MĀNUKA-DOMINATED RIPARIAN PLANTINGS FOR THE MITIGATION OF DIFFUSE AGRICULTURAL NITROGEN

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ABSTRACT

The disruption of nutrient cycles in agricultural settings, particularly pastoral farming, is responsible for up to 70% of the nitrogen (N) loads entering streams in Aotearoa New Zealand, resulting in the widespread degradation of freshwater ecosystems. Riparian plantings are one strategy to mitigate the losses of N from land to water, removing N by denitrification and plant uptake. Some types of vegetation are more effective than others at intercepting N, due to their ecology, impact on soil quality and production of root exudates, which can alter N cycling. Previous research suggested that mānuka (*Leptospermum scoparium*) could be a biological nitrification inhibitor (BNI), limiting nitrate (NO_3^-) production in soil. For this reason, this species could be a good candidate to mitigate N losses and add co-benefits such as farm diversification through apiculture or essential oil production.

A 1.6 ha experimental site was set up in 2017 in Nikau Farm to investigate the role of mānuka-dominated riparian plantings in reducing the inputs of N from farming activities in an adjacent waterway. The experimental site consisted of grassed and unplanted plots, as well as mānuka-dominated plots. The area was equipped with suction cups and dip wells for monitoring the movement of water. Soil physical properties were also measured.

Results showed that both the mānuka and grassed plots effectively reduced N concentrations throughout the buffer up to 80%. Water management by the mānuka was the most important factor regulating the losses of NO_3^-, which were 21% smaller compared than the grassed plots. The higher concentration of NO_3^- at 50 cm soil depth, and lower concentration of ammonium in the topsoil, demonstrate that apart from water management, further mechanisms (i.e. mineralization, nitrification and/or denitrification) might be playing an important role in the movement of N in these systems. Soil bulk density and macroporosity improved by 17% and 38% respectively, which will likely have a positive effect in further mitigation of water pollution in the future, as well as recovering biodiversity and ecosystem functioning.

KEYWORDS

Nitrogen, riparian planting, water quality, soil quality, ecosystem restoration

PRESENTER PROFILE

Olivia María Adamson completed a Masters in Environmental Sciences in December 2021 and recently joined the Waikato Region Council as an Environmental Monitoring Scientist. Her MSc research was part of a multidisciplinary and collaborative effort to better understand how soil, vegetation, hydrology and land-use management/change interact to influence water quality.

1. INTRODUCTION

The disruption of nutrient cycles in agricultural settings, particularly pastoral farming, is responsible for up to 70% of the nitrogen (N) loads entering streams in Aotearoa New Zealand, resulting in the widespread degradation of freshwater ecosystems. Howard-Williams et al. (2010) estimated that diffuse sources of N & phosphorus (P) from modified landscapes, predominantly pastures, accounted for 75% of the total flux delivered to sea.

Riparian plantings are one strategy to mitigate the losses of N from land to water, removing N by denitrification and plant uptake. Some types of vegetation are more effective than others at intercepting N, due to their ecology, impact on soil quality and production of root exudates, which can alter N cycling. Although the literature addressing optimal buffer widths (Vidon and Hill 2004, Mayer, Reynolds Jr. et al. 2007) and positions (Zhou, Helmers et al. 2010) is abundant, there is a lack of science-based advice when recommending the best plant species for the management of N (Franklin, Robinson et al. 2019). Plant traits play a large role in mediating the N cycle (van Groenigen, Huygens et al. 2015), largely because they modify the physical and chemical characteristics of soil (Franklin et al., 2019) — and due to their role in supporting microbial communities with nutrients and energy (van Groenigen, Huygens et al. 2015). In contrast, some plants such as myrtaceae species, may antagonise pathogens in the soil (Prosser, Woods et al. 2016, Halford, Gutiérrez-Ginés et al. 2021).

Previous research suggested that mānuka (*Leptospermum scoparium*) could be a biological nitrification inhibitor (BNI), limiting nitrate (NO_3^-) production in soil. A study by Esperchuetz et al. (2017) found that, although mānuka is adapted to live in low-fertility environments, it can thrive in high nutrient environments. In addition, leaf extracts of this species have been found to decrease NO_3^- production relative to *Lolilum perenne* (perennial ryegrass) by 60% (Downward 2013). These results indicate that mānuka could potentially be a Biological Nitrification Inhibitor species (BNI) — limiting the levels of NO_3^- in soil (N remaining as ammonium, NH_4^+) and thus reducing N losses via leaching and denitrification (given that NH_4^+ is held more readily in soil than NO_3^-) . These results are supported by the findings of Esperchuetz et al. (2017) who found that, after a series of urea fertiliser applications, mānuka significantly reduced NO_3^- leaching compared to pine (2 kg ha^{-1} versus 53 kg ha^{-1}). Moreover, Esperchuetz et al. (2017a) and Halford et al. (2021) indeed found differences in the speciation of N under mānuka, having less NO_3^- and more NH_4^+ compared to *Pinus radiata* and *L. perenne*. Moreover, studies have found that mānuka may also diminish the proliferation of pathogens in soil (Prosser, Woods et al. 2016, Gutierrez-Gines, Alizadeh et al. 2021).

The aforementioned research indicates that mānuka has high potential for mitigating the loss of N in agricultural systems, specifically in riparian plantings. However, this potential remains to be investigated outside of the laboratory, including the quantification of NO_3^- leaching (Halford et al., 2021). This information will fill a knowledge gap in the understanding of the role that mānuka may play in the mitigation of diffuse agricultural pollution. For this reason, this species could be a good candidate to mitigate N losses and add co-benefits such as farm diversification through apiculture or essential oil production. When native plants are used, riparian plantings have been proposed as an opportunity to increase on-farm biodiversity (providing and improving habitat for bird life and aquatic species) (Dybala, Steger et al. 2019, Kelly 2019), which has been in a steady decline in NZ (MfE 2018).

The objectives of this study were to:

- Investigate how vegetation type (mānuka and unplanted control) influences the physical properties of soil (using soil quality indicators, bulk density and macroporosity),
- Assess the efficacy of a riparian ban for improving water quality by measuring the volume and quality of subsurface water as it passed through the different types of vegetation

2. METHODOLOGY

2.1 SITE CHARACTERISATION

An opportunity that arises from the poor ecological state of the Lake Waikare catchment is to investigate alternative land uses for this area (e.g. mānuka planting). This can assist in decision making to match land use with land suitability in the catchment, while improving water quality and providing continued economic benefits from this land. First, however, the impacts of land use change (LUC) must be assessed, alongside whether they will achieve the desired outcome. In this spirit, 4 ha of productive land were transformed by Nikau Estate Trust to set up experimental plots (-37.474036, 175.231869) (Figure 1a & 1b). One of the plots comprises of a 272 m x 30 m riparian band planted at a density of about 1 plant/m2 during the winter of 2017. The riparian strip runs along a drain that flows into Lake Waikare, and downslope of a paddock used for dairy cow grazing until October 2019, when it was converted to maize cropping for 2020. This riparian band is divided into 10 experimental plots:

- three mānuka plots,
- three unplanted but fenced plots with a plant cover currently dominated by *Dactylis glomerata* (also known as cocksfoot), and
- four plots with a mixture of mānuka and 20 other native species appropriate for lower Waikato region in between the mānuka and unplanted plots.

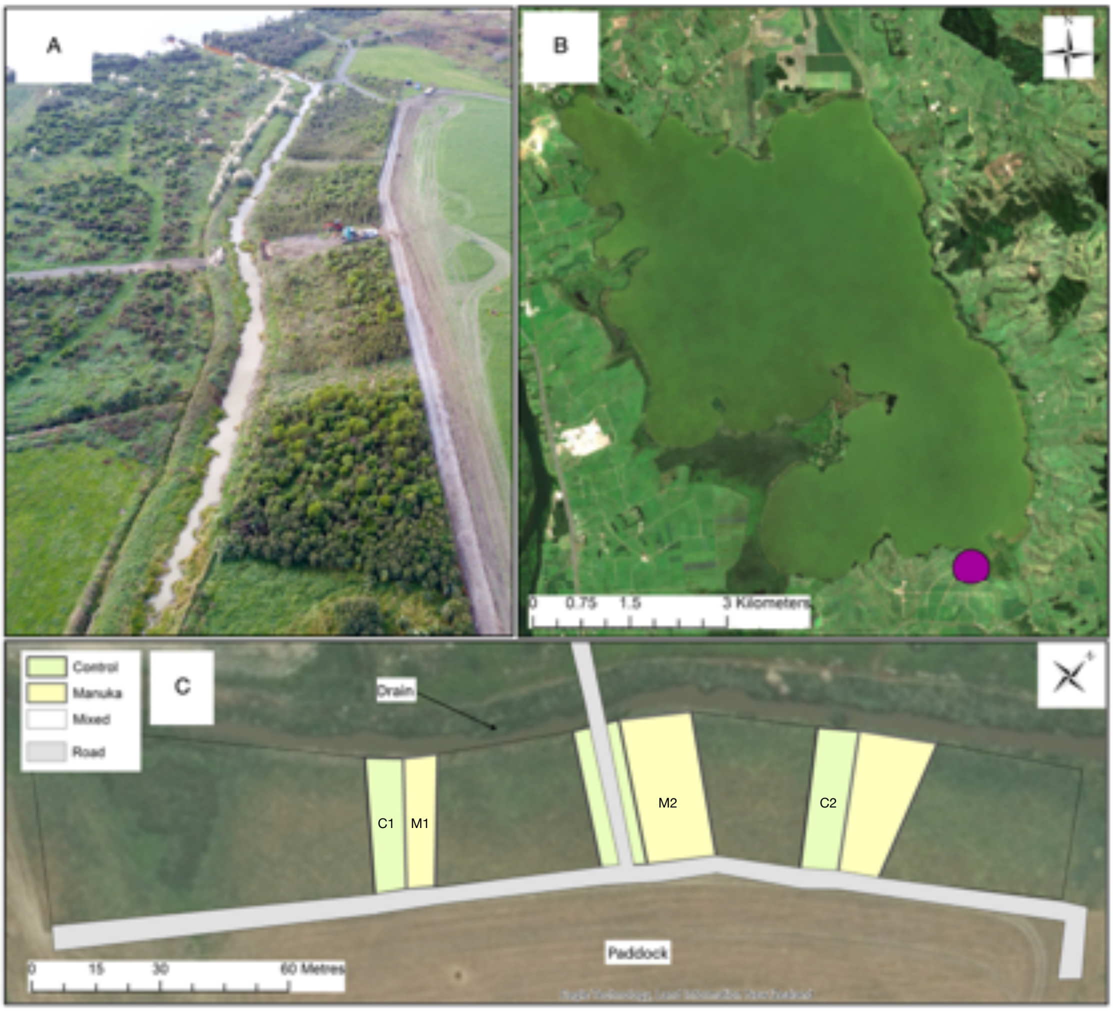

Figure 1: (A) Aerial photo of the experimental plots (July 2021), (B) aerial photo of Lake Waikare, highlighting the location of the plots, and (C) outline of the experimental plots showing the different vegetation types.

The objectives of this study focused exclusively on mānuka riparian plantings. Thus, a subset of the experimental plots was selected: Control 1 (C1), Control 2 (C2), Mānuka 1 (M1) and Mānuka 2 (M2) (Figure 1c). Plots M1 and M2 had slightly different vegetation densities— approximately 1.6 plant/m^2 and 1 plant/m^2 respectively.

The soil in the experimental plots belongs to the Mangatawhiri clay loam series (to approximately 30 cm, depth to which it is ploughed), part of the Kainui soil series, classified as an Perch-Gley Ultic soil. This is underlain by an orange-coloured, clay-rich layer below: the Hamilton Ash (Figure 2). Observation of the soil profile reveals that each layer has very different properties, which will impact the movement of water and contaminants. The topsoil (Figure 2a) is very permeable, has a good soil structure, and likely allows the easy movement of water. At around 30 cm depth, (Figure 2b), the soil becomes more clayey and sticky, with a dark orange colour. This is evidence of prolonged periods at saturation or near-saturation. At a depth of 50-60 cm, the clay becomes even thicker and paler and exhibits mottling, evidence of winter perching over this layer. This soil setting suggests that water may infiltrate downwards into the soil and flow laterally towards Lake Waikare once it encounters the slowly permeable Hamilton Ash at ~50 cm depth.

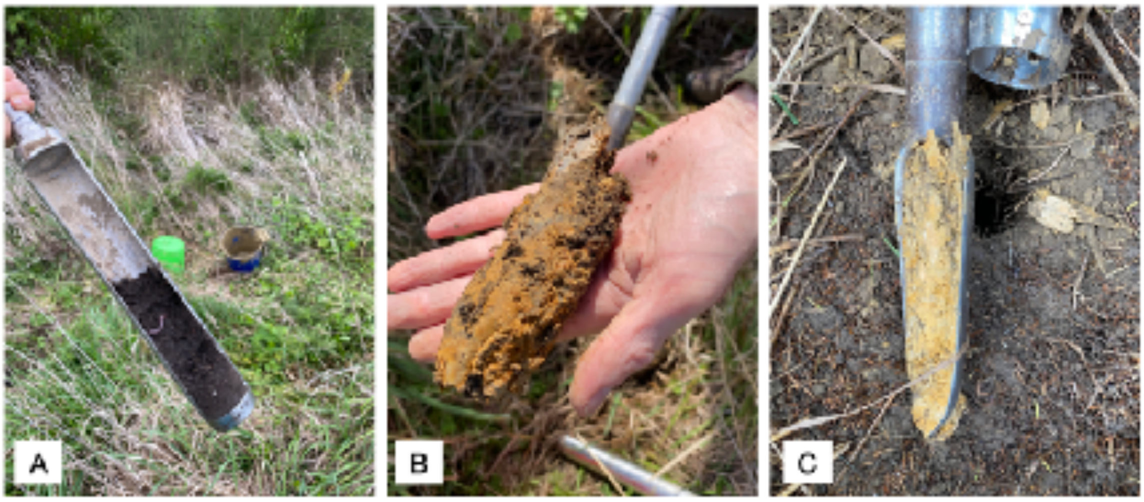

Figure 2: Sequence of soils from representative soil layers at the experimental riparian plots. (A) soil core showing the typical Mangatawhiri clay loam topsoil from plot C2 at 0-16 cm depth, (B) ~30 cm depth in plot C2, and (C) Hamilton Ash clay encountered at 50-60 cm.

2.2 MONITORING DESIGN

The monitoring design addresses each of the objectives outlined above: physical indicators of soil quality were quantified (macroporosity and bulk density), and N species in soil solution were sampled using suction cup lysimeters. Due to the complex soil setting, which suggested winter perching and lateral flow, the local hydrology was monitored using dip wells to determine the depth of the water table and its direction of movement. In addition and above- and below-canopy rain gauges and soil moisture and electrical conductivity (EC) sensors were deployed. Figure 3 shows a cross-section of one experimental plot and the different monitoring elements. Figure 4 shows a birds-eye view of the experimental design.

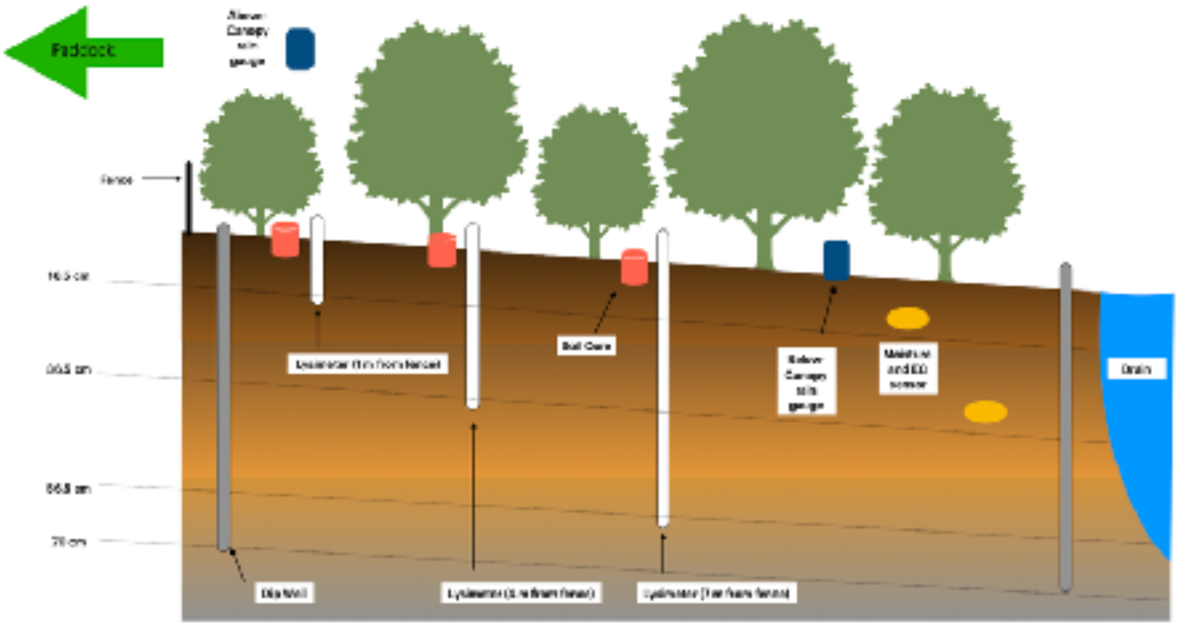

Figure 3: Schematic of monitoring design deployed in this study, showing lysimeters, dip wells, soil cores, rain gauges and soil sensors in a mānuka plot (not to scale).

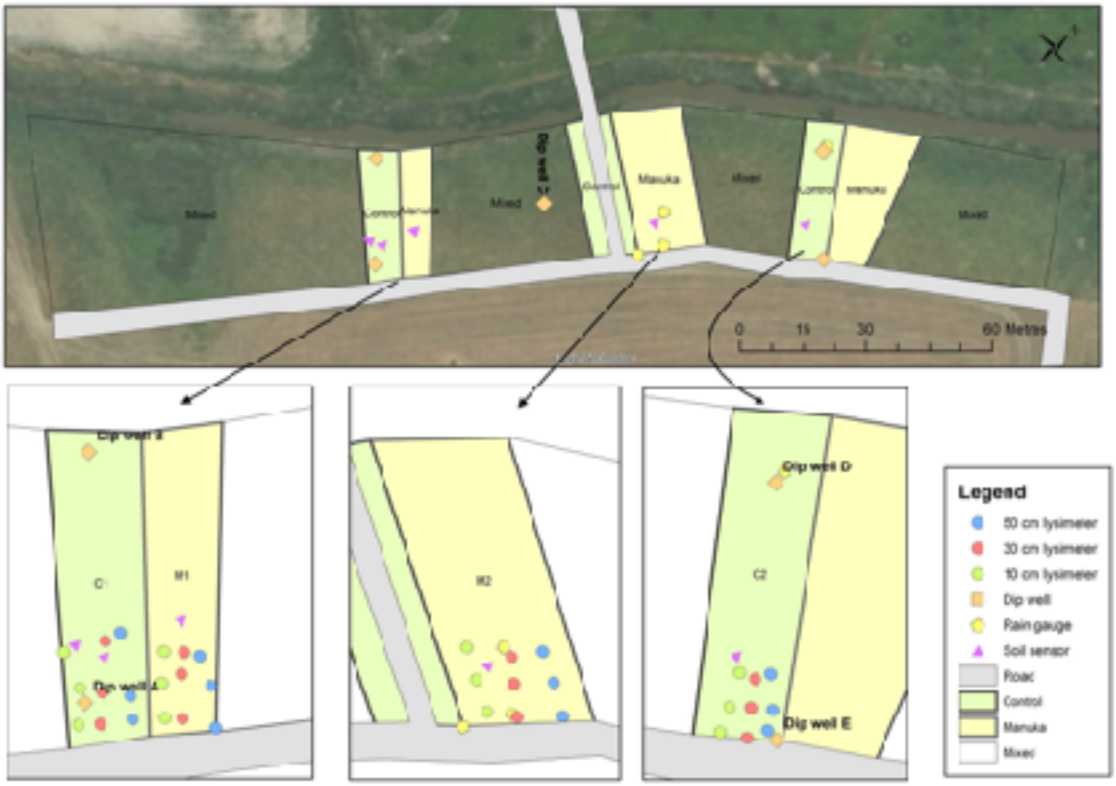

Figure 4: GIS map of the experimental riparian site picturing the boundaries of each experimental plot, lysimeters at different depths, dip wells, soil sensors and rain gauges.

2.3 SOIL PHYSICAL PROPERTIES

Three 15 cm deep and 15 cm diameter undisturbed soil cores were collected from two maanuka and two control plots (Figure 5). The cores were wrapped in plastic and transported to Manaaki Whenua Landcare Research laboratories for bulk density and macroporosity determinations with the methods described by Gradwell (1972). The results were then analysed through analysis of variance (ANOVA) using R statistical software and compared to historical measurements from the same site taken in 2017—before the riparian buffer was established (collected by Matthew Taylor, Waikato Regional Council). The graphs were created with the package ggplot2 (Wickham, 2016).

Figure 5: Soil coring process. (A) digging the core into the soil with the help of a serrated knife. (B) the soil core, just removed from the ground. (C) wrapping the core for safe transport and storage.

2.4 NITROGEN IN SUBSURFACE FLOWS

In this study, suction-cup lysimeters were used to collect pore water samples for measuring the concentration of TN, TKN and NO_3^- and NH_4^+. This method samples soil water under unsaturated conditions and from pores with longer residence times, meaning that the water sampled will have had more interaction with soil components than free-draining water would (under saturated flow) (Cabrera Corral et al., 2016). The instruments utilised in this study were purpose-built and made of 6.5 cm long ceramic cups, attached to 4 cm wide PVC drainage pipes (Figure 6).

A total of 36 lysimeters were deployed in two paired sites, with nine in each plot (Figure 4). The lysimeters were deployed to three depths to reach each of the key soil horizons in the profile; assumed to have different hydraulic characteristics (Figure 2). They were also deployed at three different distances from the fence (1, 4 and 7 m) to get a good evaluation of changes in nitrate throughout the plot— as it is suggested that most of the nitrate is assimilated or denitrified in the first few meters of a riparian band (Fennessy & Cronk, 1997). The instruments were sampled seven times between May and July 2021.

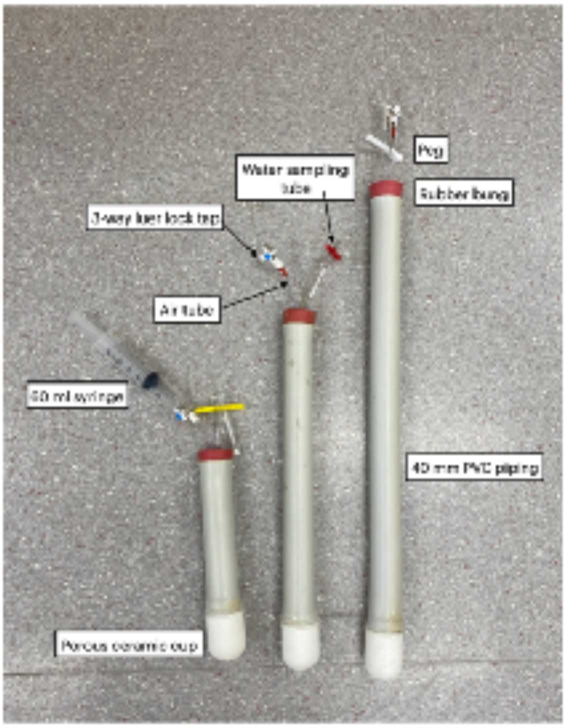

Figure 6: Lysimeters used in this study (to sample 10-16.5 cm depth, 30-36.5 cm and 50-56.5 cm)

Pore water samples were sent to Analytica Laboratories for analysis using a flow-injection analyser, with a detection limit of 0.002 mg/l. They were analysed for: NO_3^- , NO_2^-, NH_4^+ and Total Kjeldahl N (TKN). TN was calculated as the sum of all N species.

Data was analysed through analysis of variance (ANOVA) using R statistical software to test the statistical significance of the observed differences in N concentrations between distances from the fence, depth, plots and vegetation type. P-values of less than 0.05 were reported as statistically significant. Model assumptions were checked with the Q-Q plot and the residuals vs predicted plots.Leaching losses on each sampling date were calculated using the sum of TN concentrations in each plot for each date and multiplied by the volume of sample collected. Calculations were completed with RStudio (R Core Team, 2021) and the packages stats (R Core Team, 2021) and agricolae (Mendiburu & Yaseen, 2020). The graphs were created with the package ggplot2 (Wickham, 2016).

2.5 WATER TABLE MONITORING

Five dip wells were deployed in the experimental plots (Figure 4). These were made out of 4 cm wide PVC pipes with slotted sides and sealed bottom, which allowed to monitor the depth of the water table. The depth of the water table was measured during every site visit using a “bubbler”: a simple piece of bamboo with a tape measure attached to it, as well as a flexible piece of tubing. The tube is used to blow into and, when it touches the water table, the operator can hear bubbles, making note of the depth with the tape measure (Figure 7). In addition, a LEVELScout data logger was installed in one of the wells to continuously measure the water depth. The data collected was extracted twice (one month after deployment and at the end of the sampling period). Measurements from the LevelSCOUT data logger were calibrated to barometric pressure using information from nearby Kopuatai Bog monitoring station (provided by David Campbell, from the University of Waikato). The manual dip well measurements were then incorporated into the dataset and plotted using Excel.

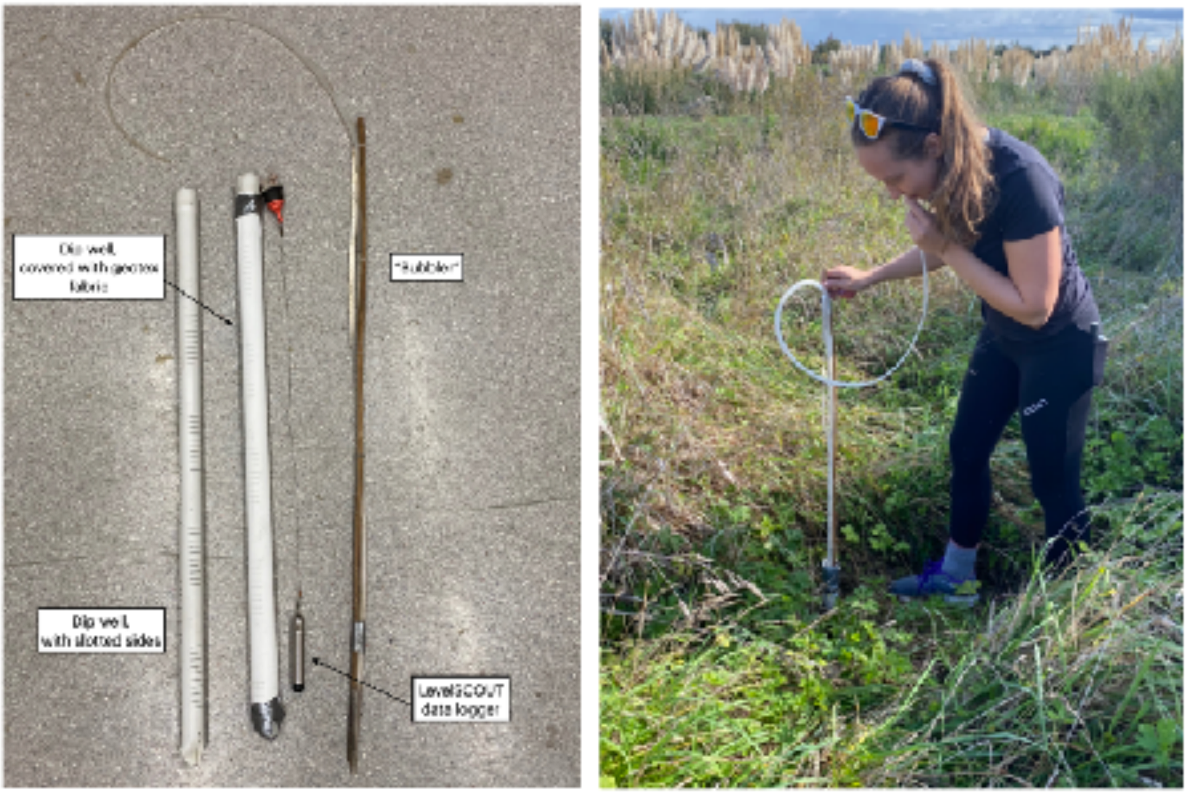

Figure 7: (Left) Dip wells, data logger and “bubbler”, and (right) Collecting water table measurements at plot C2 using the “bubbler”

2.6 WEATHER STATION AND SOIL PARAMETERS

A weather station and automatic above- and below-canopy rain gauges were installed by Auckland University in June 2021. Soil moisture, electrical conductivity and temperature were continuously monitored with 12 TEROS12 (METER Group) soil sensors installed in the maanuka and control plots at depths of 15 cm and 30 cm. The University of Auckland’s purpose-built devices transmitted the data to a cloud via a Sigfox network. A weather station Aercus WeatherRanger recorded weather data continuously, including above- and below-canopy rainfall. With a WiFi connection, it sent that data to the same cloud storage. Both datasets were processed and plotted using R statistical software.

3. RESULTS AND DISCUSSION

3.1 SOIL PHYSICS

Regarding the soil's physical properties, there was an inverse relationship between soil density (ρb) and macroporosity (MP), with the highest average ρb found in plots with the lowest average macroporosity and vice versa (Figure 8). The average ρb in the Experimental Plot (control and maanuka combined) was 1.08 t/m^3, 17 % lower than in the nearby paddock (1.30 t/m^3). The average MP of the Experimental Plot (11.6 %) was 38% higher than in the paddock (4.43%). The effect of plant roots, macroinvertebrates, earthworm activity and lack of compaction by machinery, livestock or disturbance from cultivation are likely causes for the improvement of soil physical quality in the Experimental Plot, compared with the adjacent paddock (McLaren & Cameron, 1996). Based on these results, it can be expected that ρb will continue to decrease while MP will increase over the coming years as the vegetation continues to grow and mature.

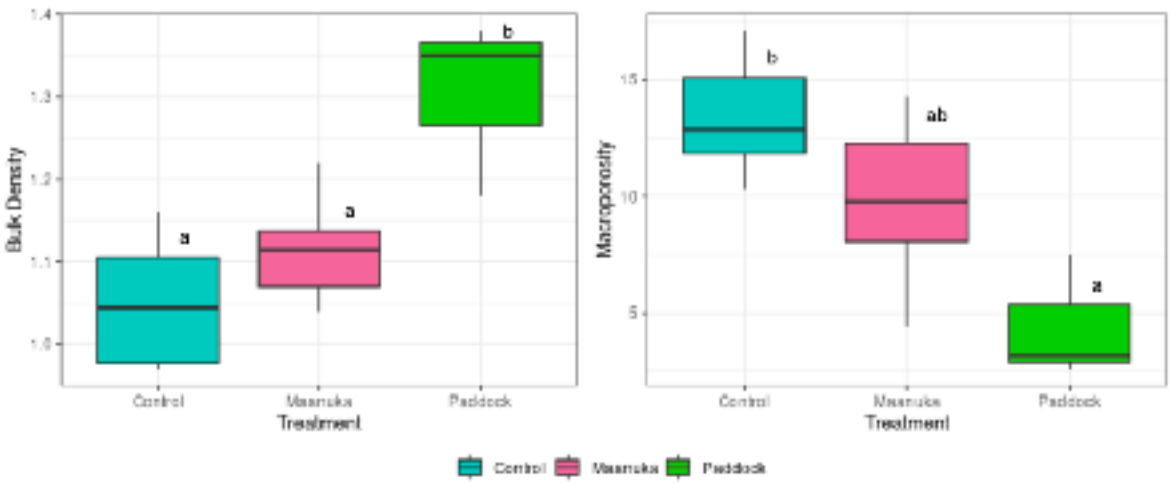

Figure 8: Bulk density (t/m^3) and macroporosity (v/v%, @-10 kPa) results for six different soil cores in the maanuka and control plots, and three in the adjacent paddock in July 2021. Different letters indicate significant differences between treatments (Tukey's HSD test, $p < 0.05$).

A soil's MP is strongly correlated with its infiltration capacity (Taylor et al., 2009): a soil with high MP will require a very intense rainfall event to overwhelm the macropore and drainage system and produce overland flow (McLaren & Cameron, 1996). Hence, the soil quality improvements in the riparian band will provide a better flood defence during intense rainfall events— which are predicted to increase in frequency and intensity as climate change advances (MfE, 2018). Less overland flow also reduces erosion, which is severe in the Lake Waikare catchment (Dean-Speirs, 2014). Macroporosity impacts the N cycle given that nitrifying organisms require aerobic conditions to produce NO_2^- and then NO_3^- ions, and are thus favoured in well-drained and well aerated soils. Less aeration results in less air for roots and less N fixation and nitrification (given that many beneficial microorganisms are aerobic), and thus, a decrease in plant productivity. Macroporosity is also important because it determines the amount of water that can be held in large pores (i.e. providing drainage) and form micro-sites where denitrification can occur in unsaturated soil conditions. Hence, this is a desirable characteristic for the management of N in all arable systems, as well as in riparian plantings, which remove N through denitrification and uptake.

Although the control plots showed a greater improvement in physical soil quality indicators, the differences observed between the control and mānuka plots were not very large (although lack of repetition prevents a robust statistical analysis). The similarity between vegetation types could be attributed to the originally poor condition of the soil (meaning that fencing alone would already create an improvement) and the young age of the riparian plants— so differences due to vegetation type might not yet be detectable. Moreover, changes in many soil properties are generally slow and can take several years before a statistically measurable difference can be found.

3.2 NITROGEN IN PORE WATER

Given that NO_3^- is the contaminant that poses the highest risk for water quality via leaching (Di & Cameron, 2002) soil pore water was only analysed for the different forms of N. Soil pore water, collected by the suction cups, gives an indication of potential losses of N in the subsoil, which could contaminate groundwater, or the adjacent drain by lateral flow. However, our dataset was insufficient to quantify the net leaching. The average TN concentration of all samples analysed (regardless of plot, vegetation, distance or depth) was 5.6 mg/L, the average NO_3^- - N concentration was 4.3 mg/L, and the average TKN was 1.4 mg/L. Nitrate concentrations were exceeding NPS-FM (2020) limit of 2.4 mg/L, which could indicate that leaching losses may contribute to NO_3^- contamination. However, due to the negative pressure of the suction cups, the NO_3^- in the samples does not necessarily represent the actual concentration in the soil solution, and due to the size of the devices they do not capture the heterogeneity of the soil, or preferential flow pathways (Weihermüller et al., 2007). The predominant form of N in all the samples with high levels of N was NO_3^-, while in the samples with lower levels of N, organic and NH_4^+ (TKN) were the dominant forms of N (Fig. 23). Within TKN, NH_4^+ contributed an average of 5 % to the total Kjeldahl nitrogen, which means that most of the nitrogen was in organic form. Given this N speciation in the samples, the results represent only the concentrations of NO_3^- - N and TKN.

3.3 RAINFALL, SOIL MOISTURE AND WATER TABLE

The total rainfall collected under the maanuka canopy at the end of the three-month measurement period (September 2021) was 25 % of the total rainfall (Figure 9). This can explain, in general terms, the lower water content of the top soil in the maanuka plots compared with the control plots (Figure 10), as well as the fact that there was about one month delay in the extraction of soil pore water from maanuka compared with control, highlighting that the soil was drier under maanuka (Figure 12).

The volumetric water content (VWC) represented in Figure 10 shows results from May to September 2021. Flat lines in the graph indicate that no data was recorded, this was due to technical problems with the sensor connection. At 15 cm depth, M2 (maanuka) was generally drier than the other plots. M1 (maanuka) was offline in May and was similar to the control plots until September, when it was lower than the control plots. At 30 cm depth, the VWC varied more between plots than treatments (control and maanuka). Plot M2 (maanuka) had the highest VWC throughout the measurement period. Similar to the rest of the results, the variation among the plots is large and indicates that the VWC is rather heterogeneous.

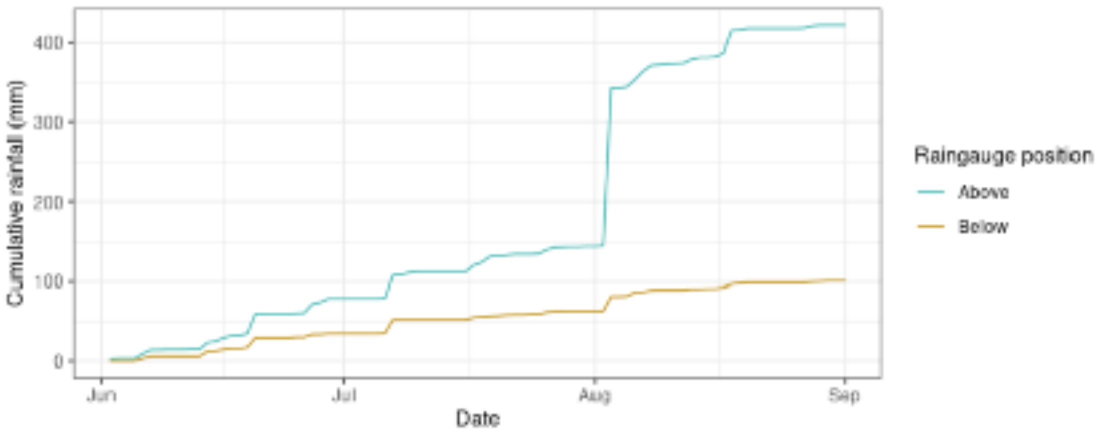

Figure 9: Cumulative rainfall recorded with the automatic rain gauges placed above and below the maanuka canopy in 2021

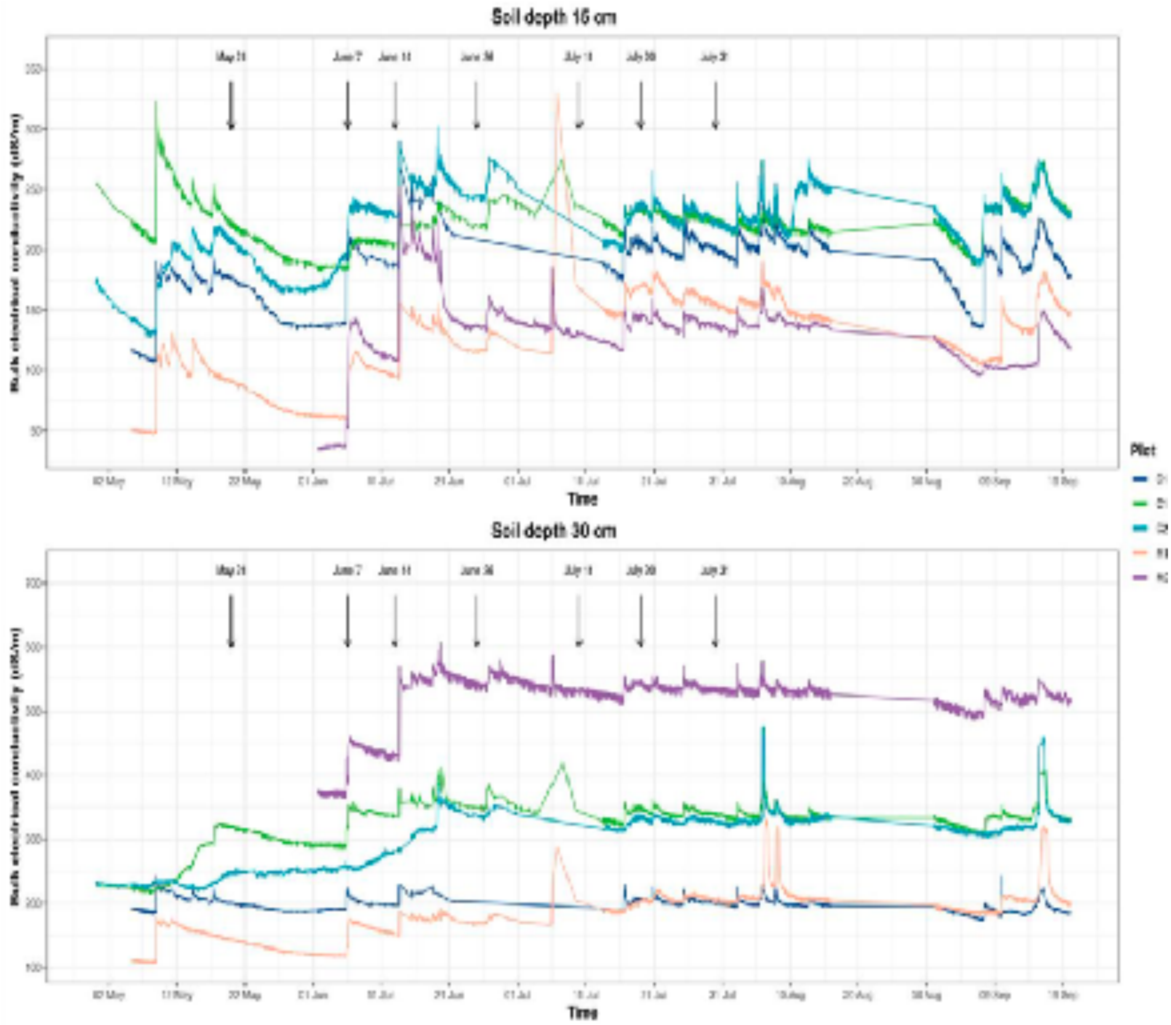

Figure 10: Measurement for volumetric water content (m^3/m^3) from soil sensors deployed at the Experimental Plot at 15 cm and 30 cm depth. The dates of soil pore water sampling dates indicated by arrows. C – control, Mk – maanuka.

Figure 11 shows the depth of the water table through time, with both manual and automatic measurements, which coincide well. The peaks in water table height at dip well “C” aligned with peaks of rainfall events. Dip well “D”, which was lower down the slope and next to the drain, was the only other one which consistently had water within it. The water level at this location remained closer to the surface (up to 10 cm depth), and seemingly for longer (although the frequency of the data is significantly smaller).

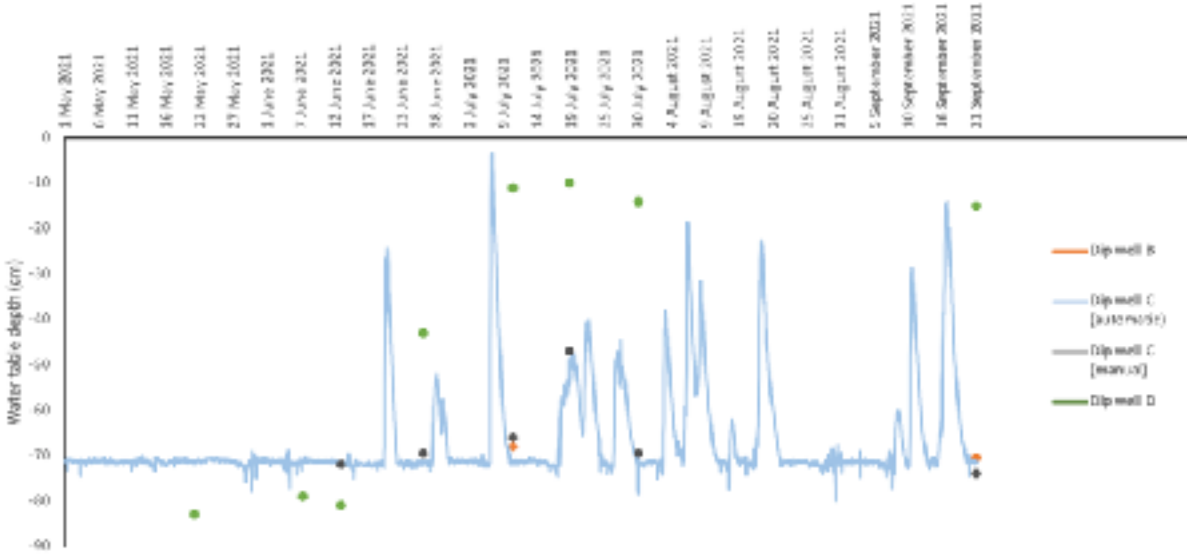

Figure 11: Water table depth (cm) as measured manually and by a LevelSCOUT data logger at the experimental riparian plots in Lake Waikare.

3.4 SUBSURFACE WATER FLOWS AND NITROGEN

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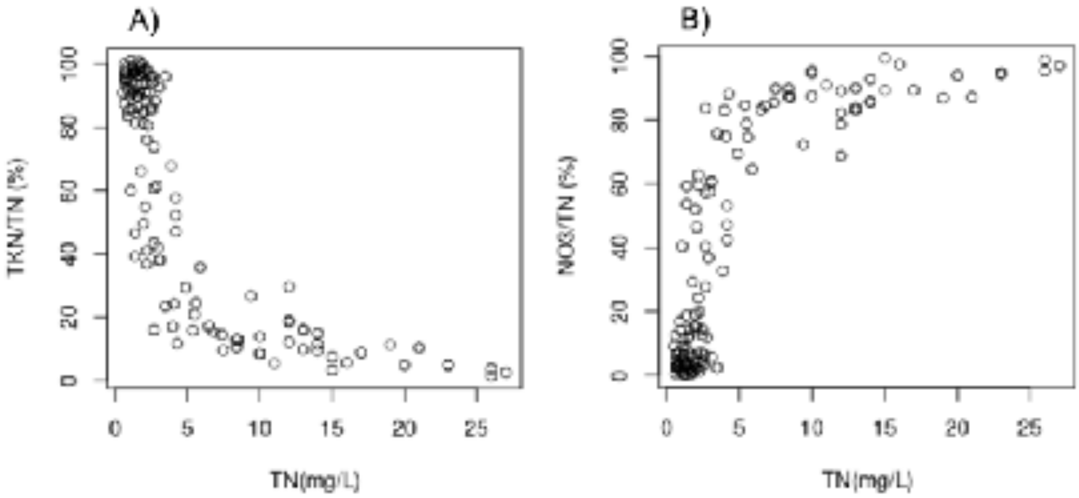

Figure 12: A) Percentage of the total nitrogen as organic and ammonium (Kjeldahl nitrogen, TKN), and B) percentage of total nitrogen in the form of nitrate, in relationship with the total nitrogen.

Table 1 shows the variables considered in this study (plot, vegetation, depth, distance from fence and sampling day) and their statistical effect on the different N species (TN, TKN, NO_3^- and NH_4^+) measured in pore water samples. Here, TKN represents dissolved organic N (<45 um). TN is affected by all variables analysed, in significance order *distance from fence* > *depth* > *plot* > *vegetation*.

Table 1: ANOVA results of significant interactions between variables and N species as indicated by p-values. *** p < 0.001, ** p < 0.01, * p < 0.05, ° p < 0.1

N Species	Distance from fence	Depth	Plot	Vegetation	Distance from fence * Depth	Distance from fence * Vegetation	Vegetation * Depth	Distance from fence * Depth * Vegetation
TN	***	***	**	°	***	***	**	**
NO_3^-	***	***	**	*	**	***		
TKN	°	***	*	*	**			
NH_4		*						

TN concentrations decreased significantly throughout the length of the riparian band, from an average of 9.32 mg/l at 1 m from the fence to 2.03 mg/l at 7 m. NO_3^- was the main form of N being removed, decreasing 10-fold within the sampled area (from an average of 7.97 to 0.75 mg/l). This shows that the buffer is fulfilling its purpose and successfully removing N from subsurface flow. Considering that only the first 7 of the 30 m of the buffer were sampled, it can be expected that concentrations will continue to decrease farther into the riparian band, and be substantially lower at the bottom of the plots than what was found in this study (i.e. close to the drain, Figure 3).

The mean concentration of TN was significantly higher at 50 cm than at 10 cm, while the middle depth (30 cm) did not significantly differ from the other two. Similarly, the NO_3^- concentration declined significantly with distance from the fence and was 10 times lower at 7 m from the fence compared to 1 m from the fence (Table 1 and Figure 13). When all distances and vegetation types were combined, NO_3^- significantly increased with depth from a mean concentration of 1.7 mg/L at 10 cm to a mean concentration of 7.3 mg/L at 50 cm. The vegetation type significantly affected the results of NO_3^-, but most importantly as an interaction with Depth and Distance from the fence (Table 1). Figure 12 shows that NO_3^- was higher under maanuka than grass (control plots) in the topsoil (10cm), but significantly lower under maanuka than grass at 50 cm depth.

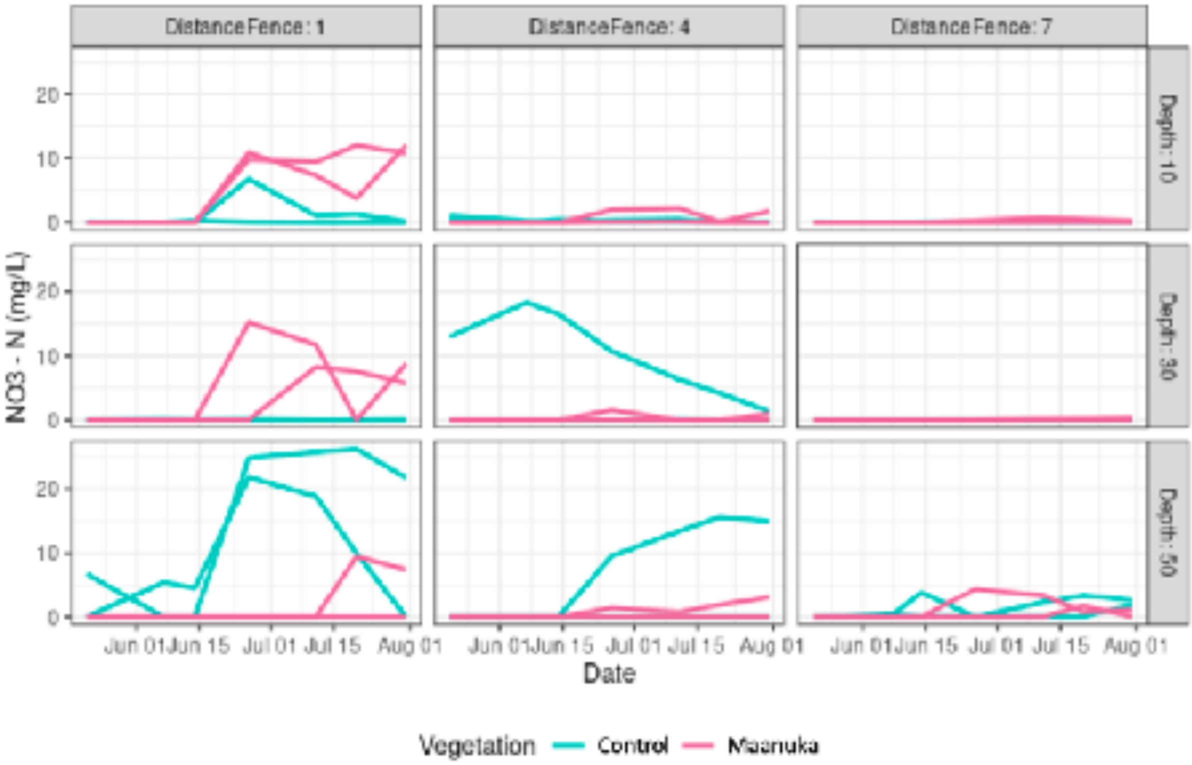

Figure 12: Concentration of nitrogen as nitrate in soil pore water collected at 10 cm, 30 cm and 50 cm deep, and at 1m, 4m, and 7m from the fence in control and swamp maanuka plots. Note that for better visualisation of the graphs, when no sample was obtained, results are represented as 0.

TKN was mostly affected by soil depth (Table 1), with highest concentrations at 10 cm depth (1.73 mg/L mean concentration) and lowest concentrations at 50 cm depth (0.92 mg/L mean concentration). This is expected, since organic N is the main contributor to this fraction of N, and therefore related to the distribution of organic matter in the soil. TKN did not significantly differ between the three distances from the fence. However, TKN concentrations were significantly affected by vegetation type ($p<0.05$, Table 1), with higher TKN in the control than the maanuka plots.

Although the soil pore water data is insufficient to quantify the leaching risk, they can indicate the relative mobility of N under each of the plots. When the pore water volume is multiplied by the concentration of TN in the leachate in each plot, we obtained a mass of N "total N extracted" (Figure 13). When all depths were combined, 21 % more N was extracted from the control plots than the maanuka plots. The difference between the control and maanuka plots was most pronounced at 50 cm depth, where the extracted N was approximately six times higher in the control than the maanuka plots. This indicates that there was more mobile N in the control plots than in the maanuka plots, and that N leaching is likely to be lower under maanuka.

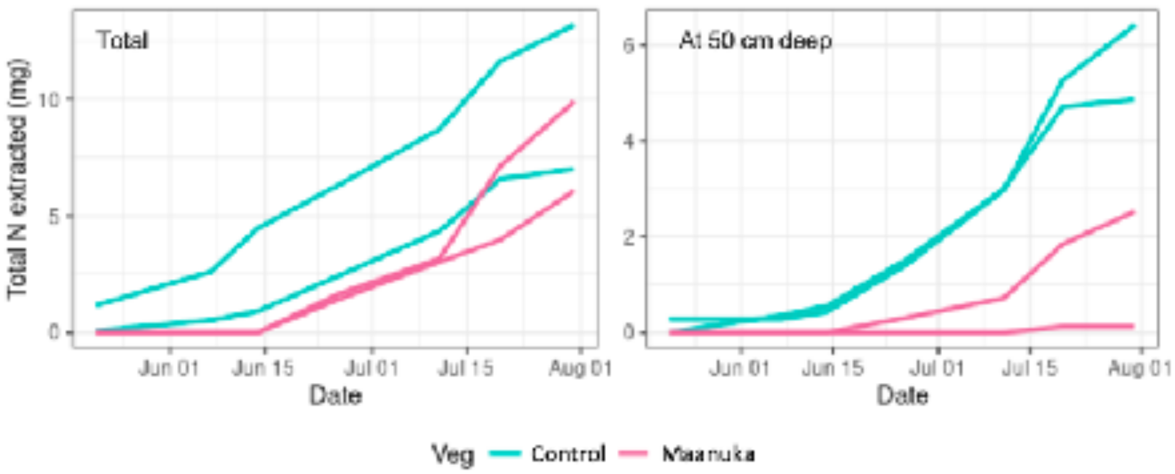

Figure 13: Total cumulative nitrogen extracted from each of the plots along the monitoring months. A) in the monitored soil profile (10 cm, 30 cm and 50 cm), B) only at 50 cm at all monitored distances (1 m, 4 m and 7m).

Our results demonstrate that planting riparian buffers with maanuka provide extra benefits for reducing NO_3^- exports compared with unplanted grassed buffers (Figure 13). Although both the control and maanuka plots showed a reduction in NO_3^- at 7 m from the fence, this reduction was up to six times more pronounced under maanuka.

There are numerous interrelated mechanisms that can explain or affect these results. Given this complexity, it is difficult to assume which mechanisms explain the differences in N movements between maanuka and control plots. We consider that the different water fluxes in the control and maanuka plots are a very important factor affecting the results. The "umbrella effect" or rain inception by maanuka canopy reduced the amount of water that arrived at the soil (four times lower, Figure 9), compared with the control. Having less water in the soil reduces the risk of NO_3^- leaching. Increased infiltration by preferential flow created by taproots (Mishra, 2018) is another mechanism by which maanuka can affect water flux. Although we did not measured infiltration directly, we expected to see less runoff collected in the maanuka vs control plots, which would indicate higher infiltration by maanuka compared with pasture, and which was shown by Mishra (2018). In addition, macroporosity can prove indirect data on infiltration as higher macroporosity is associated with higher infiltration (Taylor et al., 2008). This can be one reason for lower NO_3^- in deeper horizons in maanuka compared with pasture (Fig. 12). Potentially, maanuka taproots (which can grow down to 1.2 m, Watson and O'Loughlin (1985)) growing through the Hamilton Ash layer of the subsoil, could create a channel for exports of water and NO_3^-.

Nitrogen uptake by plants is another process that affects N exports. In this experiment we did not quantify the N uptake by maanuka or grass in the control plots. In a cut and carry system, the usual N removal by pasture is ~ 200 kg N/ha/y (Gutierrez-Gines et al., 2020). However, the pasture biomass was not removed from the system here. Maanuka might have taken up an important amount of N from the soil during its growth. However, some of that N is clearly returning to the soil as leaf litter, where it accumulates in the soil. Other research carried out on site revealed a higher accumulation of organic matter in the soil under maanuka compared with control (as seen as higher TC and TN in soil under maanuka) (Gutierrez-Gines et al., 2022). This can increase N bound to organic matter, making it less mobile, and as a consequence, less susceptible to exports in the leachate.

Even more complex are the potential effects that maanuka might have in the N cycle (mineralization, nitrification, and denitrification). The potential biological nitrification inhibition demonstrated by J. Esperschuetz et al. (2017), and suggested by Halford et al. (2021) could explain the lower NO_3^- exports under maanuka compared with control, but not the higher NH_4^+ in soil in control plots compared with maanuka plots. This higher NH_4^+ in soil under control is consistent with the wetter conditions in this soil compared with maanuka plots (Figure 10). Although not measured or investigated in this project, denitrification could be an important mechanism to reduce the risk of N leaching, and it is considered by some authors as the main mechanism for N reductions in riparian bands (Fennessy & Cronk, 1997; Neilen et al., 2017). Waterlogged, low permeable soils, like the ones in our experiment, are good environments for creating anaerobic microsites in the soil, where denitrification would occur (McLaren & Cameron, 1996). However, we cannot know to what extent maanuka vs control could favour this process.

3.5 LATERAL FLOW

This study has shown evidence of the existence of a short-lived perched water table at the Hamilton Ash boundary, over which water and contaminants are likely to move laterally towards the drain. A number of observations support this theory. Good soil structure in the surface horizons allows for infiltration through the soil profile, until water reaches the more impermeable and compact Hamilton Ash layer, at which point lateral movement is favoured. Gleying can be seen from 30 cm depth, as well as mottling— and the Mangatawhiri clay loam is indeed classified as a Perch-Gley Ultic Soil. Personal observations suggest that the micro-topography of the area is very heterogeneous, while soil sensors show restricted drainage at 30 cm depth in plot M2. Higher N concentrations at depth also suggest that N-loaded water is perched upon the clay-rich Hamilton Ash layer. Perching is further evidenced by the large volume of pore water samples extracted on July 20th, which suggested that the lysimeters could be sampling the perched water table.

FURTHER RESEARCH

The main limitation of this study is that TN extracted (i.e. TN concentration x volume of sample) was used as a proxy for drainage rather than directly quantifying leaching. Hence, future research at this site might be dedicated to creating a soil water balance to estimate leaching, which would provide a more complete picture of the processes occurring at the experimental site. This might be done utilising a simple bucket model (i.e. drainage = precipitation - evaporation - soil storage) where above/below canopy rainfall are measured for each vegetation type in further detail, evaporation is estimated by the $FAO5_6$ equation (if not measured directly), and storage calculated by soil water deficit (as developed by Woodward et al., 2001) (Chibnall, 2013). Alternatively, models such as APSIM or EVACROP could be used (Vogeler et al., 2020).

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