Final report (June 2017): A lysimeter experiment and field trial to determine options for the beneficial reuse of wastewater from Duvauchelle and Akaroa, Banks Peninsula

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This report provides end-of-contract outcomes from lysimeter and field trials. This project has been the subject of postgraduate research by Cameron McIntyre, Saloomeh Seyedalikhani, Minakshi Mishra and Obed Lense. Their dissertations and related publications will be made available when they are complete.

Note that the field trials will continue until at least the 30th of June 2018. The field trials will be the subject of postgraduate research at the University of Canterbury and the Centre for Integrated Biowaste Research (CIBR). Updates will be provided on:

http://www.kiwiscience.com/duvauchelle.html

Executive summary

- In 2014, the Christchurch City Council (CCC) commissioned Lincoln University to determine options for the beneficial reuse of Treated Municipal Wastewater (TMW) from Duvauchelle and Akaroa, Banks Peninsula through a lysimeter experiment and a field trial.

- Following an initial assessment of the soils where the TMW would be applied, a lysimeter trial was set up at Lincoln University in December 2014. This trial comprised 18 50 cm x 70 cm lysimeters containing intact soil cores from the golf course at Duvauchelle (12 lysimeters) and an area between Takamatua and Akaroa (6 lysimeters). The soils from Duvauchelle and Takamatua were Barry's soil and a Pawson silt loam, respectively.

- From December 2014 until April 2015, these lysimeters were irrigated with 10 mm per day, resulting in all lysimeters draining approximately equal volumes. On the 22nd of April, treatments started with municipal wastewater from Duvauchelle. Treatments comprised a control (Duvauchelle, Akaroa), 440 mm/yr (Duvauchelle), 825 mm/yr (Duvauchelle, Takamatua) and 1650 mm/yr (Duvauchelle). These treatments continued until the 3rd of October 2016. The lysimeters were then deconstructed and analysed.

- All lysimeters drained freely and there was no ponding. Nitrogen leaching was negligible in all treatments, although mineral nitrogen accumulated in the soil profile of the 1650 mm/yr treatment. It is unlikely that phosphorus, potassium, sulphur, calcium and magnesium will cause problems with either fertility or environmental quality in a system irrigated with TMW.

- Sodium-induced degradation of soil structure is a major concern when using TMW as irrigation water. Sodium accumulated in the soil columns in all the TMW treatments. The rate of accumulation was not proportional to the TMW application rate, indicating that sodium was moving down through the soil profile and leaching. The sodium accumulation ratio of the TMW was 15, indicating that in the long term (>10 years) at a moderate irrigation rate (<1000 mm) the soil may need to amended with gypsum, lime or dolomite to maintain soil structure.

- Pasture growth in the lysimeters was significantly enhanced by the TMW throughout the entire experiment. There were no signs of toxicity.

- A field trial comprising 11 native species, namely *Leptospermum scoparium, Kunzea robusta, Olearia paniculata, Pseudopanax arboreus, Coprosma robusta, Podocarpus cunninghamii, Griselinia littoralis, Pittosporum eugenioides, Cordyline australis, Phormium tenax, Phormium colensoi* was established on ca. 1000 m^2 of land near Pipers Valley Road. Trees irrigated with TMW grew better than or the same as unirrigated trees. There were no signs of toxicity. The plants with the greatest positive response to TMW were *Leptospermum scoparium, Olearia paniculata, Coprosma robusta, Podocarpus cunninghamii, Cordyline australis,* and *Phormium tenax.* The field trial will continue until at least June 2018.

- The use of TMW to produce valuable biomass such as cut-and-carry pasture, grazed pasture, or valuable native products such as manuka honey or essential oils constitutes the beneficial reuse of a valuable resource that is less environmentally damaging than disposal into the sea.

- It is recommended that the effluent be applied at a rate of 500 – 800 mm per year and that the soil is periodically monitored for aggregate stability. Gypsum, dolomite, or lime may need to be added periodically. A successfully designed system requires a hydrological and geotechnical assessment of the area to be irrigated.

Contents

Introduction

Land application of treated municipal wastewater

In New Zealand, the land application of Treated Municipal Wastewater (TMW) is 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). Compared to direct discharge into water, Irrigation of TMW onto land reduces the contaminants that enter waterways and therefore has positive effects on the water quality (Herath, 1997). 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. TMW can reduce or eliminate the need for mineral fertilisers such as superphosphate, which contain elevated concentrations of toxic cadmium, fluorine and uranium that can accumulate in soil (Kim and Robinson, 2015). In many countries, including NZ, TMW is used to irrigate pasture, crops and forestry (Barton et al., 2005; Capra and Scicolone, 2004).

The application of TMW to land also carries risks that need to be mitigated for a successful operation. There are numerous examples of where land application of TMW has been discontinued because of environmental degradation. Excessive rates of TMW application to land can result in unacceptable nutrient leaching (Houlbrooke et al., 2003), runoff, soil instability and erosion, as well as accumulation of some components, such as sodium, in the topsoil (Cameron et al., 1997). High sodium concentrations can reduce plant growth through salinity and sodicity as well as degrade soil structure through the dispersion of clays (Mojid and Wyseure, 2013). The nature of the risks of the land application of TMW and therefore the design of a successful system is dependent on the quality of the TMW and the local environment. Therefore, every system needs to be specifically designed.

Potential for land application of TMW on Banks Peninsula

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. They are often imperfectly drained and may contain a fragipan (an 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.

The Christchurch City Council seeks to reduce the direct disposal of TMW into Akaroa harbour. Several small communities now have their wastewater irrigated onto woodlots. There is now an on-going program of options analysis for alternatives to harbour disposal for the settlement of Duvauchelle. Potentially, some of the effluent produced in Akaroa could also be land-applied. Duvauchelle produces some 27600 m^3 of wastewater per year (based on 2016 data provided), which is currently discharged directly into the harbour through one long harbour outfall.

In 2014, the Christchurch City Council (CCC) approached Lincoln University regarding the possibility of irrigating TMW from Duvauchelle onto the local golf course. In subsequent discussions with stakeholders during public open days in 2015 and 2016, this brief was expanded to include cut-and-carry pasture as well as NZ native vegetation. While there are numerous examples of successful irrigation onto cut-and-carry pasture in NZ and elsewhere, there is a shortage of information on how native species will interact with TMW. Potentially, TMW could be irrigated onto NZ native vegetation, with a view to increasing the production of valuable native products or the creation of zones of ecological value (Meurk, 2008; Franklin et al., 2015). Manuka (*Leptospermum scoparium*) is an obvious candidate species because of its associated high-value honey and essential oils. Moreover, mānuka 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 kanuka (*Kunzea robusta*) for essential oil production, horopito (*Pseudowintera colorata*), which produces antifungal compounds, harakeke (*Phormium tenax*) for fibre production, and a whole suite of species, including kapuka (*Griselinia littoralis*) that may be a nutritious supplement due to tannins and trace elements (Dickinson et al., 2015).

It is unclear whether TMW would confer the same growth benefits to native vegetation as to pasture. Many NZ-native species, such as mānuka, are adapted to low-fertility soils and it may not respond well to the addition of high concentrations of plant macronutrients. Franklin et al., (2015) reported that some responded positively to N (200 kg/ha equiv.), but *Leptospermum scoparium* did not. Dickinson et al. (2015) reported that biosolids improved the growth of *Grisilinea littoralis* and *Kunzea robusta*, but not *Dodonaea viscosa*.

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 be no significant removal of nutrients or contaminants from the system. It is likely that nitrate leaching and phosphorous accumulation in the soil would therefore be greater.

Aims

We aimed to determine the suitability of soils from the Duvauchelle golf course and Takamatua peninsula to receive treated municipal wastewater from the Duvauchelle Wastewater Treatment Plant. Specifically, we sought to determine whether irrigation rates of up to and in excess of 1000 mm per year would result in ponding, excess nitrate leaching, accumulation or depletion of elements in soil, changes in pasture growth and quality, change in the survival and growth of NZ native vegetation.

Materials and methods

Site description

On the 28th of August 2014, a site visit was made to Duvauchelle Golf Course (Barry's soil) and the Takamatua Peninsula (Pawson silt loam). Soil pits were opened with a view to ascertain whether the soils would be suitable for lysimetry, namely that they would have an adequate permeability to allow significant through-flow of water. Soil pits revealed both soils to be imperfectly drained (some mottling) but no evidence of a fragipan, perched water, or impermeably (reduced iron). The mean (standard deviation) of the size fractions for these soils are: course sand 1.2 (0.2)%, fine sand 44.5 (0.9)%, silt 28.1 (2.1)% and clay 24.0 (2.2%) (Anon, 1939). Fig. 1 shows the locations of the experimental sites.

Fig. 1. Locations where the lysimeters were excavated and of the ongoing field trial where TMW is being irrigated onto NZ native vegetation.

Lysimeter experiment

Two intact lysimeters were collected from the golf course at Duvauchelle on the 18th of September 2014. These lysimeters were taken to Lincoln University and irrigated with water (10 mm per day) until drainage stabilised in late October 2014. This demonstrated that the intact cores would drain and therefore be suitable for the full experiment. In November 2014, a further 10 lysimeters were taken from the golf course in Duvauchelle (43°44'53.06"S, 172°55'41.44"E) and six were taken from a paddock containing cattle (43°47'33.11"S, 172°57'16.96"E) between Takamatua and Akaroa (Fig. 1). Each lysimeter cylinder was placed on the soil surface, and gently tapped into the soil, while the soil surrounding the cylinder was excavated (Fig 2). Molten Vaseline was poured around the edge of the intact soil core before removal to the Lincoln University lysimeter facility.

The lysimeters, replete with intact soil cores, were installed at the Lincoln University lysimeter paddock (43°38'53.54"S, 172°28'7.69"E) in December 2014. The original vegetation was left upon the lysimeters. The Duvauchelle lysimeters were covered with a fescue / browntop mixture, while the Takamatua lysimeters were dominated by perennial ryegrass. A decision was taken not to remove and re-sow the pasture because this would have resulted in significant topsoil disturbance and consequent flush of nitrogen through the soil profile.

Between December 2014 and April 22nd 2015, the lysimeters were irrigated with 2 L (10 mm) of water per day. The lysimeters started to drain in February 2015 and by March 2015, similar volumes of leachate were obtained for all lysimeters. On the 22nd of April 2015, effluent application of the lysimeters began. Treated Municipal Wastewater (TMW) was collected by the Christchurch City Council (CCC) and delivered to Lincoln University in a 1000 L tank. Samples of the stored effluent were taken weekly. The tank was refilled as needed. There were three replicates of five treatments. Namely:

1) Barry’s soil. Control (no effluent application)
2) Barry’s soil. Wastewater added at ca. 500 mm / yr (0.4 L/day, 5x per week)
3) Barry’s soil. Wastewater added at ca. 1000 mm / yr (0.75 L/day, 5x per week)
4) Barry’s soil. Wastewater added at ca. 2000 mm / yr (1.5 L/day, 5x per week)
5) Pawson silt loam. Control.
6) Pawson silt loam. Wastewater added at ca. 1000 mm/yr (0.75 L/day, 5x per week)

Note that the actual annual rates were slightly less than anticipated. The actual annual rates for the 500 mm, 1000 mm, and 2000 mm treatments were 440 mm, 825 mm and 1650 mm per year. Drainage volumes were measured weekly or more often following high rainfall events. Pasture was harvested periodically, typically every three weeks, during the growing season. Fig. 3 shows the installed lysimeters, with PhD student, Minakshi Mishra measuring pasture growth and Dr Maria Jesus Gutierrez-Gines irrigating effluent and collecting drainage. On the 16th of November 2016, the lysimeters were deconstructed. Following a final harvest of the pasture, soil samples from 0-15 cm, 15-30 cm, 30-45 cm, and 45 – 60 cm were taken and stored for chemical analyses.

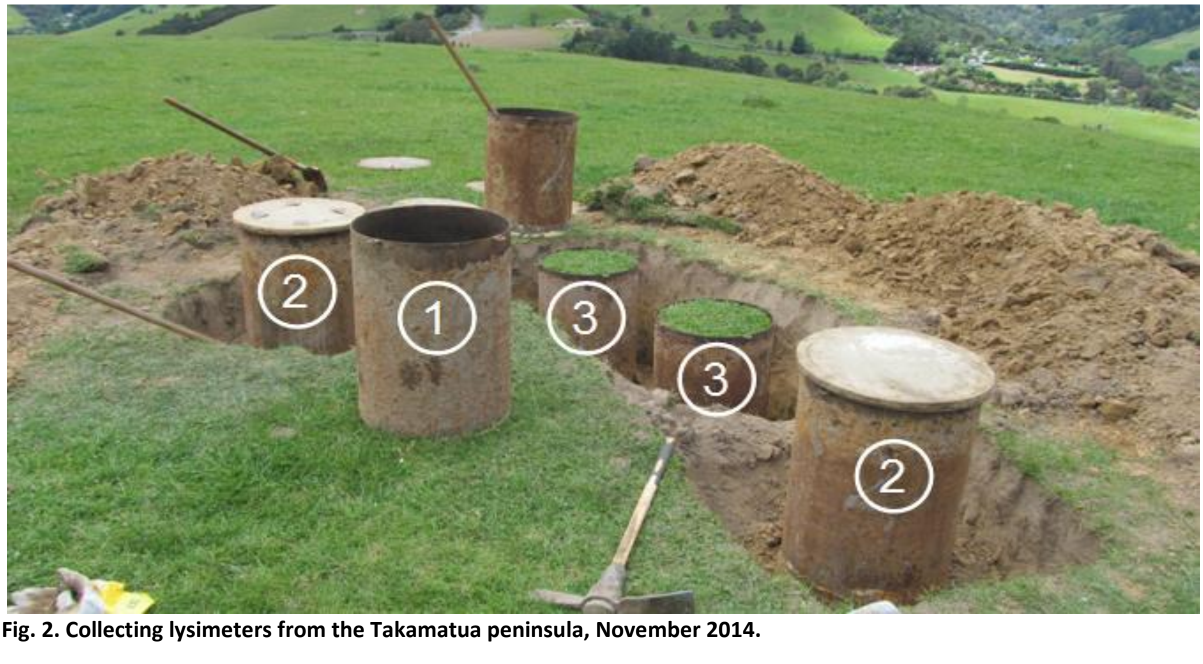

Fig. 2. Collecting lysimeters from the Takamatua peninsula, November 2014.

Fig. 3. Top: The installed lysimeters showing the six Pawson silt loam soil cores (front-left) and the 12 Barry's soil cores (rear-right). Centre left: Effluent application. Centre right: Drainage collection. Bottom: Destructive sampling of the lysimeters at the conclusion of the experiment. 16th of November, 2016.

Field trial

In July 2015, we planted 1350 native trees (Fig. 4), divided into 27 blocks of three different vegetation types (Table 1). Twelve of the 27 blocks are receiving treated municipal wastewater at a rate of 500 mm during the growing season (October – April), a similar rate to that used on an irrigated dairy farm in Canterbury. Effluent irrigation started in January 2016. Weeds were controlled using a lawnmower. An information board was installed near the roadside describing the aims of the experiment.

In May 2017 the survival of the plants was recorded along with the canopy volume of each individual plant. Soil and plant samples have been taken for chemical analysis. In June 2017, all areas within the plot that were not under native vegetation were planted with silver tussock (*Poa cita*). It is hoped that these tussocks will minimise the need for further weed control at the site.

Fig. 4. The field trial in Piper's valley road shortly after planting. The gate is at the top left of the picture.

Table 1. Composition of the thee vegetation types used in the experiment. The design of the field plot is shown below.

Vegetation type 1			**Vegetation type 2**			**Vegetation type 3**	
Mānuka	*Leptospermum scoparium*		Akiraho	*Olearia paniculata*		Kapuka	*Griselinia littoralis*
Kānuka	*Kunzea robusta*		Puahou	*Pseudopanax arboreus*		Tarata	*Pittosporum eugenioides*
			Karamu	*Coprosma robusta*		Tī kōuka	*Cordyline australis*
			Hall's tōtara	*Podocarpus cunninghamii*		Harakeke	*Phormium tenax*
						Wharariki	*Phormium colensoi*

1C	3E	3C	1E	2C	2E	1C	3E	C	gate
3C	2E	2C	2E	1C	3E	3C	2E	C	
2C	1E	1C	3E	3C	1E	2C	1E	C	

C=control E=effluent 1,2,3=vegetation type

Chemical analyses

Inorganic nitrogen species in soils were determined using an extraction on fresh soil (Blackmore et al., 1987). After adding 40 mL of a 2M KCl reagent to 4 g of soil, the solution was shaken on an end-over-end shaker for 1 h, centrifuged at 2000 rpm for 10 min and subsequently filtered through Whatman 41 filter paper. Extracted solutions, along with leachate and TMW samples were kept at -20°C until analysed. Nitrate-N (NO_3-N), nitrite-N ,(NO_2-N) and ammonium-N (NH_4-N) were determined using a flow injection analyser (FIA FS3000 twin channel analyser, Alpkem, USA).

Soils were dried at 105 ^{o}C and sieved to <2mm using a Nylon sieve. Plant samples kept in labelled paper envelopes and left in an oven at 70°C until a constant weight was obtained (approximately one week). Paper envelopes were immediately transferred in sealed polythene sacks to prevent absorption of moisture from the air. After weighing and grinding, samples were placed in sealed plastic vials.

Soil pH was determined using 10 g of soil and 25 mL of deionised water (18.2 MΩ resistivity; Heal Force® SMART Series, SPW Ultra-pure Water system, Model-PWUV) at a solid/water ratio of 1:2.5. The mixture was shaken, left to equilibrate for 24 hr before measurement and shaken again before determination with a pH meter (Mettler Toledo Seven Easy) (Blakemore, 1987). An Elementar Vario-Max CN Elementar analyser (Elementar ®, Germany) was used to analyse the total carbon and nitrogen content in the soil and plant samples.

Elemental analyses of plants, soils, and effluents were carried out using microwave digestion (MARSXPRESS, CEM Corporation, USA) of 0.5 g of sample in 8 mL of Aristar^{TM} nitric acid (± 69%) and filtered by means of Whatman no. 52 filter paper (pore size 7 µm) after dilution with milliQ water to a volume of 10 mL. Certified Reference Materials (CRMs) for soil (International Soil analytical Exchange - ISE 921) and plant samples (International Plant analytical Exchange IPE 100) from Wageningen University, The Netherlands, were also digested.

Concentrations of Cd, B, Ca, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, P, S and Zn were determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES Varian 720 ES - USA) in soils (Kovács et al., 2000) and in plants (Simmler et al., 2013; Valentinuzzi et al., 2015). Extraction and digestion solution and method blanks were analysed in triplicate as part of standard quality control procedure for the analysis and were as below the ICP-OES's detection limit for all metals. Recoverable concentrations of the CRMs were within 93% - 110% of the certified values.

Statistical analysis

Data were analysed using Minitab® 17 (Minitab Inc, State College, Pennsylvania, USA) and Microsoft Excel 2013. The ANOVA with Fisher's Least-Significance-Difference post-hoc test was used to assess the effects of different treatments. The significance level for all statistical analyses was $P<0.05$.

Results and discussion

Characteristics of the wastewater and soils

Table 2 shows the characteristics of the Treated Municipal Wastewater (TMW) from the Duvauchelle Wastewater Treatment Plant. The composition of the TMW is similar to data provided by the Christchurch City Council (CCC) from various times the past five years (data not shown). Of note are the elevated concentrations of nitrate (above drinking water standard of 11.3 mg/L nitrate-N), phosphate, and sulphur. When discharged into water bodies such as Akaroa harbour, these nutrients can exacerbate algal blooms, which can damage fisheries and tourism. The TMW contains sodium at a concentration that may pose a “slight to moderate” risk if irrigated onto the foliage of sensitive crops (Ayers and Westcot, 1985). Most pasture species are not overly sensitive. Although, the sodium tolerance of NZ native vegetation has not been well quantified, salt tolerance is expected in coastal and seaside species.

The Sodium Adsorption Ratio (SAR) is the sodium concentration divided by the square root of half the calcium and magnesium concentrations. The SAR is used in combination with EC (Electrical Conductivity) to indicate the likelihood that irrigation water will result in aggregate instability (dispersion of clay colloids) in soil, resulting in a breakdown in soil structure and consequent problems with infiltration, aeration, and drainage. The SAR of the TMW is at a level that may cause aggregate instability if used over the long term (Ayers and Westcot, 1985). Soil quality can be maintained by the occasional application of gypsum, dolomite, or lime (FAO, 2017). The total concentration of Ca and Mg in the soil is relatively large compared to the irrigation water (Table 2), so it is likely that irrigation could occur for many years before remedial measures would need to be taken. Nevertheless, the fertility of both soils could be improved with liming and the pH of the Pawson Silt Loam from the Takamatua peninsula is below the range recommended for agricultural soil (McLaren and Cameron, 1996).

Table 2. Characteristics of the Treated Municipal Wastewater used in the lysimeter experiment. Values in brackets represent the standard deviation of the mean (*geometric mean and standard deviation range). n=54 except trace elements n=9.

	Treated Municipal Wastewater	Barry’s soil (Duvauchelle)	Pawson Silt Loam (Takamatua peninsula)
pH	7.5	5.2	4.8
EC (uS/cm)	423 (40)	-	
Total suspended solids (g/m3)	32	-	-
NH_4^+-N (mg/L)	0.49 (0.15 – 0.80)*	10.1 (7.5)	11 (6.8)
NO_3^--N (mg/L)	18 (7.5)	17.1 (13.2)	4.4 (1.1)
NO_2^--N (mg/L)	0.86 (0.09)	-	-
Total C (%)	-	4.4 (0.6)	5.4 (0.3)
Total N (%)	<25	0.38 (0.05)	0.48 (0.03)
Al (mg/L)	0.43 (0.11 – 1.7)*	32731 (1418)	34903 (3699)
B (mg/L)	0.10 (0.04)	-	
Ca (mg/L)	59 (12)	6770 (393)	5852(187)
Cd (mg/L)	<0.001	-	-
Cu (mg/L)	0.04 (0.03)	7.7 (0.2)	5.1 (1.4)
Fe (mg/L)	0.96 (0.25 – 3.6)*	20155 (2852)	16806 (4098)
K (mg/L)	22 (5.0)	4491 (346)	4008 (365)
Mg (mg/L)	19 (5.5)	4251 (76)	3575 (463)
Mn (mg/L)	0.06 (0.03)	624 (9)	496 (50)
Na (mg/L)	95 (21)	290 (10)	374 (30)
P (mg/L)	11 (5.0)	1046 (30)	599 (125)
S (mg/L)	25 (11)	490 (21)	430 (5)
Zn (mg/L)	0.17 (0.11)	68 (3)	62 (7)
Sodium Accumulation Ratio (SAR)	15 (2.6)	-	-

Table 3 shows the masses of the individual elements added if TMW were to be irrigated at 500 mm / yr. The annual mass of nitrogen added per hectare is approximately half of the maximum rate permitted in many jurisdictions (200 kg/ha/yr). Phosphorus and potassium are within the ranges that these nutrients would be added to maintain an intensively grazed pasture (DairyNZ, 2017a). However, the sulphur loading is more than double rates normally applied (20 – 50 kg/ha/yr). This excess is likely to leach because sulphur is poorly retained by most NZ soils, including the Banks Peninsula loess.

The values of the nutrients were calculated using the lowest cost fertiliser sold by Ballance Ltd. Note that the value of the nutrients is less than the sum of the individual elements because some fertilisers contain more than one element, for example, superphosphate contains both phosphorus and sulphur. The average cost of irrigation in NZ is $770 per ha/yr (Curtis, 2016). Combining the irrigation value with the savings from reduced fertiliser use give a total value of >$1178 /ha/yr.

Table 3. Mass and value of plant macronutrients added through irrigating treated municipal wastewater at a rate of 500 mm per year. The value was calculated from prices listed on http://www.ballance.co.nz/Our-Products/PriceListing. Accessed April 2017. Note that the total value of the nutrients is less than the sum of the individual elements because some fertilisers contain more than one element.

Element	Mass (kg/ha/yr)	Value of element in cheapest fertiliser (NZ$/ha/yr)
N	95	103
P	55	193
K	110	287
S	125	375
Mg	95	250
Ca	295	356

Lysimeter experiment

Irrigation with effluent visibly increased the vigour of the pasture in all the treatments (Fig. 5). Over the course of the experiment, there were significant increases in the biomass of nearly all the treatments (Table 4).

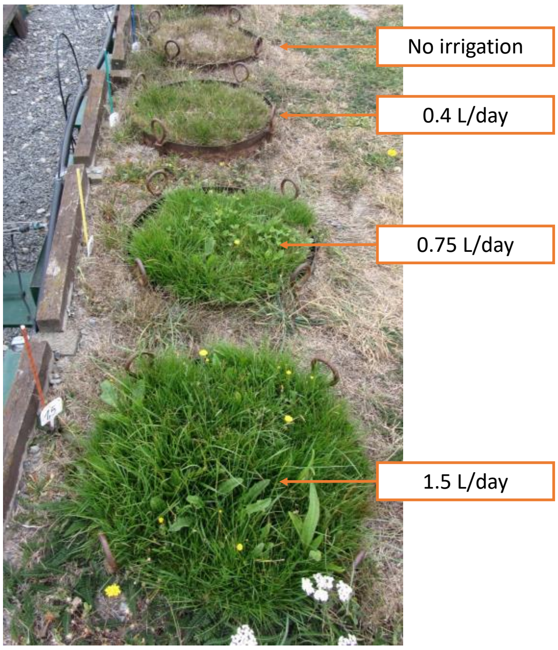

Fig. 5. Pasture growth on four lysimeters containing Barry's soil in February 2016. The numbers to the right of the picture indicate the volume of treated municipal wastewater that the lysimeter was receiving Monday – Friday.

Table 4. General parameters from the 21st of May 2015 until the 3rd of October 2016. Values in brackets represent the standard error of the mean (n=3).

Treatment	Total Irrigation (mm)	Total Rainfall (mm)	Total drainage (mm)	Total Evapotranspiration (mm)	Biomass production (t/ha equiv.)
Barry's soil					
Control	0	779	169 (22)^{a}	610	5.4 (1.0)^{a}
440 mm/yr	637		485 (23)^{b}	931	6.3 (0.6)^{a}
825 mm/yr	1190		736 (17)^{c}	1233	8.9 (0.6)^{b}
1650 mm/yr	2375		1375 (11)^{d}	1779	12.3 (0.2)^{c}
Pawson silt loam					
Control	0	779	148 (2)^{a}	631	6.0 (0.3)^{a}
825 mm/yr	1190		609 (32)^{b}	1360	13.3 (0.7)^{b}

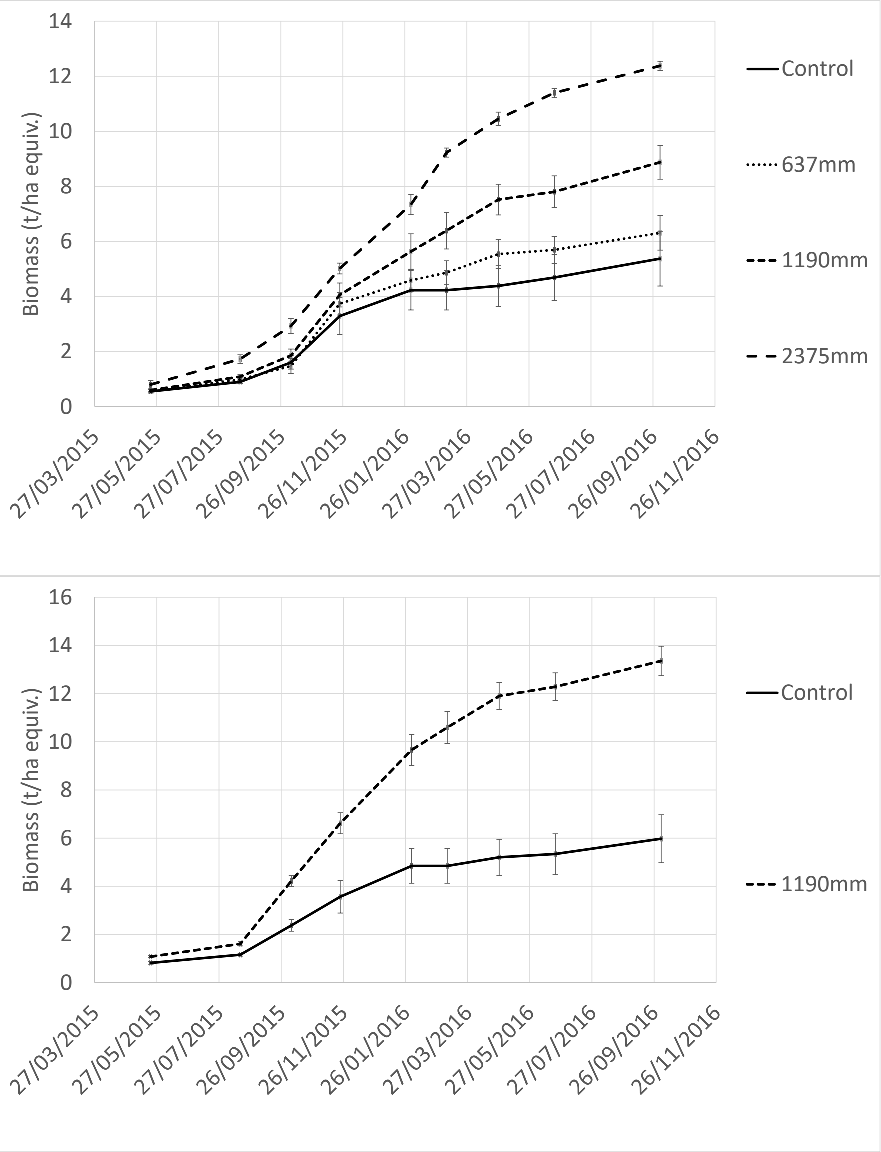

Fig. 6. Cumulative biomass production in the lysimeter experiment for the Barry's soil (top) and Pawson silt loam (bottom), expressed as tonnes per hectare equivalent. Bars represent the standard error of the mean (n=3).

Fig. 6 shows the cumulative biomass production for the pasture in the lysimeters. The biomass increase of the pasture in the treatments was greater than the controls for the whole duration of the experiment, even at the highest treatment rate. This indicates that increase in fertility resulting from the TMW application was maintained and that pasture growth was not significantly perturbed by any sodium or any other element in the TMW. The pasture growth in the Pawson silt loam lysimeters was significantly higher than in the lysimeters containing Barry's soil. This is most likely due to differences in the pasture composition as well as previous soil management. The Barry's soil lysimeters contained a fescue / browntop mixture, while the Pawson silt loam lysimeters were dominated by perennial ryegrass. Note that there were also other species present (Fig. 5), which were not removed so as not to disturb the soil. The Pawson silt loam was maintained as a graze pasture and possibly had historically received higher fertiliser additions than the Barry's soil, which was the fairway on the Duvauchelle Golf Course.

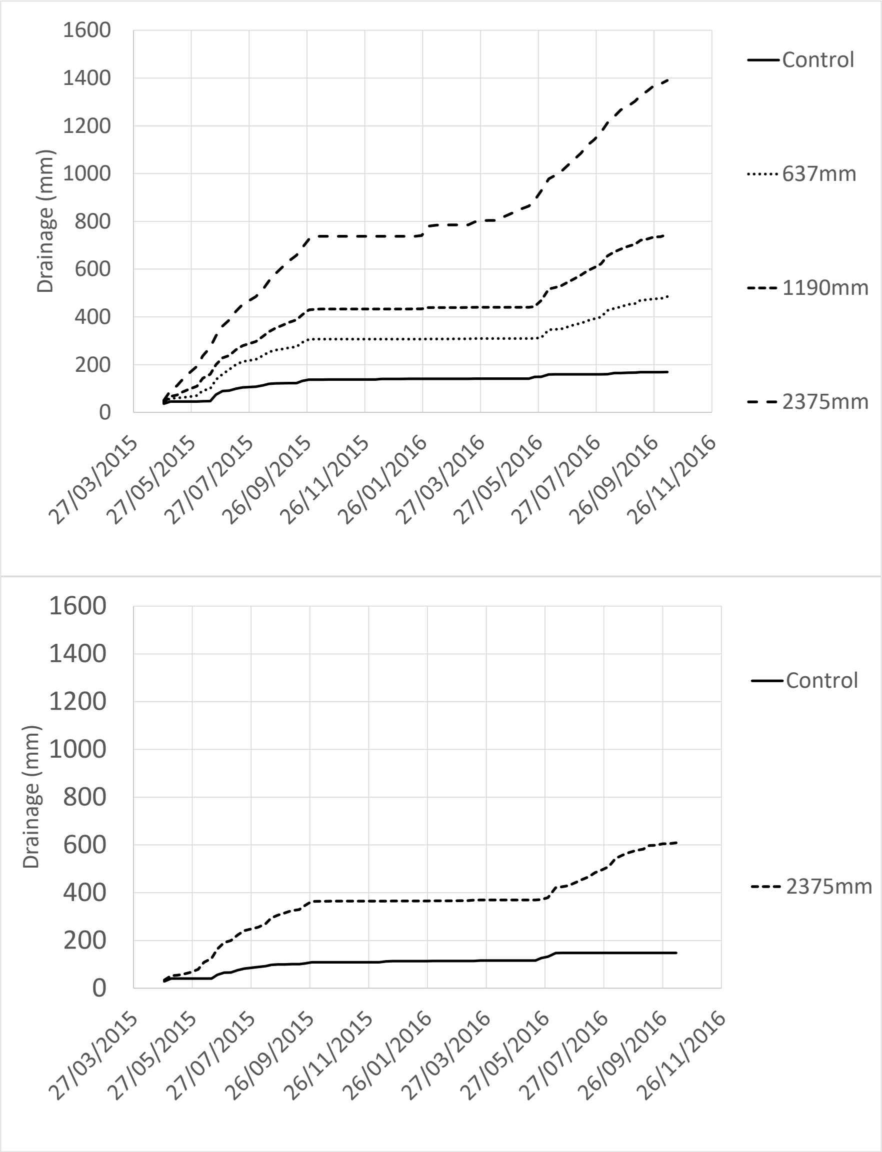

Fig. 7. Cumulative drainage from the lysimeters for the Barry's soil (top) and Pawson silt loam (bottom).

Drainage

All the lysimeters receiving TMW drained throughout the experiment, even at the highest application rate. There was no ponding or visible evidence that the soil structure had been degraded. Infiltration at various tensions forms part of an MSc degree by Cameron McIntyre. These data will be made available upon completion of his thesis, expected in late 2017.

Fig. 7 shows that all the treatments significantly increased drainage relative to the control. In a TMW application system on Banks Peninsula, drainage is unavoidable, irrespective of the vegetation type. Nevertheless, there would be marginally less drainage from a closed-canopy forest of high water-use trees because a significant portion of the incident rainfall is re-evaporated from the canopy before infiltration occurs (McNaughton and Jarvis, 1983). Unlike a dryland system, where deep rooted trees continue to transpire after pasture species have become dormant (Vogeler et al., 2001), rooting depth will have little impact on plant water use because the irrigation will ensure that the plants never become water stressed. Increased drainage does not necessarily imply that there will be unacceptable leaching of nitrogen or other potential contaminants. High levels of leaching requires both high drainage and a significant concentration of the contaminant in soil solution. If the contaminant is retained on the soil colloids, broken down, or taken up by the plant, then leaching will be minimal even under high drainage conditions.

Table 5. Mass of nitrogen (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation N (kg/ha equiv.)	Pasture N (%)	Pasture N (kg/ha equiv.)	Soil mineral N (kg/ha equiv.)	Leached N (kg/ha equiv.)
Barry's soil					
Control	<1	2.17 (0.13)^{ab}	115 (21)^{a}	71 (12)^{a}	0.32 (0.03)^{a}
637 mm	111	1.89 (0.12)^{b}	124 (14)^{a}	59 (7)^{a}	0.72 (0.08)^{b}
1190 mm	207	2.07 (0.09)^{ab}	193 (14)^{a}	87 (4)^{a}	1.09 (0.03)^{c}
2375 mm	415	2.47 (0.15)^{a}	288 (113)^{b}	149 (16)^{b}	1.97 (0.18)^{d}
Pawson silt loam					
Control	<1	2.66 (1.4)^{a}	151 (13)^{a}	72 (16)a	0.37 (0.06)^{a}
1190 mm	207	2.64 (1.4)^{a}	314 (11)^{b}	72 (17)a	1.05 (0.05)^{b}

Nitrogen

Irrigation with TMW had little effect on the pasture's nitrogen concentration (Table 5). This is environmentally important because grazing animals excrete excess nitrogen in their urine, which then subsequently leaches (Woods et al., 2016). Nevertheless, the TMW treatments significantly increased the amount of nitrogen that was extracted from the soil, primarily because of the increased pasture growth. This indicates that at least in part, nitrogen was limiting pasture growth in the lysimeters because under nitrogen sufficient conditions, additional nitrogen results in increase pasture concentration, a process called luxury uptake (McLaren and Cameron, 1996). For TMW irrigation rates up to 825 mm/yr, the mass of nitrogen extracted by the pasture was similar to or greater than the nitrogen that was applied. Given that our lysimeter experiment comprised two winters and just one summer, relatively less nitrogen was extracted than would be the case if we included a second growing season. It is therefore likely that pasture could remove the nitrogen added with TMW at rates above 1000 mm/yr. In the highest treatment (1650 mm/yr), the mass of N added was significantly greater than that which was removed in the pasture. This additional nitrogen was found as mineral nitrogen principally (NH_4^+, NO_3^-) in the soil profile. None of the other treatments showed accumulation of nitrogen in the soil. The mass of nitrogen leached from all treatments was <2 kg/ha equiv., which is negligible compared to the nitrogen leached from a grazed pasture, which can be >40 kg/ha/yr (Menneer et al., 2004).

Phosphorus

The phosphorus applied to the lysimeters with the TMW was 5 – 7 fold greater than the phosphorus removed by the pasture (Table 6). This discrepancy is normal because of phosphorus fixation in soil, a process that renders this nutrient unavailable for plant uptake (McLaren and Cameron, 1996). The strong adsorption of phosphorus in soil also results in negligible amounts of phosphorus being leached. Therefore, in a TMW irrigated soil, phosphorus will accumulate, just as it does in all NZ soils that receive phosphate fertilisers. Phosphorus can cause serious environmental issues when it enters waterways (Tilman et al., 2001). This could occur via runoff from a TME-irrigated area, particularly if it is accompanied by soil erosion. TMW irrigation onto a cut-and-carry pasture or NZ native vegetation will always be less than phosphorus losses from a grazed pasture (TMW irrigated or otherwise) because of the mechanical disturbance of soil by the animals' hooves (McDowell et al., 2003).

Table 6. Mass of phosphorus (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation P (kg/ha equiv.)	Pasture P (mg/kg)	Pasture P (kg/ha equiv.)	P leached (kg/ha equiv.)	Soil P (0 – 60 cm) (kg/ha equiv.)
Barry's soil					
Control	<1	2606 (36)^{a}	13 (2)^{a}	<1	3975 (495)^{a}
637 mm	77	2593 (165)^{a}	16 (2)^{a}	<1	3268 (598)^{a}
1190 mm	144	2648 (55)^{a}	25 (3)^{b}	<1	3154 (198)^{a}
2375 mm	289	3196 (82)^{b}	40 (1)^{c}	<1	3437 (339)^{a}
Pawson silt loam					
Control	<1	3651 (184)^{a}	20 (2)^{a}	<1	5808 (303)^{a}
1190 mm	144	3663 (8)^{a}	45 (2)^{b}	<1	4863 (425)^{a}

Potassium

As with phosphorus, more potassium was added with the TMW than was removed by the pasture (Table 7). Most of this potassium will accumulate in the soil, with only minor amounts leached. Leached potassium is relatively environmentally benign compared to nitrogen and phosphorus. The accumulation of potassium in soil is insignificant because the soil concentrations are at least one hundredfold greater than the amount being added. At the highest TMW application rate (1650 mm/yr), the pasture took up significantly more potassium than the controls. High potassium in animal feeds can induce magnesium deficiency in livestock, resulting in grass staggers. In extreme cases, this requires that the animals be supplemented with magnesium (DairyNZ, 2017b).

Table 7. Mass of potassium (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation K (kg/ha equiv.)	Pasture K (mg/kg)	Pasture K (kg/ha equiv.)	K leached (kg/ha equiv.)	Soil K (0 – 60 cm) (kg/ha equiv.)
Barry's soil					
Control	1	11624 (263)^{ab}	65 (12)^{a}	1 (0)^{a}	34597 (493)^{a}
637 mm	177	8990 (723)^{c}	68 (4)^{a}	2 (0)^{a}	34848 (785)^{a}
1190 mm	331	10349 (510)^{bc}	112 (8)^{a}	3 (0)^{a}	35627 (908)^{a}
2375 mm	662	13060 (1150)^{a}	179 (6)^{b}	4 (1)^{a}	35165 (1134)^{a}
Pawson silt loam					
Control	1	17252 (1847)^{a}	104 (15)^{a}	6 (2)^{a}	40824 (1322)^{a}
1190 mm	331	17933 (518)^{a}	229 (16)^{b}	21 (6)^{a}	37392 (3319)^{a}

Sulphur

Irrigation with TMW provided an excess of sulphur (Table 8), which will eventually leach through the soil profile to receiving waters. Sulphur leaching does not provoke eutrophication like nitrogen or phosphorus. There were no significant effects of the TMW irrigation on the sulphur concentration in the pasture or in the soil profile.

Table 8. Mass of sulphur (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation S (kg/ha equiv.)	Pasture S (mg/kg)	Pasture S (kg/ha equiv.)	S leached (kg/ha equiv.)	Soil S (0 – 60 cm) (kg/ha equiv.)
Barry's soil					
Control	<1	2376 (40)^a	14 (3)^a	7 (2)	2389 (169)^a
637 mm	169	2653 (169)^a	17 (2)^a	21 (5)	2190 (168)^a
1190 mm	317	2649 (113)^a	24 (2)^b	40 (13)	2065 (75)^a
2375 mm	634	2676 (60)^a	35 (2)^b	67 (14)	2294 (124)^a
Pawson silt loam					
Control	<1	2941 (164)^a	17 (2)^a	11 (1)	2275 (96)^a
1190 mm	382	3111 (76)^a	40 (0)^b	45 (8)	1989 (196)^a

Calcium and magnesium

The TMW provided net additions of magnesium and calcium to the soil (Tables 9 and 10). These elements are important in maintaining soil pH as well as offsetting the negative effects of sodium on soil structure (FAO, 2017). Despite being applied in excess of pasture requirements, neither element was taken up at higher concentrations in the TMW treatments. Potential increases in magnesium uptake may have been offset by the elevated potassium levels in the TMW (McLaren and Cameron, 1996).

Table 9. Mass of calcium (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation Ca (kg/ha equiv.)	Pasture Ca (mg/kg)	Pasture Ca (kg/ha equiv.)	Mg leached (kg/ha equiv.)	Soil Ca (0 – 60 cm) (kg/ha equiv.)
Barry's soil					
Control	3	3879 (527)^a	24 (5)^a	20 (5)^a	48351 (1620)^a
637 mm	371	3373 (216)^a	26 (4)^a	55 (13)^a	46775 (748)^a
1190 mm	696	3350 (69)^a	39 (3)^{ab}	61 (10)^a	47506 (1059)^a
2375 mm	1392	3327 (170)^a	51 (0)^b	92 (18)^a	48786 (1433)^a
Pawson silt loam					
Control	<1	5581 (396)^a	31 (2)^a	22 (6)^a	53218 (3475)^a
1190 mm	696	4890 (183)^a	68 (2)^b	92 (5)^a	49948 (4004)^a

Table 10. Mass of magnesium (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation Mg (kg/ha equiv.)	Pasture Mg (mg/kg)	Pasture Mg (kg/ha equiv.)	Mg leached (kg/ha equiv.)	Soil Mg (0 – 60 cm) (kg/ha equiv.)
Barry's soil					
Control	<1	2065 (279)^{a}	13 (3)^{a}	6 (1)^{a}	33017^{a}
637 mm	124	1823 (110)^{a}	15 (2)^{a}	21 (7)^{a}	32580^{a}
1190 mm	232	1964 (52)^{a}	23 (1)^{ab}	23 (1)^{a}	32074^{a}
2375 mm	463	1960 (210)^{a}	33 (3)^{b}	50 (17)^{a}	32469^{a}
Pawson silt loam					
Control	<1	2481 (106)^{a}	16 (1)^{a}	5 (1)^{a}	42274 (2734)^{a}
1190 mm	463	2572 (78)^{a}	38 (2)^{b}	30 (2)^{a}	40351 (2596)^{a}

Sodium

Elevated concentrations of sodium in irrigation waters are concerning because accumulation of sodium can lead to aggregate instability and reduced permeability of soil (Tanji, 1997). Table 11 shows that significantly more sodium was added to soil than was taken up by the pasture. Some of this excess sodium leached, while the remainder accumulated in the soil profile (Fig 7). There were significantly higher sodium concentrations in the TMW-irrigated effluent on the Pawson silt loam, but surprisingly, not on the Barry's soil. This elevated sodium concentration indicates that TMW from Duvauchelle is not suitable for irrigation onto plants that are sensitive to sodic or saline conditions. Elevated concentrations of sodium in pasture increase its palatability to stock (Chiy et al., 1998) and farmers occasionally "fertilise" their pastures with sodium for this reason.

Fig. 8 shows the distribution of sodium within the soil profile of the control and TME-treated lysimeters. The TMW treatments had significantly higher sodium concentrations than the controls at the 0-15 cm and 15 – 30 cm depths. The greatest difference in soil sodium concentrations was between the control (ca. 285 mg/kg) and the 440 mm/yr treatment (ca. 375 mg/kg). Doubling the irrigation rate to 825 mm/yr only increased the sodium in the surface soil to ca. 405 mg/kg, and quadrupling the TMW irrigation rate increased sodium to ca. 420 mg/kg. This indicates that above ca. 400 mg/kg, sodium is not strongly retained by the soil and migrates down through the soil profile and will eventually be lost via leaching. This effect has been replicated in laboratory columns containing a Pawson silt loam, where sodium-spiked TMW (up to 260 mg/L) was irrigated (C. McIntyre, unpublished data). It is therefore unlikely that in the short-to-medium term (<10 years), sodium will accumulate to unacceptable levels in soils. Over the long term, the soils may require periodic amendments with gypsum or dolomite to maintain structure (FAO, 2017).

Table 11. Mass of sodium (kg/ha equiv) in the treated municipal wastewater, pasture, soil and drainage water over the entire lysimeter experiment. Values in brackets represent the standard error of the mean (n=3). For each soil type, values with the same letter are not significantly different. The Barry's soil and Pawson silt loam were tested independently.

	Irrigation Na (kg/ha equiv.)	Average Pasture Na (mg/kg)	Pasture Na (kg/ha equiv.)	Na leached (kg/ha equiv.)	Soil Na (0 – 60 cm) (kg/ha equiv.)
Barry's soil					
Control	5	2243 (475)^{a}	10 (3)^{a}	45 (6)^{a}	2492 (76)^{a}
637 mm	605	2256 (241)^{a}	13 (3)^{a}	159 (18)^{b}	2840 (137)^{ab}
1190 mm	1131	2651 (159)^{a}	23 (3)^{ab}	264 (23)^{b}	2980 (106)^{b}
2375 mm	2256	3109 (308)^{a}	45 (6)^{b}	412 (61)^{b}	3113 (122)^{b}
Pawson silt loam					
Control	5	2525 (198)^{a}	13 (1)^{a}	30 (0)^{a}	2428 (181)^{a}
1190 mm	1131	4038 (273)^{b}	50 (2)^{b}	232 (32)^{b}	2610 (239)^{a}

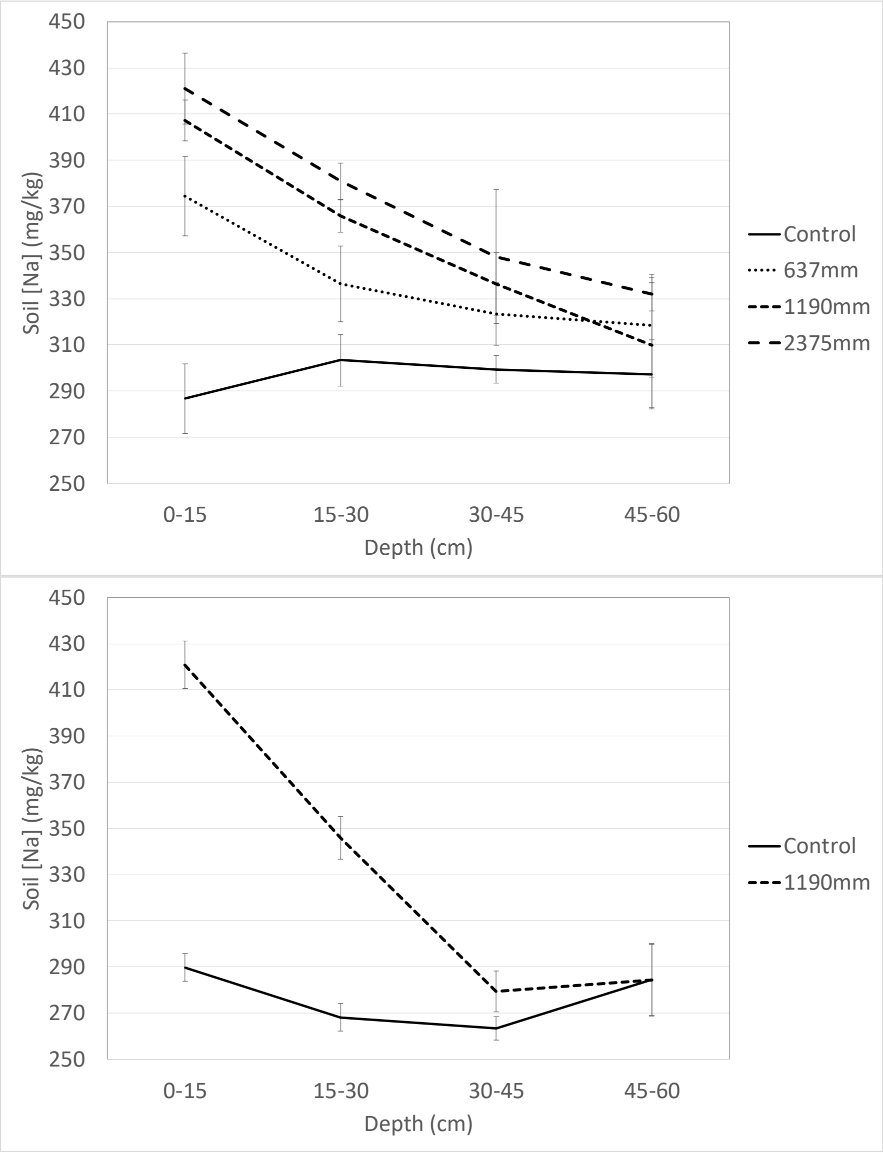

Fig. 8. Soil sodium concentration as a function of depth at the end of lysimeter experiment for the Barry's soil (top) and Pawson silt loam (bottom), expressed as tonnes per hectare equivalent. Bars represent the standard error of the mean (n=3).

Field trial

Plant survival

Fig. 9 shows the survival of individual species in the field plot as a percentage of the number planted. Most of the plant deaths occurred during the spring of 2015 - which was extraordinarily dry – before irrigation with TMW had started. Survival in March 2016 was similar to May 2017 (data not shown). As of May 2017, there were no significant differences between the irrigated and non-irrigated plots. Note that Fig. 9 does not include the additional control plots, at the Southern end of the field trial. These non-irrigated plots have a higher mortality, which we attribute to the soils, which are distinct (stonier) than the remainder of the field trial.

The only significant failure is *Pseudopanax arboreus*. This species has survived well in areas of the trial that are protected from the wind, but elsewhere survival is very poor. Potentially, this species could be used for wastewater treatment, but it should be planted in sheltered areas once the other species have become established.

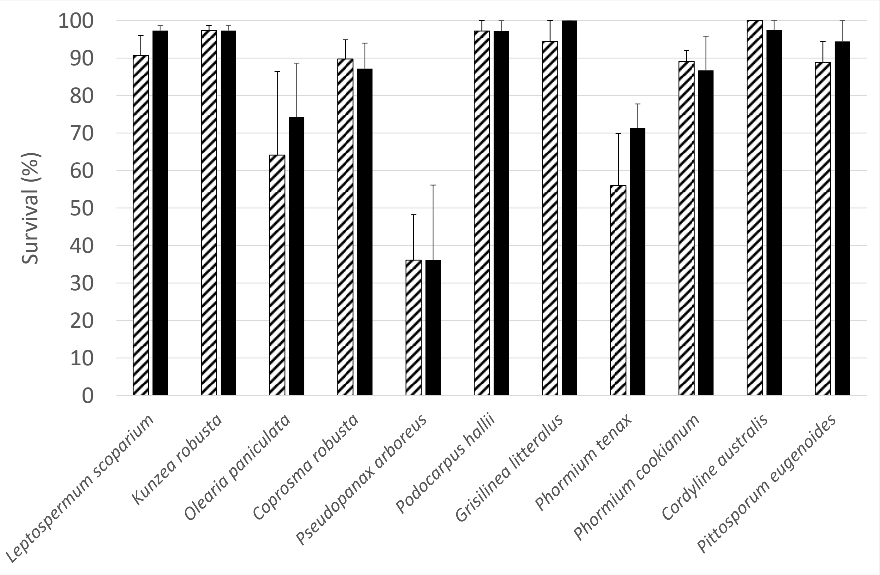

Fig. 9. Percentage survival of the plants in the field plot on Pipers Valley Road as of May 2017. There were no significant differences between the controls (striped bars) and treatments (black bars). Error bars represent the standard error of the mean of three plots, with each plot containing 5 – 25 plants.

Plant growth

Fig. 10 shows the field trial, along with the information board. Plants growing in the effluent-treated plots are visibly larger than the control plots. This observation is borne-out by measurement of the canopy volume (Fig. 11). Compared to the control, the canopy volume of all species in the TMW plots is either larger or not significantly different. There are no signs of toxicity or salt damage (burning of the leaves) on any of the plants. Nevertheless, there are stark differences between the species in how they respond to effluent. *Griselinia littoralis*, *Phormium cookianum*, and *Pittosporum eugenioides* are not significantly larger in the TMW-irrigated plots and are, in general, smaller than the other species in the trial.

Fig. 10. The field plot on Pipers Valley Road in June, 2017, showing the plant trial, information board, and boarders that were planted with *Poa picta* in May 2017.

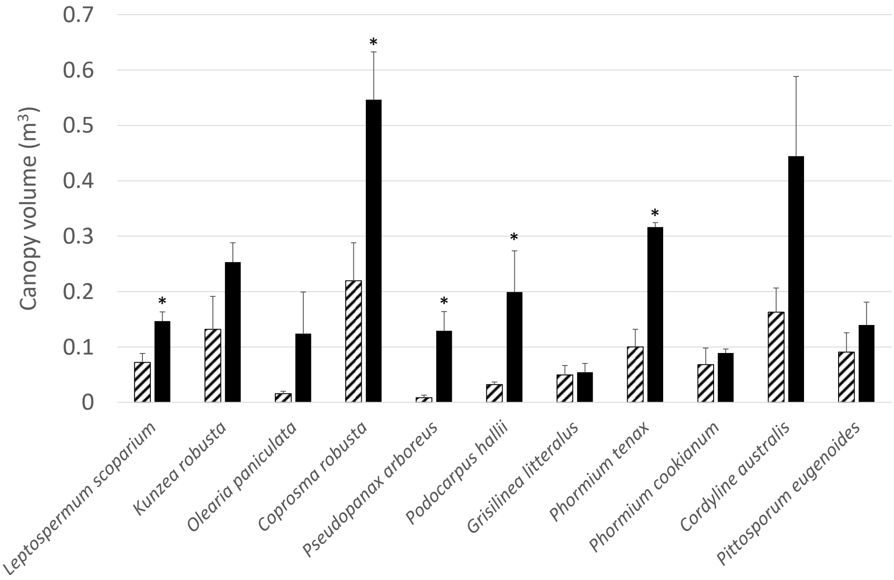

Fig. 11. Canopy volume of the plants in the field plot on Pipers Valley Road as of May 2017. Asterisks (*) signify significant differences between the controls (striped bars) and treatments (black bars). Error bars represent the standard error of the mean of three plots, with each plot containing 5 – 25 plants.

Plant stability in a wet area

One of the TMW-treated plots in the trial was established on a boggy area, as evidenced by waterlogging at the time of planting. Two trees have fallen over in this area (Fig 12). It is likely that TMW irrigation will reduce plant stability because the nutrients contained therein increase the shoot: root ratio of most plants (Agren and Franklin, 2003), thereby creating "top heavy" trees that are more likely to topple in soft substrates. *Cordyline australis* and *Phormium tenax* are more suited to grow in boggy patches.

Fig. 12. Fallen *Pittosporum eugenoides* and *Kunzea robusta* in the field plot at Pipers Valley Road in June, 2017.

In general, NZ native species will take up less water and nitrogen than pasture species from an irrigated shallow rooted environment. However, in the Banks Peninsula environment, the water flux through closed-canopy native vegetation and pasture may be similar because of the "umbrella effect", whereby a significant proportion of rainfall is re-evaporated from the canopy before it reaches the ground (McNaughton and Jarvis, 1983). A mature stand of irrigated native vegetation is likely to leach more nitrogen than irrigated cut-and-carry pasture because little nitrogen is being removed from the system.

Next steps

In each plot of the field trial, five soil samples have been taken and sub-samples from five replicates of each plant species have been analysed. Results from this sampling will be made available upon completion of the PhD theses of Obed Lense and Saloomeh Seyedalikhani. This is expected to occur in early 2018. The field plots will be monitored for various postgraduate projects for at least another three years.

Irrigation of treated municipal wastewater onto NZ native plants: beneficial reuse or disposal?

Disposal of TMW implies discharge into an environment with the aim of minimising negative environmental effects but not gaining value from the TMW. Examples of disposal include discharge to waterways, the ocean, and the application of TMW to land at rates that are far in excess of plant requirements for water and nutrients. This contrasts with beneficial reuse where the irrigation value and nutrient value of the TMW is used to produce valuable biomass, offsetting costs for fertilisers and irrigation that would otherwise have to be met by the landowner. Using this definition, irrigation of TMW to produce of cut-and-carry pasture or pasture for grazing is an example of beneficial reuse.

Clearly, TMW irrigation is not required to establish and grow NZ native plants on Banks Peninsula – nor is it required to grow pasture. Therefore, TMW-irrigation onto NZ native plants can only be considered a beneficial reuse if it generates more value than would otherwise be realised on a non-irrigated system. Irrigating TMW onto mānuka (*Leptospermum scoparium*) ecosystems for the production of honey or essential oils would be an example of beneficial reuse of the water and nutrients contained within TMW because most of Banks Peninsula is too dry to support mānuka production (there are small pockets of mānuka in Nikau Palm Gully and on Quail Island). Moreover, mānuka has been demonstrated to be effective in reducing nitrogen losses from soil (Esperschuetz et al., 2017a). Using TMW to accelerate the production of any product derived from native plants is an example of beneficial reuse.

NZ native plants may have a role in the land application of TMW even if no valuable native product is realised. Native plants, including mānuka and kānuka, could be used on paddock margins of TMW-accelerated pasture (cut-and-carry or grazed) to reduce environmental impacts. There are innumerable examples of where NZ native plants have been used successfully to improve environmental outcomes on conventional farms. Replacing a conventional grazed pasture with a well-designed TMW-application system is likely to improve the water quality of the local streams.

References

Agren G.I., Franklin O. (2003) Root : shoot ratios, optimization and nitrogen productivity. Annals of Botany 92:795-800. DOI: 10.1093/aob/mcg203.

Anon. (1939) Soil Survey of Banks Peninsula. Akaroa Mail and Banks Peninsula Advertiser LXIII.

Ayers R.S., Westcot D.W. (1985) Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29 rev I.

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.

Blakemore L.C. (1987) Methods for chemical analysis of soils. NZ Soil Bureau scientific report 80:71-76.

Cameron K.C., Di H.J., McLaren R.G. (1997) Is soil an appropriate dumping ground for our wastes? Australian Journal of Soil Research 35:995-1035. DOI: 10.1071/s96099.

Capra A., Scicolone B. (2004) Emitter and filter tests for wastewater reuse by drip irrigation. Agricultural Water Management 68:135-149. DOI: 10.1016/j.agwat.2004.03.005.

Chaudhry Q., Blom-Zandstra M., Gupta S., Joner E.J. (2005) Utilising the synergy between plants and rhizosphere microorganisms to enhance breakdown of organic pollutants in the environment. Environmental Science and Pollution Research 12:34-48. DOI: 10.1065/espr2004.08.213.

Chiy P.C., Al-Tulihan A.L.A., Hassan M.H., Phillips C.J.C. (1998) Effects of sodium and potassium fertilisers on the composition of herbage and its acceptability to dairy cows. Journal of the Science of Food and Agriculture 76:289-297. DOI: 10.1002/(sici)1097-0010(199802)76:2<289::aid-jsfa959>3.0.co;2-l.

Curtis A. (2016) Cost of Irrigation Scheme Water Supply in New Zealand. Irrigation New Zealand Publication www.irrigationnz.co.nz.

DairyNZ. (2017a) Fertiliser and Nutrient Management. https://www.dairynz.co.nz/publications/farmfacts/fertiliser-and-nutrient-management/ Accessed June, 2017.

DairyNZ. (2017b) Grass Staggers. https://www.dairynz.co.nz/animal/cow-health/grass-staggers/ Accessed June 2017.

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 39:224-242. DOI: 10.1080/21683565.2014.967438.

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

Esperschuetz J., Anderson C., Bulman S., Katamian O., Horswell J., Dickinson N.M., Robinson B.H. (2017b) Response of Leptospermum scoparium, Kunzea robusta and Pinus radiata to contrasting biowastes. Science of the Total Environment In press.

FAO. (2017) Water Quality and Crop Production. http://www.fao.org/docrep/x5871e/x5871e07.htm Accessed June, 2017.

Herath G. (1997) Freshwater algal blooms and their control: Comparison of the European and Australian experience. Journal of Environmental Management 51:217-227. DOI: 10.1006/jema.1997.0138.

Houlbrooke D.J., Horne D.J., Hedley M.J., Hanly J.A., Snow V.O. (2003) The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. New Zealand Grassland Association 65:179-184.

Kim N., Robinson B. (2015) Cadmium: a clandestine threat to food safety. Food Quality & Safety:49-51.

Kovács B., Prokisch J., Györi Z., Kovács A.B., Palencsár A.J. (2000) Studies on soil sample preparation for inductively coupled plasma atomic emission spectrometry analysis, Communications in soil science and plant analysis, Marcel Dekker Journals. pp. 1949-1963.

Mandal S., Mandal M.D., Pal N.K. (2007) Antibacterial potential of Azadirachta indica seed and Bacopa monniera leaf extracts against multidrug resistant Salmonella enterica serovar Typhi isolates. Archives of Medical Science 3:14-18.

McDowell R.W., Drewry J.J., Muirhead R.W., Paton R.J. (2003) Cattle treading and phosphorus and sediment loss in overland flow from grazed cropland. Australian Journal of Soil Research 41:1521-1532. DOI: 10.1071/sr03042.

McLaren R.G., Cameron K.C. (1996) Soil Science: sustainable production and environmental protection, Oxford University Press, Greenlane.

McNaughton K.G., Jarvis P.G. (1983) Effects of Vegetation on Transpiration and Evaporation, in: T. T. Kozlowski (Ed.), Water Deficits and Plant Growth, Academic Press, New York. pp. 1-47.

Menneer J.C., Ledgard S.F., Gillingham A.G. (2004) Land Use Impacts on Nitrogen and Phosphorus Loss and Management Options for Intervention. Client report for Environment Bay of Plenty https://www.boprc.govt.nz/media/33190/Report-040600-LandUseImpactsonNitrogenPhosphorusLossManagementOptionsIntervention.pdf.

Mojid M.A., Wyseure G.C.L. (2013) Implications of municipal wastewater irrigation on soil health from a study in Bangladesh. Soil Use and Management 29:384-396. DOI: 10.1111/sum.12056.

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 & Biochemistry 96:1-3. DOI: 10.1016/j.soilbio.2015.12.007.

Simmler M., Ciadamidaro L., Schulin R., Madejón P., Reiser R., Clucas L., Weber P., Robinson B. (2013) Lignite reduces the solubility and plant uptake of cadmium in pasturelands. Environmental science & technology 47:4497-4504.

Sonune A., Ghate R. (2004) Developments in wastewater treatment methods. Desalination 167:55-63. DOI: 10.1016/j.desal.2004.06.113.

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 44:107-116. DOI: 10.1071/sr05084.

Tanji K.K. (1997) Irrigation with marginal quality waters: Issues. Journal of Irrigation and Drainage Engineering-Asce 123:165-169. DOI: 10.1061/(asce)0733-9437(1997)123:3(165).

Tilman D., Fargione J., Wolff B., D'Antonio C., Dobson A., Howarth R., Schindler D., Schlesinger W.H., Simberloff D., Swackhamer D. (2001) Forecasting agriculturally driven global environmental change. Science 292:281-284. DOI: 10.1126/science.1057544.

Valentinuzzi F., Mimmo T., Cesco S., Al Mamun S., Santner J., Hoefer C., Oburger E., Robinson B., Lehto N. (2015) The effect of lime on the rhizosphere processes and elemental uptake of white lupin. Environmental and Experimental Botany.

Vogeler I., Green S.R., Clothier B.E., Kirkham M.B., Robinson B.H. (2001) Contaminant Transport in the Root Zone, in: I. K. Iskandar and M. B. Kirkham (Eds.), Trace Elements in the Soil, Bioavailability, Flux and Transfer, Lewis Publishers, Boca Raton, FL. pp. 175-198.

Woods R.R., Cameron K.C., Edwards G.R., Di H.J., Clough T.J. (2016) Effects of forage type and gibberellic acid on nitrate leaching losses. Soil Use and Management 32:565-572. DOI: 10.1111/sum.12297.