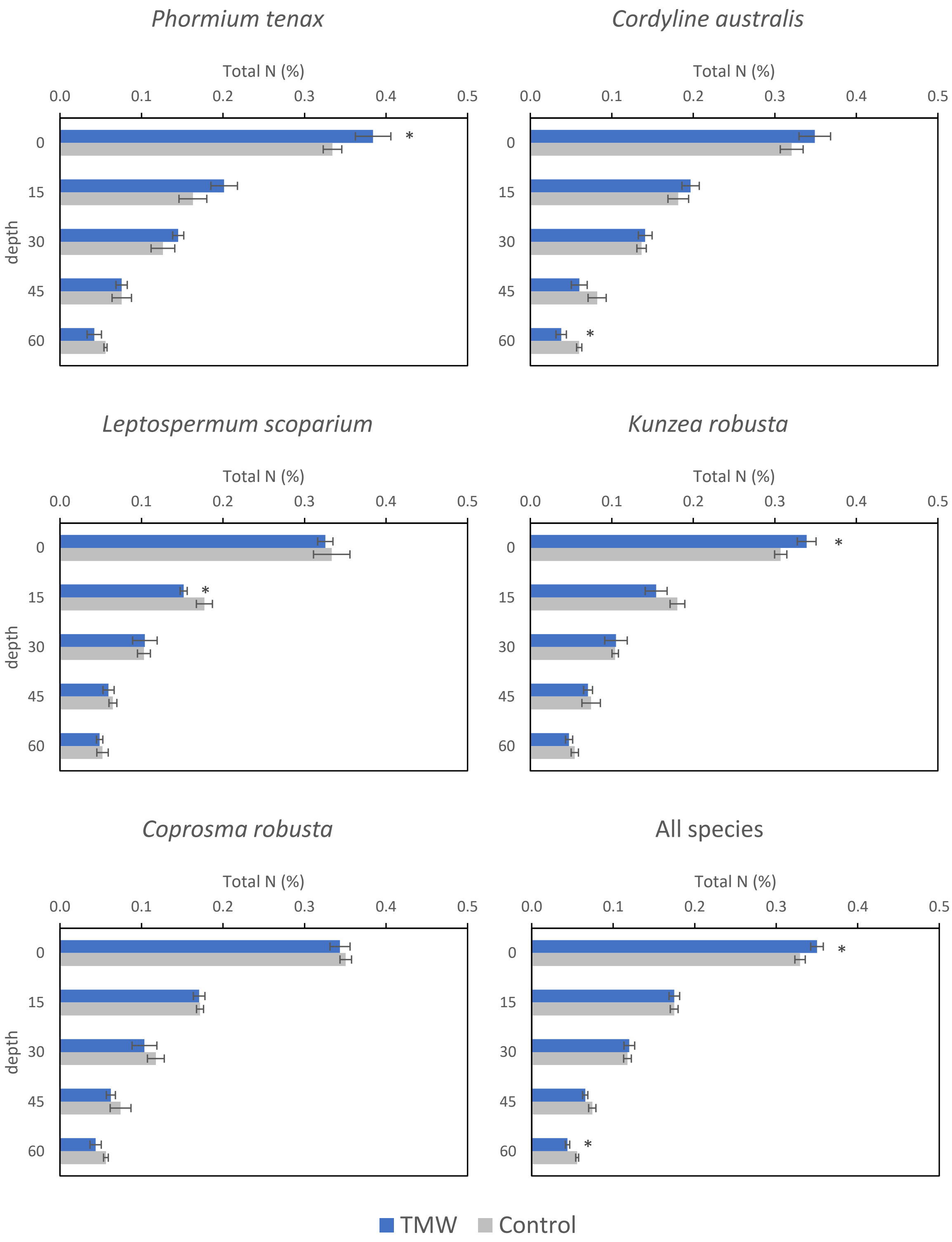

Figure 7: Soil total nitrogen concentration (%) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at p<0.05 indicated by (*).

Ammonium

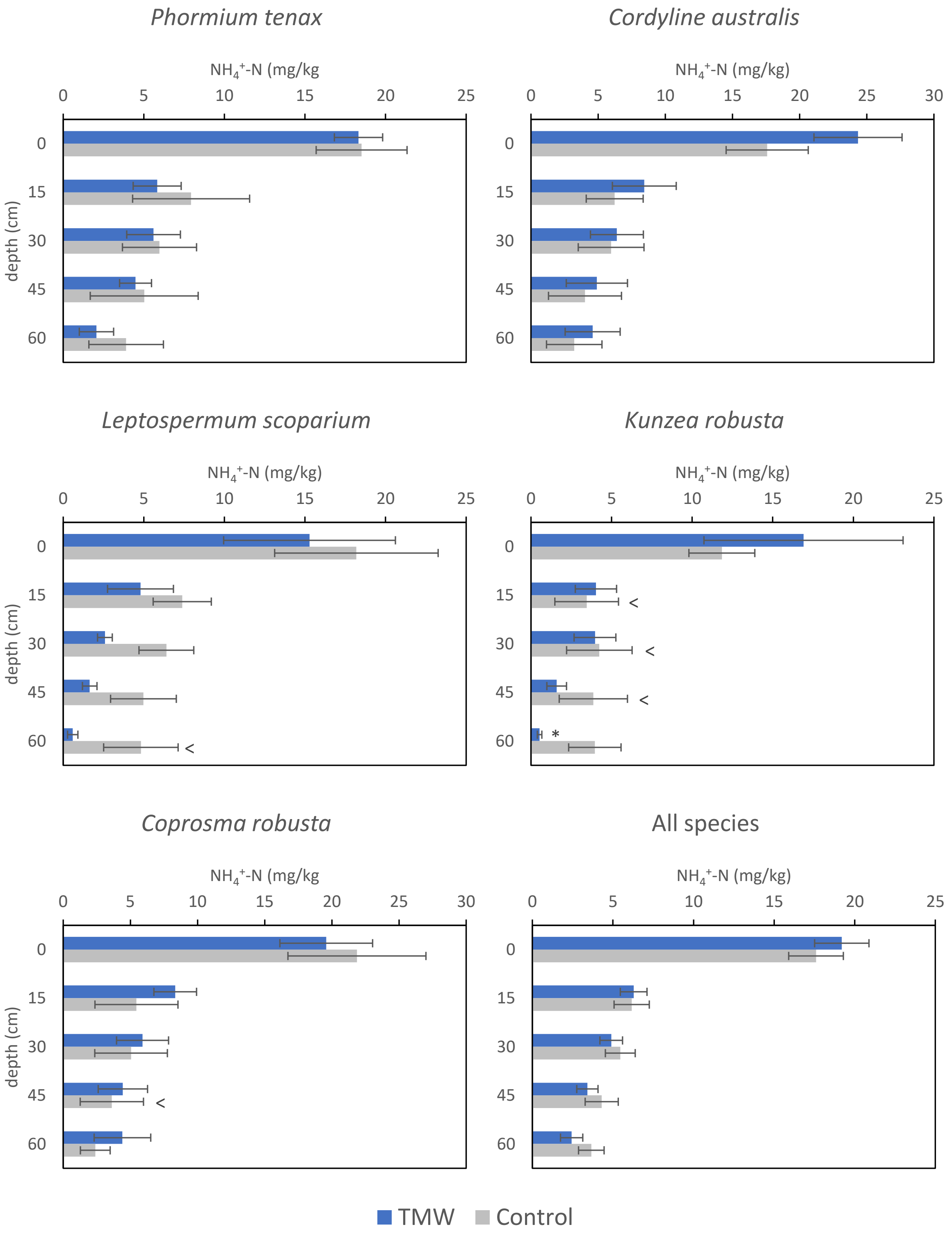

Figure 8: Soil ammonium concentration (mg/kg) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at $p<0.05$ indicated by (*).

Nitrate

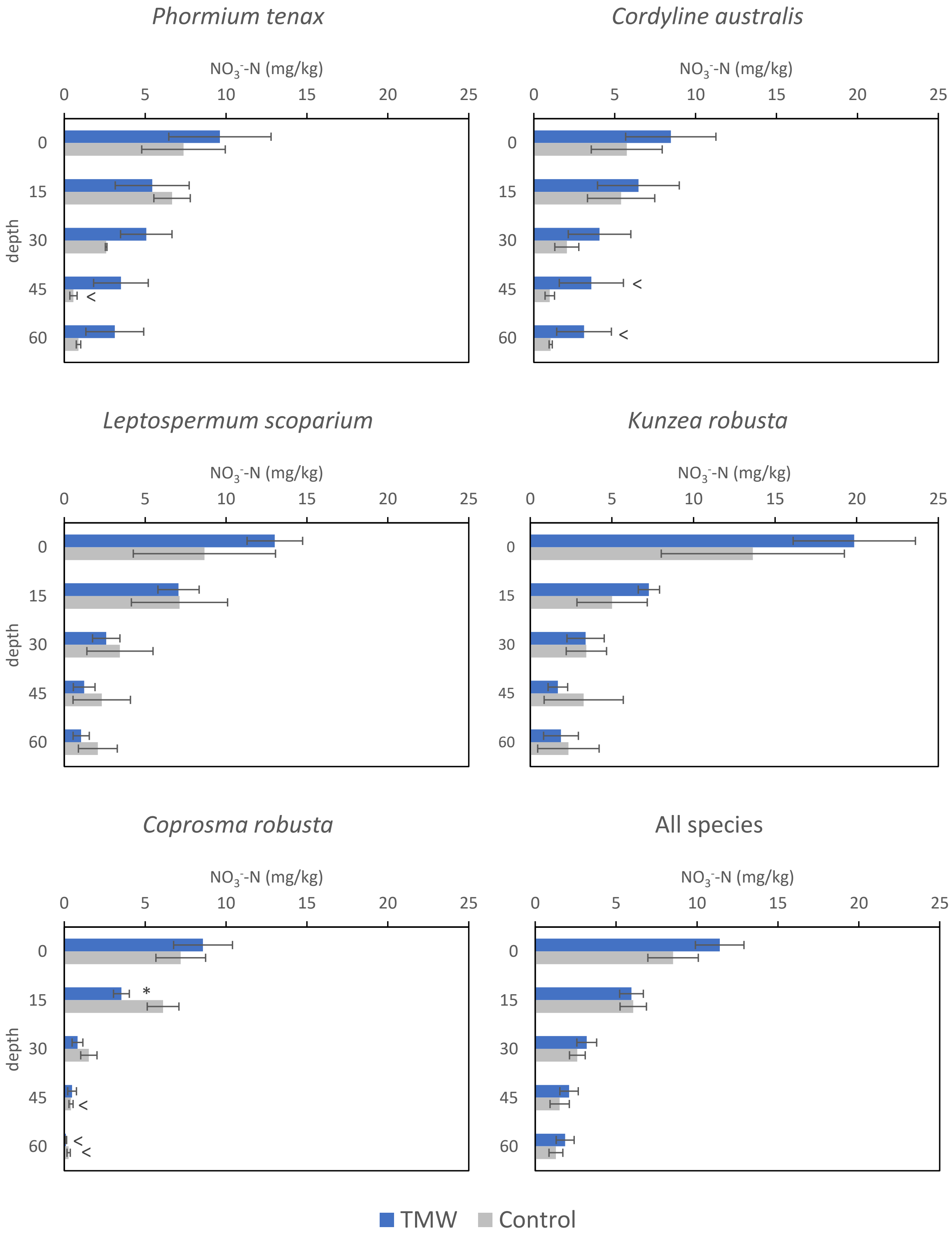

Figure 9: Soil nitrate concentration (mg/kg) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at p<0.05 indicated by (*).

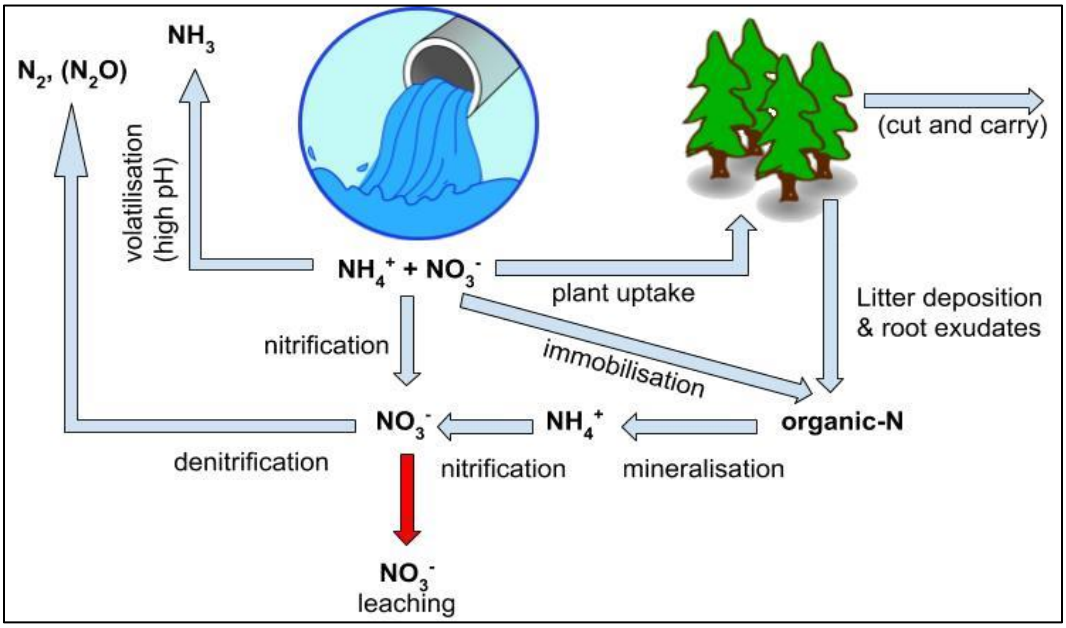

Figure 10: Nitrogen fluxes in irrigated systems (Meister et al. 2019, Appendix 2).

Nitrate leaching

Table 5 shows the calculated nitrate-nitrogen concentrations under the five species with and without TMW irrigation. These results (2 - 47 kg/ha) are lower than those estimated in our preliminary report (15 - 60 kg/kg). Overall, there was a 44% increase in nitrate leaching under the effluent-irrigated vegetation. These values are significantly greater than nitrate leaching that would occur under TMW irrigated cut-and-carry pasture (Gutiérrez-Ginés et al., 2020) and are similar to nitrate leaching rates that occur under grazed-pasture in conventional farming systems (Stats, 2019). There were significant differences between C. robusta and the other species: NO3- leaching was negligible (<4 kg/ha/yr). This may, in part, be due to the greatly accelerated growth of C. robusta under TMW irrigation (see section plant development). These results indicate that under a TMW irrigation rate of 500 - 800 mm/yr, nitrate leaching will be similar to grazed pasture.

Table 5: Mass of nitrate-nitrogen leached (kg/ha/yr equivalent) calculated from measurements taken in October/November 2018.

	Control	TMW irrigated
Phormium tenax	13.2	46.8
Cordyline australis	15.6	46.5
Leptospermum scoparium	31.1	15.7
Kunzea robusta	35.0	28.2
Coprosma robusta	4.04	1.59
All species	19.2	27.8

Phosphorus[2]

Irrigation with TMW caused a significant (11%) increase in the total phosphorus concentration in the topsoil (Table 4), although there was no significant difference when considering the whole soil profile (0-60 cm). This is because the amount of phosphorus added over the entire experimental period (312 kg) was small compared to the total phosphorus in the soil profile (7606 kg). The rate of accumulation is similar to that calculated using a model system for the potential Akaroa wastewater system (Appendix 3).

The strong adsorption of phosphorus in soil means that only a small part of the applied phosphorus is taken up by plants or leached (McLaren and Cameron, 1996). Therefore, in a TMW irrigated soil, phosphorus will accumulate, just as it does in all NZ soils that receive fertilizers. Under flax, where we observed higher levels of P down to 45 cm depth (Figure 11), preferential flow might lead to the percolation of TMW through the soil profile, and accumulation of phosphorus at greater depths (Gupta et al., 1999). Phosphorus can cause serious environmental issues when it enters waterways (Tilman et al., 2001). This could occur via runoff from a TMW-irrigated area, particularly if it was accompanied by soil erosion. However, no signs of runoff and increased erosion were observed in Duvauchelle. Phosphorus losses will be higher from grazed pasture (irrigated or otherwise) than TMW irrigated NZ-native vegetation due to the mechanical disturbance of soil by the animals (McDowell et al., 2009).

Only a small fraction of phosphorus in soil is available for plants, this is commonly measured by an extraction to give so-called 'Olsen-P' (Olsen, 1954). There were no significant differences in the concentrations of Olsen-P between the TMW-irrigated plots and the controls (Figure 12). This may be because the available P was being accumulated by the vegetation. Available phosphorus (Olsen-P) was within the range (10 - 30 mg/kg) typically found on extensive farming systems (Moir et al., 1997), and well below concentrations reported on soils irrigated with high-phosphorus effluent (Bickers 2005).

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[2] Provisional results. These results are precise (i.e. relatively correct. Relative Standard Error <4%), however, accuracy (i.e. absolute value) to be revised.

Phosphorus

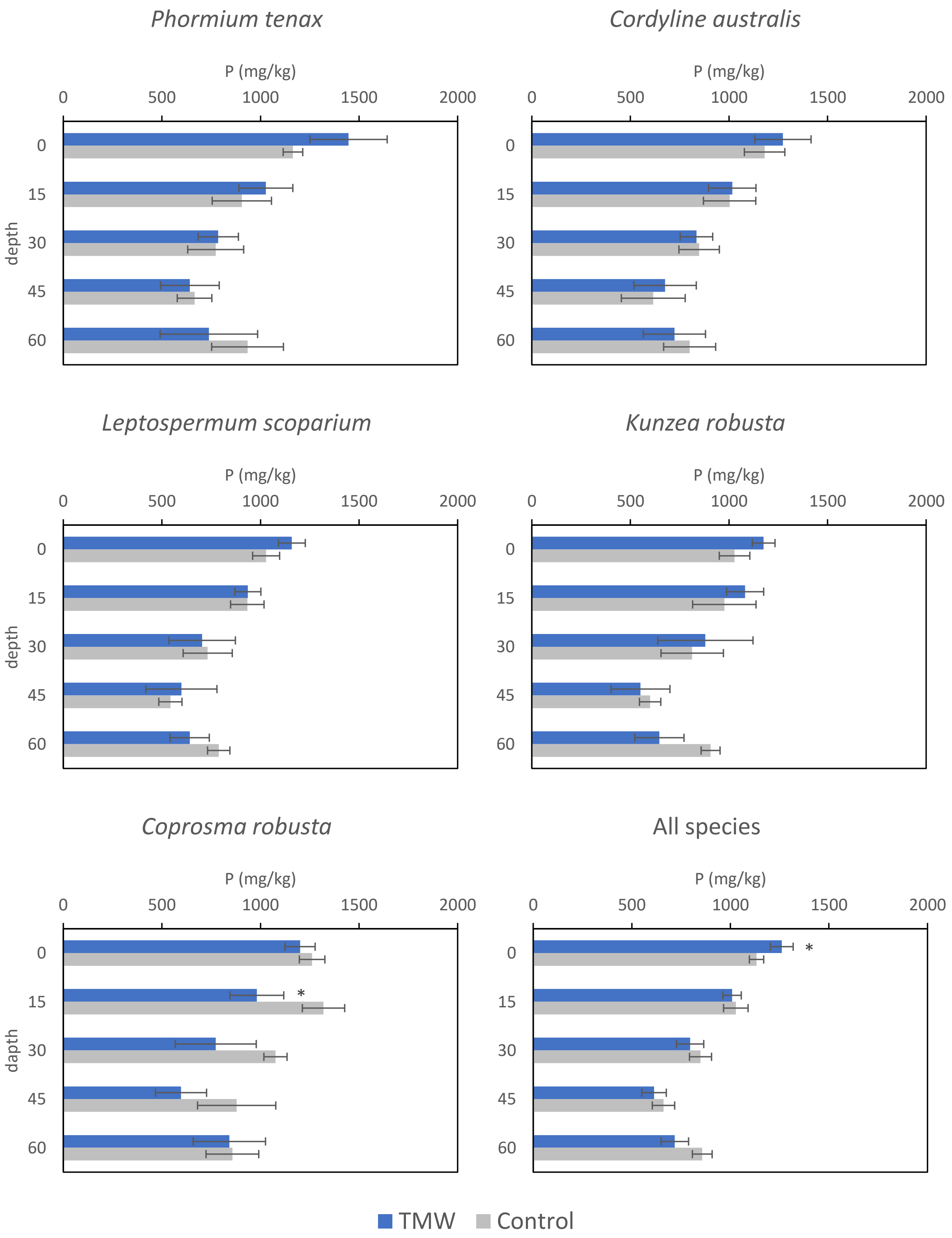

Figure 11: Soil phosphorus concentration (mg/kg) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at p<0.05 indicated by (*).

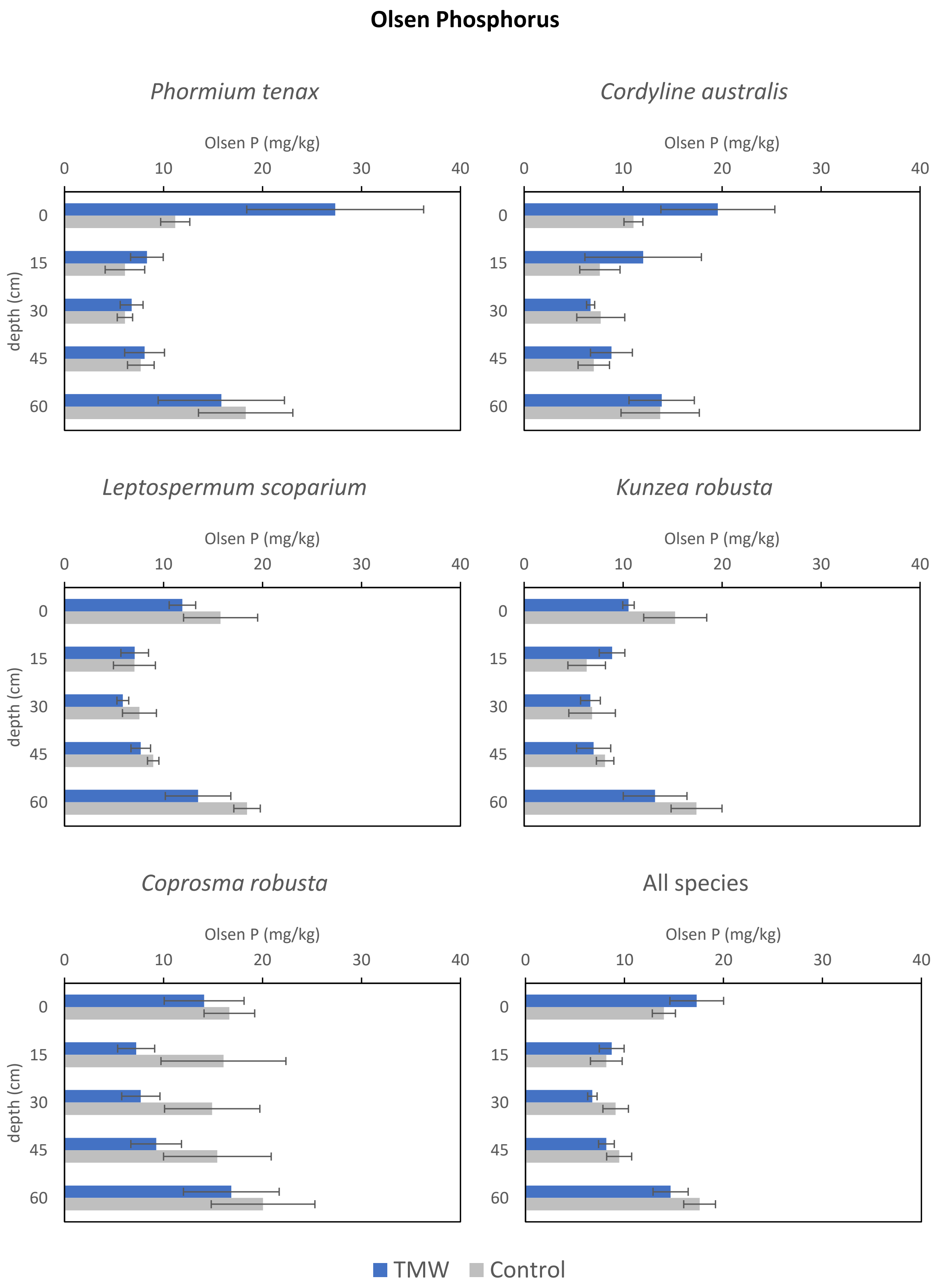

Figure 12: Olsen Phosphorus concentration (mg/kg) under different species. Mean and standard error of the mean (n=4). Significant difference between treatments at p<0.05 indicated by (*)

Other elements

None of the other elements were significantly affected by the TMW application. Soil concentrations of copper, manganese and zinc were similar to the background concentrations reported for Canterbury soils (Percival et al., 1996). Similarly, with the soluble trace elements, there were few significant differences between the TMW irrigated plots and the controls. Only aluminium and chromium were significantly reduced by TMW application in the topsoil (0-5 cm, Table A-5, Appendix 1). Neither of these elements are essential for plant growth, and a reduction in soluble aluminium can benefit plant growth in acid soils (Jones, 1960). These results indicate that the accumulation of toxic heavy metals in soils receiving TMW as a nutrient source is likely to be less than soils receiving nutrients through mineral fertilizers (Taylor et al., 2016).

Plant development

Most of the plant deaths occurred shortly after planting and before the onset of TMW irrigation: the spring of 2015 was extraordinarily dry. During the first two years of growth (measured in May 2017), the application of effluent either had no effect on growth (*K. robusta, O. paniculata*, *G. littoralis, P. cookianum, P. eugenioides)* or significantly increased growth *(L. scoparium, C. robusta, P. arboreus, P. hallii, P. tenax, C. australis* (Figure 15).

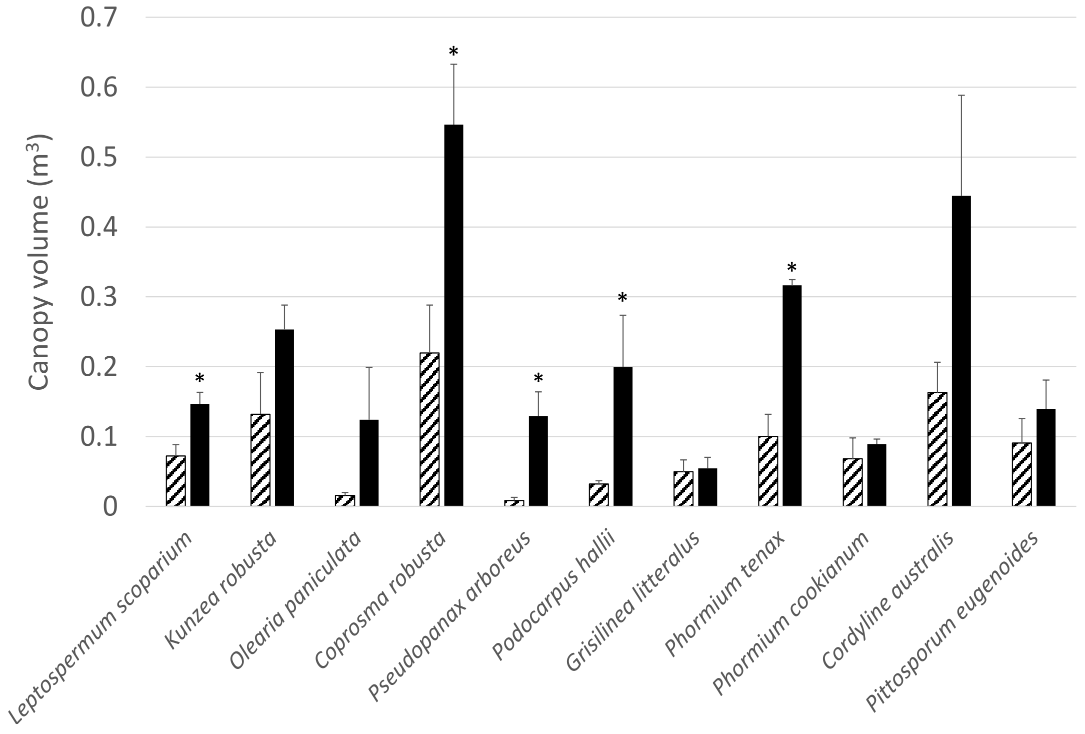

Figure 13: Canopy volume of the plants in the field plot as of May 2017. (*) indicates significant differences between the control (striped bars) and TMW (black bars), Gutierrez-Gines et al. 2017.

By autumn 2018, the canopy of the plants had closed (Appendix 4), eliminating the need to weed between the plants, although weeding occurred on the plot margins. The establishment of *Poa cita* in 2017, reduced the need to remove weeds between the plots and at the margins of the site. This species did not receive TMW. As of 2020, there was no indication of invasive weeds such as *R. fruticosus, S. mauritianum*, *S. dulcamara, P. octandra* or *C. vitalba* that may threaten the site. The weed burden may have been reduced by establishing the native trees into pasture, rather than into bare ground (for example if the site were sprayed-out before planting). In a full-scale planting operation, the plant spacing would likely be 5000 stems per hectare compared to the 20000 stems per hectare equivalent that was planted in the trial plot (to enable results to be obtained in a shorter time frame). At a lower planting density, weeding is likely required for at least another year.

In July 2019, there were 857 surviving plants on the site. The plants have begun to self-thin, i.e. smaller specimens are succumbing to competition from their larger neighbours. Across all species average height of the native vegetation receiving TMW (2.1 m) was significantly greater than the controls (1.9 m). Figure 14 shows the heights of the individual species. While all native species tolerated TMW irrigation (i.e. there were no significant decreases in height), there were significant differences between species.

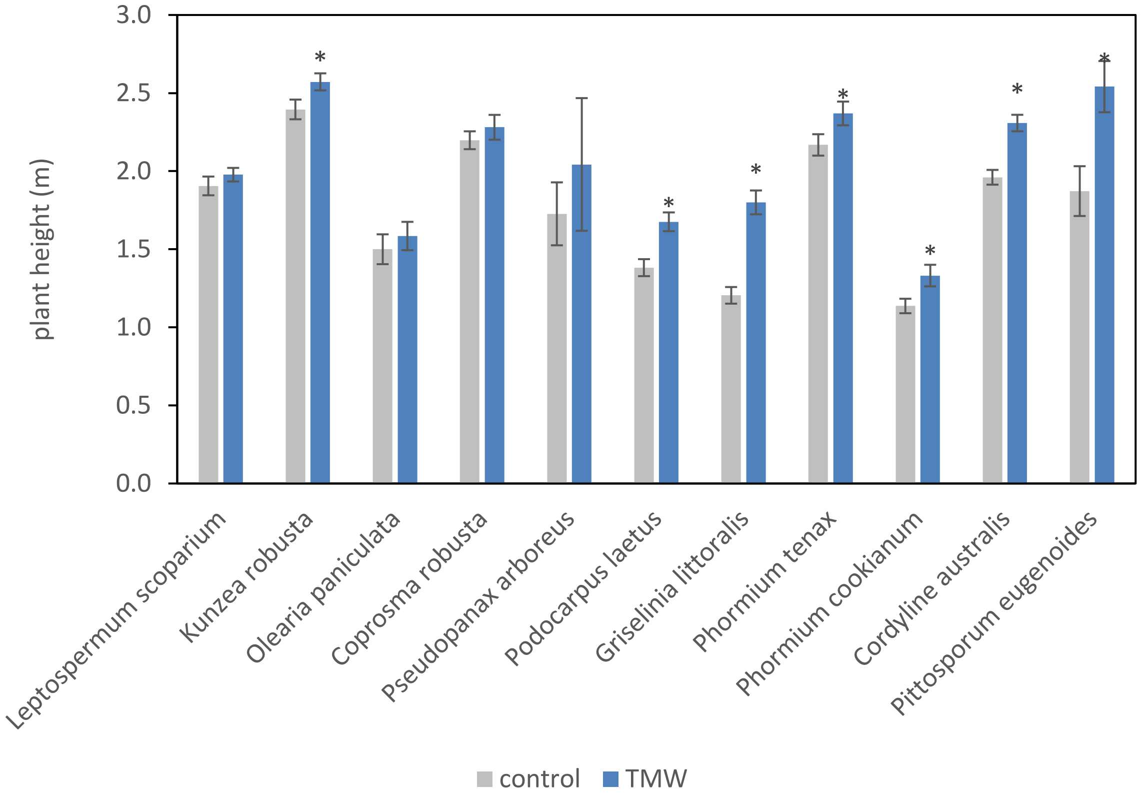

Figure 14: Plant height in July 2019 by species and treatment. Mean and standard errors of the mean.

Observations of individual species, however, indicate that *C. robusta, C. australis*, and *G. littoralis* performed particularly well at the site (Figure 15). In contrast, *L. scoparium*, *P. arboreus,* and *O. paniculata* were not well adapted to the site, with evidence of stress (chlorosis) or disease on trees in both the control and TMW-irrigated plots. In particular, *L. scoparium* has become infected with the common manuka-scale insect (*Eriococcus orariensis*) resulting in sooty-mould growth on the leaves (Figure 15). The survival of *L. scoparium* at this site is uncertain.

Figure 15: *C. robusta* (left), *C. australis* and *P. tenax* (middle) performed well at the site. *L. scoparium* (right) became infected with *E. orariensis,* resulting in the growth of sooty mould.

Plant elemental composition

There were no significant differences in plant-N concentration between the TMW-irrigated plots and the control plots, although there were significant differences between species (Figure 17). This indicates that nitrogen was the limiting factor for plant growth (Marschner, 1995). If nitrogen levels were sufficient, the plant nitrogen concentration would have increased due to luxury uptake (McLaren and Cameron, 1996). This is consistent with previous findings in a lysimeter study by Gutiérrez-Ginés et al. (2020) who measured pasture growth. This indicates that there will be no negative effects on the ecosystem by increased plant nitrogen, such as the biological food chain.

The phosphorus concentration increased in all plants following TMW application. This indicates that P was not limiting plant growth and that plants took up higher amounts of P following TMW application (luxury uptake). This is also consistent with findings by Gutiérrez-Ginés et al. (2020).

There were few other differences in the elemental compositions of the other plants (Table A-6, Appendix 1). Even sodium, which was significantly elevated in the soil, was unchanged by TMW irrigation. These results indicate that irrigating TMW onto NZ-native vegetation will not perturb nutrient status of the plants, nor introduce toxic elements into local ecosystems.

Concentration of elements in plant shoots

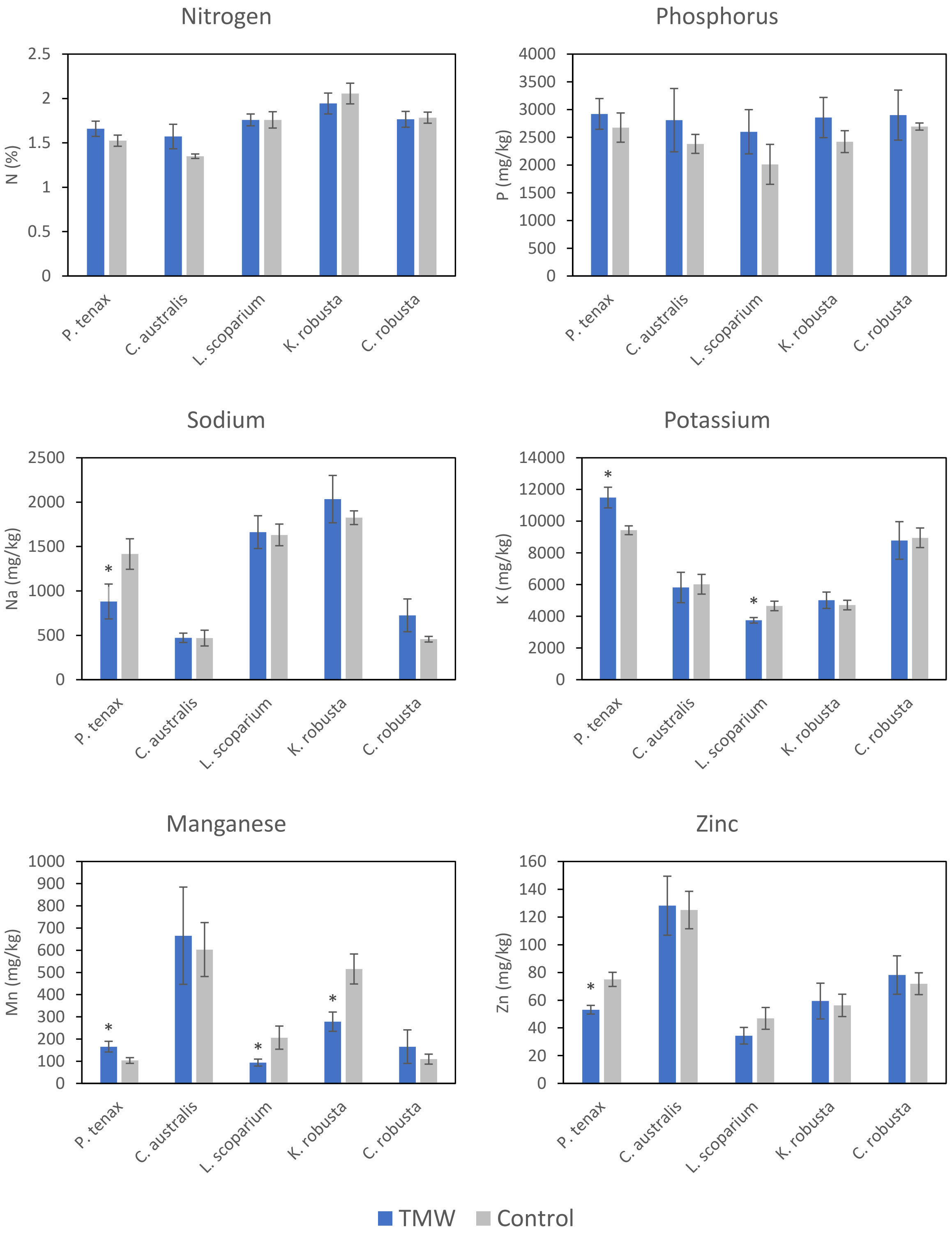

Figure 17: Concentration of elements in the plant shoot dry matter (mg/kg). Mean and standard error of the mean (n=4). Significant difference between treatments at $p<0.05$ indicated by (*).

Conclusions

The application of TMW to the Pawson Silt Loam on Banks Peninsula can occur at rates of at least 1000 mm/yr without significant soil degradation, accumulation of toxic elements, or induction of nutrient imbalances. However, we recommend a rate of 500 - 800 mm/yr, at least initially. The continual application of sodium may eventually result in depletion of soil calcium, which could be replaced by the occasional application of gypsum ($CaSO_4$). While there was a small increase in the total nitrogen concentration in the topsoil (0-5 cm), the total nitrogen in the TMW-treated plots was not significantly greater than the control plots. There was no evidence of phosphorus accumulation in the soil, probably because the amount of phosphorus added in the TMW was small compared to the mass of P in the soil profile. Available phosphorus (Olsen-P) was within the range typically found on extensive farming systems, and well below concentrations reported on soils irrigated with high-P effluent. Soil concentrations of potentially toxic heavy metals were not affected by TMW application. The concentrations of these elements were similar to background values reported for Canterbury Soils.

The effluent had a negligible effect on the concentrations of nutrients and contaminants in the plant tissues. While the growth of all species was accelerated by the effluent, there was no indication of luxury uptake of plant nutrients or increased concentrations of elements that may be harmful. This indicates that TMW is unlikely to affect ecological food chains.

None of the tested species showed reduced growth following TMW irrigation. However, some species were not well adapted to the site, including *L. scoparium*, *P. arboreus* and *O. paniculata*. In contrast, *C. robusta*, *C. australis* and *G. littoralis* performed particularly well at the site and showed accelerated growth under TMW irrigation compared to the control.

The critical success factor for establishing NZ-native vegetation are **species selection** and **weed control**. The trial at Pipers Valley Road has indicated the NZ-native species that respond well to TMW. These species should be selected for the majority of plantings on Banks Peninsula. Weed control should form part of the planting plan and include the contractors who will do the weeding. Planting into grass such as *Holcus lanthus* (Yorkshire Fog), has better outcomes than blanket spraying and planting into bare soil. Spot spraying may be appropriate. Close (1 m x 1 m, 10,000 stems/ha) plant spacing reduces the time that the site needs to be weeded but can reduce weeding options. Close planting is also more expensive. Compared to close planting, Lower density planting (e.g. 4000 stems per hectare) is less expensive to plant and to remove weeds, but weed control will be required for a longer period, adding to costs. A critical success factor is the appointment of a site manager who can monitor weeding and intervene as appropriate.

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Appendix 1: Supplementary data

Soil properties at 15, 30, 45 and 60 cm

Table A-1: Soil properties of the irrigated and non-irrigated plots for the Duvauchelle field trial at 15 cm. Mean and standard error of the mean in brackets (n=20).

	Total		$Ca(NO_3)_2$-extractable	
	Control	TMW application	Control	TMW application
pH	5.65 (0.04)	5.75 (0.04)*	na	na
Carbon (%)	1.60 (0.05)	1.63 (0.07)	na	na
Plant nutrients				
Nitrogen (%) Ammonium (mg/kg) Nitrate (mg/kg)	0.17 (0.02) <6.16 (1.09) 6.06 (0.81)	0.17 (0.03) 6.29 (0.83) 5.95 (0.73)	na	na
Phosphorus (mg/kg) Olsen-P	1028 (62) 8.17 (1.60)	1009 (47) 8.71 (1.25)	na	na
Potassium (mg/kg)	2363 (131)	2475 (139)	nd	nd
Sulphur (mg/kg)	462 (58)	549 (52)	nd	nd
Calcium (mg/kg)	6787 (264)	7220 (411)	nd	nd
Magnesium (mg/kg)	7241 (959)	9378 (1443)	nd	nd
Copper (mg/kg)	15.1 (0.55)	17.7 (1.40)*	0.023 (0.007)	<0.011 (0.003)
Manganese (mg/kg)	1678 (120)	1821 (162)	1.06 (0.12)	1.18 (0.14)
Zinc (mg/kg)	81.5 (4.29)	72.8 (1.68)*	0.074 (0.013)	0.047 (0.005)*
Contaminants				
Sodium (mg/kg)	655 (36)	>800 (47)*	nd	nd
Cadmium (ug/kg)	nd	nd	0.53 (0.06)	0.49 (0.03)
Lead (ug/kg)	nd	nd	<0.90 (0.29)	1.11 (0.74)

na=not applicable

nd=not determined

* significant difference between treatments ($p<0.05$)

< mean is lower than reported value due to some sample concentrations being below detection limit

> mean is higher than reported value due to some sample concentrations being above the measurement range

Table A-2: Soil properties of the irrigated and non-irrigated plots for the Duvauchelle field trial at 30 cm. Mean and standard error of the mean in brackets (n=20).

	Total		$Ca(NO_3)_2$-extractable	
	Control	TMW application	Control	TMW application
pH	5.94 (0.04)	5.97 (0.05)	na	na
Carbon (%)	0.20 (0.04)	0.26 (0.06)	na	na
Plant nutrients				
Nitrogen (%) Ammonium (mg/kg) Nitrate (mg/kg)	0.12 (0.00) <5.46 (0.93) 2.60 (0.49)	0.12 (0.01) 4.89 (0.70) 3.19 (0.61)	na	na
Phosphorus (mg/kg) Olsen-P	849 (56) 9.11 (1.29)	796 (42) 6.76 (0.47)	na	na
Potassium (mg/kg)	2386 (135)	2603 (173)	nd	nd
Sulphur (mg/kg)	258 (28)	388 (42)*	nd	nd
Calcium (mg/kg)	6790 (312)	6792 (287)	nd	nd
Magnesium (mg/kg)	7114 (897)	10103 (1600)	nd	nd
Copper (mg/kg)	13.0 (0.75)	14.0 (1.28)	<0.012 (0.004)	<0.009 (0.003)
Manganese (mg/kg)	1902 (172)	2027 (181)	0.52 (0.09)	0.68 (0.09)
Zinc (mg/kg)	70.1 (2.03)	69.6 (2.08)	0.066 (0.041)	0.024 (0.003)
Contaminants				
Sodium (mg/kg)	>660 (43.4)	>720 (37.3)	nd	nd
Cadmium (ug/kg)	nd	nd	0.32 (0.06)	0.30 (0.04)
Lead (ug/kg)	nd	nd	<0.51 (0.16)	<0.40 (0.11)

na=not applicable

nd=not determined

* significant difference between treatments (p<0.05)

< mean is lower than reported value due to some sample concentrations being below detection limit

> mean is higher than reported value due to some sample concentrations being above the measurement range

Table A-3: Soil properties of the irrigated and non-irrigated plots for the Duvauchelle field trial at 45 cm. Mean and standard error of the mean in brackets (n=20).

	Total		$Ca(NO_3)_2$-extractable	
	Control	TMW application	Control	TMW application
pH	6.08 (0.22)	6.14 (0.31)	na	na
Carbon (%)	0.70 (0.04)	0.62 (0.03)	na	na
Plant nutrients				
Nitrogen (%) Ammonium (mg/kg) Nitrate (mg/kg)	0.07 (0.02) <4.30 (1.03) <1.51 (0.60)	0.07 (0.01) 3.41 (0.66) <2.09 (0.57)	na	na
Phosphorus (mg/kg) Olsen-P	661 (57) 9.46 (1.26)	613 (62) 8.18 (0.80)	na	na
Potassium (mg/kg)	2116 (109)	2505 (183)*	nd	nd
Sulphur (mg/kg)	166 (27)	254 (39)*	nd	nd
Calcium (mg/kg)	6178 (169)	6434 (303)	nd	nd
Magnesium (mg/kg)	7036 (712)	10833 (1709)*	nd	nd
Copper (mg/kg)	13.5 (0.79)	13.9 (0.91)	<0.016 (0.008)	<0.012 (0.003)
Manganese (mg/kg)	911 (93)	1177 (168)	0.14 (0.02)	0.24 (0.05)
Zinc (mg/kg)	63.6 (8.35)	52.7 (3.34)	<0.032 (0.015)	0.022 (0.009)
Contaminants				
Sodium (mg/kg)	647 (31)	683 (26)	nd	nd
Cadmium (ug/kg)	nd	nd	<0.10 (0.02)	0.11 (0.02)
Lead (ug/kg)	nd	nd	<0.66 (0.28)	<0.63 (0.21)

na=not applicable

nd=not determined

* significant difference between treatments (p<0.05)

< mean is lower than reported value due to some sample concentrations being below detection limit

> mean is higher than reported value due to some sample concentrations being above the measurement range

Table A-4: Soil properties of the irrigated and non-irrigated plots for the Duvauchelle field trial at 60 cm. Mean and standard error of the mean in brackets (n=20).

	Total		$Ca(NO_3)_2$-extractable	
	Control	TMW application	Control	TMW application
pH	6.12 (0.06)	6.16 (0.08)	na	na
Carbon (%)	0.58 (0.02)	0.43 (0.02)	na	na
Plant nutrients				
Nitrogen (%) Ammonium (mg/kg) Nitrate (mg/kg)	0.06 (0.00) 3.66 (0.79) 1.28 (0.43)	0.04 (0.00)* <2.44 (0.69) <1.85 (0.55)	na	na
Phosphorus (mg/kg) Olsen-P	857 (50) 17.6 (1.61)	718 (70) 14.7 (1.77)	na	na
Potassium (mg/kg)	1992 (100)	2225 (187)	nd	nd
Sulphur (mg/kg)	<125 (33)	181 (38)	nd	nd
Calcium (mg/kg)	5967 (164)	6217 (308)	nd	nd
Magnesium (mg/kg)	7618 (817)	11699 (1828)*	nd	nd
Copper (mg/kg)	15.1 (0.71)	15.1 (0.92)	<0.011 (0.003)	<0.023 (0.007)
Manganese (mg/kg)	731 (60)	849 (115)	<0.11 (0.02)	0.16 (0.04)
Zinc (mg/kg)	44.4 (4.40)	40.3 (3.25)	<0.016 (0.003)	<0.019 (0.005)
Contaminants				
Sodium (mg/kg)	678 (37)	699 (27.4)	nd	nd
Cadmium (ug/kg)	nd	nd	<0.06 (0.01)	<0.04 (0.01)
Lead (ug/kg)	nd	nd	<0.55 (0.15)	<1.03 (0.31)

na=not applicable

nd=not determined

* significant difference between treatments ($p<0.05$)

< mean is lower than reported value due to some sample concentrations being below detection limit

> mean is higher than reported value due to some sample concentrations being above the measurement range

Available elements in the topsoil (0-5 cm)

Table A-5: Concentration of $Ca(NO_3)_2$-extractable metals in topsoil (0-5 cm) under different species. Mean and standard error of the mean in brackets, n=4. Significant differences between treatments are expressed in %.

		P. tenax	*C. australis*	*L. scoparium*	*K. robusta*	*C. robusta*
Al	W	495 (220)	742 (257)	146 (91.5)	137 (88.8)	452 (113)
	C	660 (213)	800 (145)	1085 (292)*	1076 (365)*	462 (142)
	%			-87%	-87%	
Cr	W	0.58 (0.39)	0.12 (0.02)	0.05 (0.01)	< 0.10 (0.06)	0.14 (0.03)
	C	0.10 (0.01)	0.16 (0.06)	0.16 (0.09)	0.25 (0.04)*	0.32 (0.20)
	%				-59%	
Mn	W	2150 (260)	2236 (412)	1203 (533)	1061 (414)	2300 (343)
	C	1612 (291)	1765 (262)	2329 (342)	1983 (437)	1949 (505)
	%					
Fe	W	32.1 (6.55)	26.3 (6.72)	16.8 (6.22)	15.3 (6.94)	24.8 (7.50)
	C	32.2 (4.43)	40.3 (2.51)	30.6 (7.52)	35.9 (8.34)	31.0 (11.9)
	%					
Co	W	4.84 (1.00)	5.51 (0.61)	3.11 (0.94)	2.78 (0.73)	5.23 (1.07)
	C	7.51 (2.30)	7.61 (1.23)	7.10 (1.10)	6.25 (1.48)	7.80 (2.84)
	%					
Ni	W	6.54 (1.48)	8.14 (0.93)	4.36 (2.17)	3.93 (2.21)	8.56 (1.31)
	C	7.63 (1.52)	9.00 (1.02)	9.75 (0.96)	8.73 (1.85)	6.96 (1.69)
	%					
Cu	W	91.8 (70.9)	< 14.8 (13.5)	92.7 (59.5)	< 25.7 (14.3)	9.60 (3.33)
	C	< 18.3 (12.5)	< 13.1 (5.97)	18.0 (14.2)	7.01 (3.55)	< 4.25 (2.62)
	%					
Zn	W	150 (46.1)	91.9 (9.15)	94.0 (29.7)	108 (83.4)	82.3 (12.8)
	C	117 (51.1)	83.7 (18.4)	107 (16.3)	85.9 (14.8)	90.5 (24.4)
	%					
As	W	0.48 (0.13)	0.38 (0.09)	0.41 (0.12)	0.31 (0.02)	0.33 (0.05)
	C	0.40 (0.07)	0.45 (0.09)	0.48 (0.04)	0.44 (0.12)	0.36 (0.07)
	%					
Cd	W	0.54 (0.12)	0.52 (0.12)	0.38 (0.13)	0.36 (0.13)	0.63 (0.13)
	C	0.62 (0.06)	0.68 (0.10)	0.71 (0.11)	0.67 (0.18)	0.67 (0.17)
	%					
Pb	W	0.77 (0.41)	< 0.69 (0.46)	3.53 (2.17)	< 1.04 (0.76)	0.55 (0.23)
	C	0.76 (0.61)	0.42 (0.28)	0.99 (0.61)	0.33 (0.13)	< 0.46 (0.20)
	%					

* significant difference between treatments ($p<0.05$)

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Plant elemental composition

Table A-6: Element concentrations in plant shoots (mg/kg, unless stated otherwise). Mean and standard error of the mean in brackets, n=4.

	P. tenax		*C. australis*		*L. scoparium*		*K. robusta*		*C. robusta*	
	Control	TMW	Control	TMW	Control	TMW	Control	TMW	Control	TMW
Carbon (%)	46.5 (0.16)	45.9 (0.65)	47.0 (2.44)	45.6 (0.48)	52.0 (0.34)	40.4 (1.71)	50.3 (0.12)	50.4 (0.43)	46.1 (1.42)	43.5 (0.09)
Nitrogen (%)	1.52 (0.06)	1.66 (0.09)	1.35 (0.03)	1.57 (0.14)	1.76 (0.09)	1.76 (0.07)	2.06 (0.12)	1.94 (0.12)	1.78 (0.06)	1.77 (0.09)
Calcium	3038 (153)	6322 (3410)	12934 (1635)	12850 (1212)	5781 (581)	5878 (480)	4281 (652)	3403 296)	15391 (889)	12263 (4177)
Copper	13 (0)	21 (8)	17 (4)	17 (4)	17 (4)	19 (4)	17 (4)	19 (4)	13 (0)	16 (3)
Potassium	9428 (278)	9031 (652)*	6022 (622)	5816 (960)	4653 (300)	3747 (174)*	4709 (302)	5013 (516)	8953 (618)	8784 (1186)
Magnesium	7875 (255)	8575 (1089)	8391 (481)	8297 (801)	8794 (453)	8156 (407)	8366 (287)	7538 (688)	9009 (369)	8209 (682)
Manganese	103 (13)	166 (24)*	603 (122)	666 (219)	206 (52)	94 (16)*	516 (68)	278 (43)*	109 (22)	166 (76)
Sodium	1416 (172)	881 (196)*	469 (89)	472 (53)	1631 (122)	1663 (185)	1825 (77)	2034 (267)	456 (32)	725 (185)
Phosphorus	2675 (263)	2922 (277)	2381 (171)	2809 (570)	2013 (360)	2600 (399)	2422 (197)	2856 (362)	2694 (64)	2900 (451)
Sulphur	5441 (1359)	6169 (1989)	5591 (1230)	6231 (1654)	6053 (988)	4391 (1346)	6113 (1024)	4678 (1280)	5747 (836)	5878 (1352)
Zinc	75 (5)	53* (3)	125 (14)	128 (21)	47 (8)	34 (6)	56 (8)	59 (13)	72 (8)	78 (14)

* significant difference between treatments ($p<0.05$)

Appendix 2: Nitrogen report

Impacts of nitrogen application to Pasture and Native Plantings on Banks Peninsula

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Executive summary

- Based on effluent flow-rate data, effluent chemistry, and the land available for irrigation, the nitrogen (N) application rate in Robinsons Bay would be 125 - 172 kg N/ha/yr, which is below the threshold of 200 kg/ha/yr set by many jurisdictions in New Zealand and overseas.
- Applied N will either accumulate in the soil (which is environmentally benign), be removed in the vegetation, be denitrified into nitrogen gas or nitrous oxide, or leach into groundwater.
- Irrigation of the Treated Municipal Effluent (TMW) onto cut-and-carry pasture is likely to result in negligible (<2 kg/ha/yr) nitrate leaching. Experiments have demonstrated that the pasture will remove nearly all of the N that is applied.
- Irrigation of TMW onto grazed pasture will have similar nitrate leaching to a regular grazed pasture where fertiliser has been applied.
- Preliminary data indicate that Irrigation of TMW onto NZ native vegetation will result in nitrate leaching of 15 - 60 kg/ha/yr, similar to grazed pastures. These figures will change as data from experiments in Pipers Valley come to hand. This is expected in early 2020.
- Species selection and weed control are the critical success factors for establishing NZ native vegetation under TMW irrigation.

Introduction

Nitrogen (N), in the form of ammonium (NH_4^+) or nitrate (NO_3^-), is the most important plant macronutrient in soil. Other forms of N, such as nitrogen gas (N_2) and organic N are not available to plants and must be converted to available forms by biological processes (McLaren and Cameron, 1996). New Zealand agriculture relies on N supplementation to soil, via fertilisers (mainly urea), soil conditioners (such as compost), or N-fixation from legumes such as clovers.

While N addition usually improves plant growth, excessive N application can lead to NO_3^- leaching through the soil profile where it may contaminante surface waters or groundwater (Martin et al., 2017). Elevated N application may also result in increased emissions of nitrous oxide (N_2O), a greenhouse gas with a global warming potential some 300 times greater than carbon dioxide (Taghizadeh-Toosi et al., 2011). High concentrations of NO_3^- in drinking water can be harmful to human health, particularly infants (Knobeloch et al., 2000), while elevated NO_3^- concentrations in aquatic or marine ecosystems can exacerbate eutrophication (de Jonge et al., 2002). The New Zealand Drinking Water Standard for NO_3^- is 11.3 mg/L NO_3^--N (Di and Cameron, 2000). The Australian and New Zealand Guidelines (NIWA, 2013) for NO_3^- in freshwater range from 1 mg/L NO_3^--N for pristine environments with high biodiversity and conservation values (99% species protection) through to 6.9 mg/L NO_3^--N for environments which are measurable degraded (80% species protection).

Treated Municipal Wastewater (TMW) contains agronomically significant concentrations of N, making it a potential fertiliser replacement but also a potential source of groundwater or surface water contamination. When irrigated onto soil, this N undergoes biologically and chemically-mediated cycling (Fig. 1). Ultimately, the applied N leaves the soil via plant uptake (and removal of the harvested or grazed biomass), volatilisation as N_2 or N_2O, or leaching (as NO_3^-). The amount of NO_3^- leaching or N_2O emissions from an area irrigated with TMW depends on the irrigation rate, the N-concentration in the TMW, the climatic conditions, and the land use.

This report aims to determine the likely effect of TMW irrigation on growth of NZ-native vegetation, grazed pasture, and cut-and-carry pasture on 35 hectares of irrigable land from the Thacker farm, Banks Peninsula. The production rate and chemistry of the TMW was provided by the Christchurch City Council. The soil properties, pasture uptake rates were assessed in a previous report (Robinson et al., 2017) as well as data from an ongoing field trial in Pipers Valley, Duvauchelle. At the time of writing (August 2019), we are awaiting the final results of N-fluxes from the field trial, which is due to conclude in December 2019. As such, we will amend this report with the results of the field trial as they come to hand.

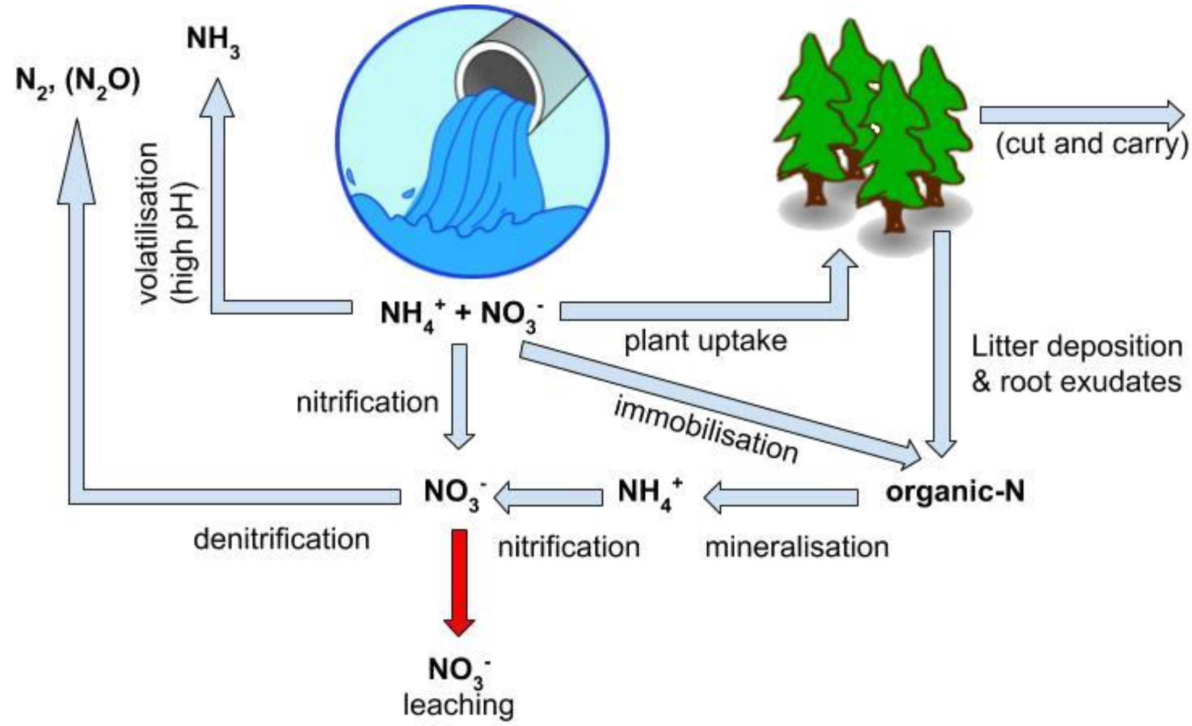

Fig. 1. Nitrogen fluxes following the application of Treated Municipal Wastewater to soil. This diagram assumes that the Wastewater has been treated to a high standard (such as is the case on Banks Peninsula) and the concentration of dissolved organic matter (and organic N) is low.

Nitrogen in the Treated Municipal Wastewater and nitrogen application rates

TMW from Duvauchelle and Akaroa (Feb 2017 - Feb 2019) had average total N concentrations of 18.5 and 25.4 mg N/L, with standard deviations of ca 7.5 mg/L in both cases. At the time of measurement, some 50% of the N was present as NH_4^+, with the remainder mostly comprising NO_3^-. However, the NH_4^+ is rapidly oxidised to NO_3^- in the environment or when the effluent is stored. (Clough et al., 2001). Once irrigated onto soil, any N added that is not taken up by plants will either oxidise to NO_3^- thence be denitrified back to N_2 (or N_2O) gas, become immobilised into soil organic matter, or leach into groundwater (Fig. 1). The rate of application affects the fate of N, with higher application rates resulting in increased N-leaching and potentially increased N_2O emissions. The likely N application rates on Banks Peninsula are 125 - 172 kg N/ha/yr shown in Table 1. These values are below the 200 kg/ha/yr threshold, which is set by many jurisdictions (Clark and Harris, 1996).

Table 1. Annual nitrogen Application (kg N/ha/yr) as a function of irrigation rate and effluent N concentration, given the area of potentially irrigable land in Robinsons Bay is some 35 ha (Barton, 2017). The likely irrigation rate is 678 mm/yr, resulting from an effluent flow rate of 650 m^3/day.

	TMW @ 18.5 mg N/L	TMW @ 25.4 mg N/L
Irrigation 500 mm	92.5	127
Irrigation 678 mm	**125**	**172**
Irrigation 1000 mm	185	254

Nitrate leaching under cut-and-carry pasture, grazed pasture and NZ - native vegetation

Previous research using lysimeter experiments on Banks Peninsula soil (Robinson et al., 2017) has shown that under cut-and-carry pasture, these irrigation rates resulted in negligible NO_3^- leaching (<1 kg N/ha/yr), even at application rates of 207 kg N/hr/yr equivalent. Compared to the previous lysimeter experiments, the groundwater at Robinsons Bay is deeper (at least 4 m (Barton, 2017), which will result in more denitrification of the applied N, thereby reducing N-leaching. However, this effect may be offset by the greater precipitation (ca. 1000 mm/yr) on the peninsula compared to the 660 mm/yr that fall at the Lincoln University lysimeter facility. Even with a small increase in drainage caused by high rainfall events on Banks Peninsula, it is likely that cut-and-carry pasture on the Thacker Farm receiving TMW will have negligible N-leaching.

In contrast to TMW-irrigated cut-and-carry systems, grazed pastures over much of the Canterbury Plains and small parts of Banks Peninsula typically leach >45 kg N/ha/yr (Stats, 2019). If the TMW-irrigated pasture were used for grazing, it is likely that the N-leaching rates would be similar to those of a non-TMW-irrigated pasture where N-fertiliser had been applied.

New Zealand native plant species have an N concentration of 0.8 - 2% (dry weight), which is significantly less than pasture, which can have up to 5% N (Dickinson et al., 2015). Given a dry biomass production under optimal conditions (i.e. under TMW-irrigation) of 5 t/ha/yr, native plants containing 1% N would remove 50 kg N/ha/yr. This is significantly less than the N being applied to the soil. Moreover, unless the vegetation is removed periodically, the N accumulated in the plants will eventually be returned to soil via leaf-fall and tree senescence (and subsequent decomposition of dead material). After the accumulation of N in soil via immobilisation, additional N will be lost via leaching or denitrification. Overseas studies have shown that 25 - 150 kg/ha of N applied N can be lost through denitrification (Paul and Zebarth, 1997; Mahmood et al., 1998). In New Zealand, studies with Dairy Shed Effluent reported that some 60 kg/ha/yr were lost through denitrification (Di and Cameron, 2000). Evidence of iron mottling in the soil profile in Robinsons Bay (Barton, 2017), indicates low-oxygen conditions that favour denitrification (Clough et al., 2001). Any N that is not removed by the biomass, fixed into soil organic matter or denitrified, will leach. Given the current data, we estimate that leaching under NZ-native vegetation under nominal conditions will be 15-60 kg N/ha/yr at Robinsons Bay, which is comparable to grazed pasture (Stats, 2019). A more accurate assessment of the likely N-leaching under NZ-native vegetation will be provided in an update report in Early 2020.

Establishing NZ native vegetation under Treated Municipal Wastewater irrigation

Irrigation with TMW significantly increases the growth of pasture and some exotic plants (Esperschuetz et al., 2016; Robinson et al., 2017). The response of NZ-native vegetation is species-dependent: while many species show significantly increased growth when irrigated with TMW, other species are unaffected or may even have lowered growth. The field trial in Pipers Valley has indicated that *Leptospermum scoparium* (mānuka), *Kunzea robusta* (kānuka), *Coprosma robusta* (karamu), *Cordyline australis* (cabbage tree), *Phormium tenax* (harakeke, flax) respond well to TMW irrigation with significantly increased growth over the four-year trial. In contrast *Griselinia littoralis* (kapuka, broadleaf)*, Phormium cookianum* (mountain flax)*, and Pittosporum eugenioides* (tarata, lemonwood) have no positive growth response. The contrasting responses of NZ-native species can result in increased weed competition during the establishment phase.

The critical success factor for establishing NZ-native vegetation are **species selection** and **weed control**. The trial at Pipers Valley Road has indicated the NZ-native species that respond well to TMW. These species should be selected for the majority of plantings in Robinsons Bay. Weed control should form part of the planting plan and include the contractors who will do the weeding. Planting into grass such as *Holcus lanthus* (Yorkshire Fog), has better outcomes than blanket spraying and planting into bare soil. Spot spraying may be appropriate. Close (1 m x 1 m, 10,000 stems/ha) plant spacing reduces the time that the site needs to be weeded but can reduce weeding options. Close planting is also more expensive. Compared to close planting, Lower density planting (e.g. 1 m x 3 m, 3333 stems per hectare) is less expensive to plant and to remove weeds, but the weeding will have to continue for several more years. A critical success factor is the appointment of a site manager who can monitor weeding and intervene as appropriate.

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Appendix 2: Phosphorus report

Phosphorus in Treated Municipal Wastewater irrigated onto NZ-native vegetation

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Executive summary

- Potentially, irrigating Treated Municipal Wastewater (TMW) onto NZ-native vegetation could result in the accumulation of phosphorus (P) in the soil to the point that the soil becomes infertile and excess P degrades local waterways. The Christchurch City Council commissioned the University of Canterbury to determine acceptable levels of P in TMW that is to be applied to NZ-native vegetation.

- An assessment was made using calculations of the likely effects of adding TMW on soil P concentrations and P losses that could lead to waterway degradation. These results of these calculations were compared with literature reports of the effects of soil P on soil fertility and P-losses. Note that the P concentration in TMW from the Akaroa wastewater treatment plant has a median P concentration of 6.6 mg/L and a maximum of 8.4 mg/L.

- Calculations revealed that irrigating 500 mm/yr of TMW containing either 5, 10 or 15 mg/L P would result in P accumulation in the soil. This is because P losses through vegetation removal, leaching, and runoff from TMW-irrigated native vegetation, are negligible compared to the P that is added to the soil.

- Over a 50-year period, the concentrations of soil P in the Pawson Silt Loam and Barry's Soil receiving 500 mm/yr of effluent containing 10 mg/L would increase by 84% and 100%, respectively. Nevertheless, even with these increases, the total average P concentrations in the top 0.3 m would remain within the range of total P concentrations found in NZ's agricultural soils.

- In the aforementioned scenario, Olsen-P, a measure of plant-available P, would also significantly increase in both soils but still remain within ranges considered optimal for a high-fertility soil (the PSL), and within a low-fertility soil (BSL). The increase in Olsen-P may be unfavourable for some NZ-native species, however, there are many other NZ-native species that will thrive under these high-P conditions. This indicates the importance of plant-selection for any treatment system.

- In the aforementioned scenario, there would be an increase in the amount of P-leaching below the top 0.3m of topsoil to around 2.2 kg/ha/yr after 50 years of application. However, most of this P would be retained in the subsoil before it reaches waterways. Given that NZ-native vegetation will decrease surface runoff and soil loss, the increase in P leaching will be

more than offset by the reduction of P entering waterways through erosion and overland flow: There is likely to be less P lost under TMW-irrigated NZ-native vegetation than an intensively-grazed pasture.

- Estimations using these calculations indicate that the application of 50 kg P/ha/yr with TMW is unlikely to cause serious soil fertility or environmental issues over a 50-year period. The life of the system could be extended using lower rates of P addition or by periodically harvesting the native vegetation.

Introduction

Treated Municipal Wastewater (TMW) contains environmentally significant concentrations of plant nutrients, including phosphorus (P). While the application of P to soil can improve plant growth (McLaren and Cameron 1996), excess P is can accumulate in soil where it may become toxic to plants (Hawkins et al. 2008). High concentrations of P in soil can increase the chance that this element can enter waterways via runoff, erosion or to a lesser extent, leaching (McDowell and Condron 2004). Elevated levels of P in waterways exacerbate eutrophication, including the uncontrolled growth of aquatic macrophytes and algae (Tilman et al. 2001).

Phosphorus is routinely added to agricultural soil in NZ. Most soils require more P to be added than is removed by plants, because much of the added P becomes immobilized and unavailable for plant uptake (McLaren and Cameron 1996). Measuring the total P in soil is a poor indicator of the P-availability to plants or P that is likely to leach into waterways, because only a fraction of the total P in soil is mobile and available to plants. Plant availability is often indicated by measurements using a mild chemical extractants. In New Zealand and elsewhere, 'Olsen-P' provides good information on the plant-availability of P in a soil (LandcareResearch 2017). Similarly, extractions using calcium chloride ($CaCl_2$), indicate the concentration of P in soil solution, which has the potential to leach through the soil profile (Sanchez-Alcala et al. 2014).

To convert a low-fertility soil, such as a forest soil, into productive pasture, a large application of P, 'capital P', is required. This can be as much as 500 kg P/ha (Dollery 2017). Thereafter, 'maintenance P' is applied, depending on the land use, usually between 5 and 40 kg P/ha/yr (McLaren and Cameron 1996). The application of P from TMW can be higher than that, which would be applied from P fertilisers. For example, the application of 500 mm/yr TMW from the Duvauchelle wastewater treatment plant, which contains an average of 11 mg/kg P(Gutierrez-Gines, McIntyre, et al. 2017) is the equivalent of 55 kg P/ha/yr. The P concentration in TMW from the Akaroa wastewater treatment plant has a median P concentration of 6.6 mg/L and a maximum of 8.4 mg/L. Irrigating 500 mm/yr of TMW from Akaroa would add 33 kg P/ha/yr.

While a significant amount of P that is added to agricultural soil is removed in the produce, the application of P to NZ native vegetation, where no plants are removed, will result in an accumulation of P in the system. This may result in toxicity to plants and or environmental degradation.

This report aims to determine the likely rate of P accumulation, P toxicity, and P mobility, resulting from the irrigation of TMW onto native vegetation on Bank's peninsula.

To assess these aims, the effects of irrigating 500 mm of TMW onto two Bank's Peninsula soils, the Pawson Silt Loam (PSL), 43°45'8.78"S 172°56'35.55"E and Barry's Soil (BSL), 43°44'53.06"S 172°55'41.44"E, also a silt loam, were estimated using mass balance calculations. These calculations used data from the PSL, BSL reported in (Gutierrez-Gines, McIntyre, et al. 2017) as well as other unpublished data from ongoing investigations. It was assumed that the amount of P removed in the NZ native vegetation was negligible. The calculations were run over a simulation period of 50 years. Other parameters used in the calculations are given in the Table.

The calculations assume that there is negligible runoff and erosion under the native vegetation because (a) the TMW would only be irrigated onto gently sloping land (<15^{o} for pasture and <19^{o} for NZ-native vegetation), (b) tree roots stabilize the soil, mitigating soil loss (Robinson et al. 2009), and (c) increase infiltration and preferential flow around the tree roots mitigate overland flow (Knechtenhofer et al. 2003; Sidle et al. 2006).

Table. Parameters used in the mass balance calculations for P application to NZ native vegetation on two soil types on Bank's Peninsula

	Pawson Silt Loam (PSL)	**Barry's Soil (BSL)**
Effluent P concentration (mg/L)	5, 10 or 15	5, 10 or 15
Effluent application rate (mm/yr)	500	500
P application rate (kg/ha/yr)	25, 50, or 75	25, 50, or 75
[1]**Water flux (mm)**	800	800
[2]**Initial soil P concentration (mg/kg)**	1046	599
[3]**Olsen-P (mg/kg)**	39	9
[4]**Water soluble P ($CaCl_2$) (mg/L)**	0.18	0.04
[2]**Soil density (t/m^3)**	1.4	1.4
Simulation depth (m)	0.3	0.3

[1]Estimated from rainfall (922 mm/yr) + TMW irrigation (500 mm/yr) – evapotranspiration (ca. 622 mm/yr)
[2]Measurements from (Gutierrez-Gines, McIntyre, et al. 2017)
[3]Unpublished data, Lincoln University
[4]Estimated from ratios with Olsen-P on similar soils from McDowell and Condron (2004) and Sanchez-Alcala et al. (2014).

Fig. 1 shows the results of these calculations. Under the nominal case of irrigating 500 mm/yr of TMW containing 10 mg/L P, over a 50-year period the total P concentration in the top 0.3 m will increase from 1046 to 1624 mg/kg in the PSL and from 599 to 893 mg/kg in the BSL. Even with this increase, the total concentration at the end of the 50-year period is still well within the range of P concentrations reported for NZ agricultural soils reported by McDowell and Condron (2004) and Reiser et al. (2014). It should be noted that the concentrations calculated here are averages and due to the highly heterogeneous nature of flow pathways in a forested soil (Knechtenhofer et al. 2003), it is likely that there will be localized areas with significantly higher concentrations. Gutierrez-Gines, McIntyre, et al. (2017) reported no significant increases in total soil P in a lysimeter experiment following the application of 2375 mm of TMW containing 11 mg/L P, probably because the total increase in P was within the measurement error and because of heterogeneity in the system.

In the nominal case, the plant-available or 'Olsen P' in these soils is likely to increase from 39 to 61 mg/kg in the PSL and increase from 9 to 14 mg/kg in the BSL. The initial Olsen-P concentration in the PSL is within the range (35-40 mg/kg) recommended by Dairy NZ to maintain high productivity on sedimentary soils (DairyNZ 2018). This is undoubtedly a result of good soil management under previous land use, grazed pasture. In contrast, the BSL, with an initial Olsen-P concentration of 9 mg/L is consistent with non-productive but managed land, in this case a golf course. Even with an increase to 14 mg/kg, the plant-available P would only be sufficient for low P-requiring crops such as for winter wheat (Tang et al. 2009). For pasture, Olsen-P values above 100 are excessive and values are considered 'high' from 50 – 100 (LandcareResearch 2017).

It is likely that the high plant-available P concentration on the PSL would inhibit the growth of some NZ-native species that are adapted to a low-P environment. LandcareResearch (2017) reports that for native vegetation, Olsen-P values of 8-12 mg/kg is considered high and 12 – 15 mg/kg is excessive. However, there are many reports that some NZ-native species can thrive with Olsen-P values manifold higher e.g. Gutierrez-Gines, Robinson, et al. (2017) and Reis et al. (2017). Indeed, 11 species of native plants are thriving on the very same PSL (with an initial Olsen-P of 39 mg/kg), which has received TMW for nearly 3-years (Figure 2).

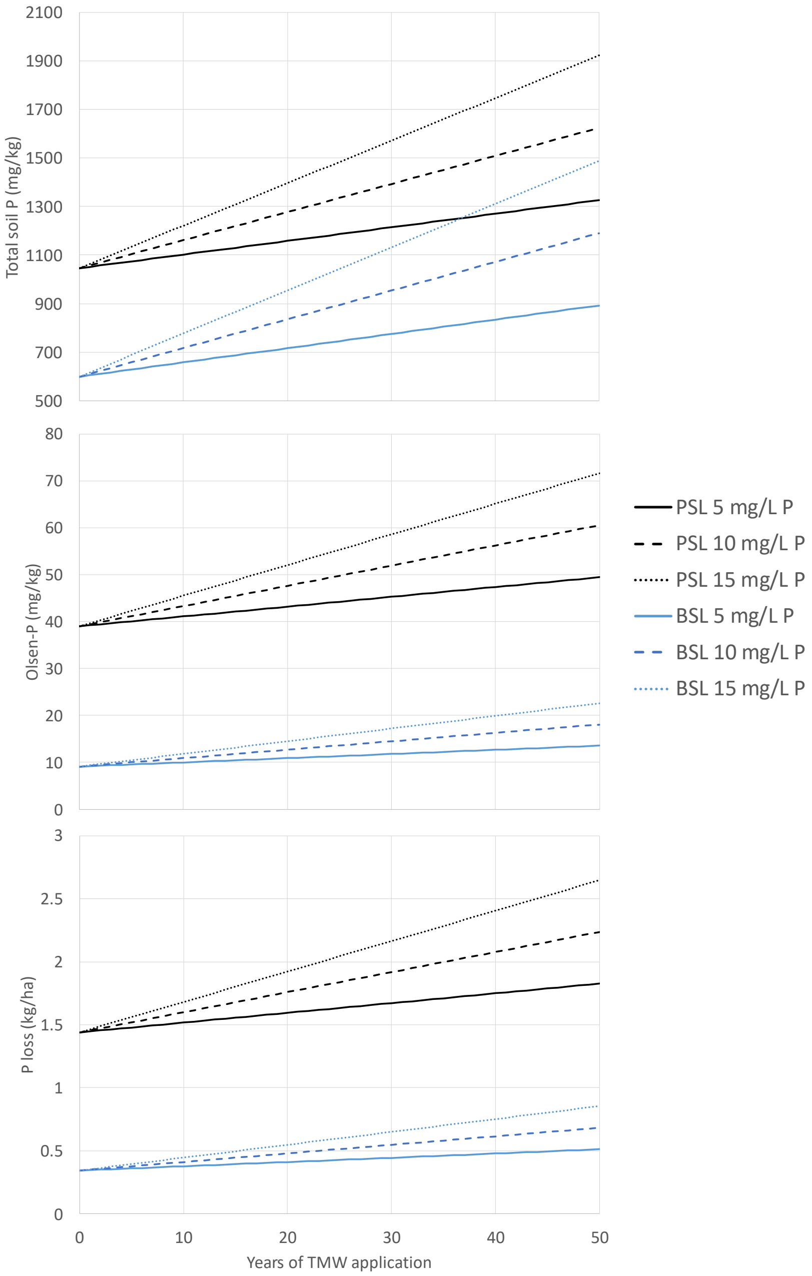

Figure 1.

Calculated phosphorus (P) in the top 0.3m of the Pawson Silt Loam (PSW) and Barry Soil (BSL) under irrigation with TMW at 500 mm/yr with a P concentration in the effluent of 5, 10 or 15 mg/L. The parameters used for the calculations are given in Table 1.

Fig. 1 also shows that irrigating TMW onto native vegetation will result in a significant increase in P leaching from the top 0.3 m of topsoil. This is because of the additional P added to the system in the TMW and the increased water flux through the soil. In the aforementioned scenario, P leaching below the top 0.3m would increase to 2.2 kg/ha/yr in the PSL and to 0.9 kg/ha/yr in the BSL after 50 years. It should be note that, depending on the depth of groundwater, most of this P lost from the top 0.3 m will be retained by the subsoil, which is rich in P-binding oxides of iron and aluminium (McLaren and Cameron 1996). In comparison, the estimated current total P-loss through soil loss from the same area under grazed pasture ranges from 2 – 15 kg/ha/yr, based on soil loss maps (https://statisticsnz.shinyapps.io/soil_erosion/). Under native vegetation irrigated with TMW, significantly less P would be lost through runoff or soil loss compared to a grazed pastureland because the trees increase infiltration and stabilize the soil (Robinson et al. 2009; Sidle et al. 2006). It is therefore likely that irrigating NZ-native vegetation with 500 mm/yr of TMW containing 10 mg/kg P will result in less P-loading on surface waters than a conventional grazed pasture.

Fig. 2. PhD candidate Alexandra Meister and Dr Jacqui Horswell among NZ native vegetation receiving Treated Municipal Wastewater, Pipers Valley Road, Duvauchelle. 12th February 2018.

The calculations indicate that TMW irrigated onto NZ-native vegetation with application P at a rate of 50 kg/ha/yr will result in soil and plant-available P concentrations that are still within the ranges of NZ agricultural soils and that excessive P-leaching is unlikely. This would be the case when irrigating 500 mm/yr of TMW from the Akaroa wastewater treatment plant, which would add the equivalent of 33 kg P/ha/yr. While it is likely that some NZ-native species will not tolerate these levels of plant-available P, there are published studies showing that many NZ-native species can tolerate such levels (Gutierrez-Gines, Robinson, et al. 2017; Reis et al. 2017). Lower P application rates will prolong the life of the system, as would periodic removal of some of the vegetation e.g. periodic harvesting of manuka or kanuka to produce high value essential oils.

The application of any element to a system at a rate than is greater than the rate that it is removed is ultimately unsustainable (Mills et al. 2005). If a soil P concentration were reached when a NZ-native ecosystem collapsed or if unacceptable concentrations of P were leaching, then the soil could usefully be converted to high-fertility agricultural soil for pasture or cropping.

Note that this report is based on calculations using soils from the Duvauchelle Golf Course and Pipers Valley Road. Soils from other locations on the peninsula (e.g. Robinson's Valley) may have different initial conditions due to differences in soil use history.

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Appendix 4: Development of the field trial from 2015 to 2019

August 2015 September 2015

November 2015 August 2016

November 2016 April 2017

Figure A-1: Development of the field trial from August 2015 to April 2017.

June 2017 November 2017

February 2018 September 2018

May 2019 September 2019

Figure A-2: Development of the field trial from June 2017 to September 2019.