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RESEARCH ARTICLE



# The effect of polyferric sulphate treated farm dairy effluent and clarified water on leaching losses, greenhouse gas emissions and pasture growth

Christopher M. W. Chisholm, Keith C. Cameron , Hong J. Di and Tim C. Green

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## ABSTRACT

A lysimeter experiment was conducted to investigate the environmental effects of applying farm dairy effluent (FDE) treated with a chemical coagulant (polyferric sulphate) to land. The coagulant was administered as part of an effluent treatment system known as ClearTech. Two products are produced from the treatment process; treated effluent (TE) and clarified water (CW). Applications were applied in May. When compared to FDE, TE and CW reduced *E. coli*, Total-P and dissolved reactive P (DRP) leaching losses. *Escherichia coli* leaching losses were reduced by 99.97% and 99.99% for TE and CW, respectively. This was because of the acidity of the added coagulant and the encapsulation of the bacteria in the flocculated sediment. Compared to FDE, Total-P leaching losses were reduced by 90.5% and 85.7% for TE and CW, respectively. DRP leaching losses were also reduced under TE and CW by 99.5% and >99.99%, respectively. Reductions in phosphorus leaching were attributed to the reduced P solubility, resulting from the iron added in the coagulant binding to the phosphorus. There was no significant difference between treatments in the amount of iron leached, greenhouse gas emissions or Mineral-N leached (except where additional ammonium-N was added to the clarified water).

## ARTICLE HISTORY

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## KEYWORDS

ClearTech; FDE; *E. coli*; DRP; Total-P; nitrogen leaching; nitrous oxide emissions; iron leaching

## Introduction

The New Zealand dairy industry has grown in size and intensity over the past 20 years, with dairy cow numbers and stocking rate increasing by 1.796 million and 0.39 cows ha<sup>-1</sup>, respectively (DairyNZ 2017). This intensification has led to an increased amount of farm dairy effluent (FDE) being produced. Traditionally, farmers have applied FDE to pastures at opportune times as it is a valuable source of nutrients which improves soil fertility and increases pasture growth (Goold 1980; Di and Cameron 2002; McLeod et al. 2014). However, if not managed correctly, the application of effluent can lead to numerous negative environmental effects, especially freshwater contamination (Cameron and Di 2004; McLeod et al. 2014; MfE 2019).

In light of these increasing environmental concerns, a new FDE treatment system, commercially known as ClearTech has been developed. ClearTech uses polyferric sulphate

(PFS), a chemical coagulant to flocculate and settle the colloidal material present in FDE, resulting in the production of clarified water (CW) and treated effluent (TE) (Cameron and Di 2019). The clarified water can either be applied to land or recycled to wash the farmyard (Cameron and Di 2019). The treated effluent can be stored and/or applied to land. Importantly, the amount of treated effluent that needs to be stored is 60% less than the original volume of untreated effluent (Cameron and Di 2019). Preliminary studies have investigated the environmental impacts of applying PFS treated effluents (TE and CW) to land (Chen et al. 2018; Cameron and Di 2019; Wang et al. 2019). Wang et al. (2019) reported that compared to FDE, TE reduced *E. coli*, DRP and Total-P leaching losses by 69%, 75% and 85%, respectively. Chen et al. (2018) reported that CW and TE had no significant effect on N<sub>2</sub>O emissions, soil ammonia oxidisers and denitrifiers compared to FDE. However, the findings in these preliminary reports need to be verified with more information on the effect of land application of PFS treated effluents, including: (i) the effect of applying CW on *E. coli*, phosphorus and nitrogen leaching losses; (ii) the effect of applying CW on greenhouse gas emissions; and in particular (iii) the effect of the addition of iron in PFS treated effluents on iron leaching losses because it has not been investigated before. The hypothesis of this study is that treating FDE with polyferric sulphate will reduce leaching losses of *E. coli*, DRP and Total-P without affecting N<sub>2</sub>O emissions, Mineral-N leaching, or leaching losses of iron.

## Materials and methods

### Site description and trial setup

The lysimeter study was conducted at Lincoln University, Lincoln, Canterbury, New Zealand (43° 38' 52"S, 172° 28' 07"E; 10 m a.s.l.), where the average annual temperature and rainfall are 11.5°C and 630 mm, respectively.

The lysimeters used in this experiment were collected from Lincoln University's Ashley Dene Research and Development Station, located on the Canterbury Plains, New Zealand (43° 38' 43"S, 172° 20' 50"E). The soil at this location is a Balmoral stony silt loam. It has a silty loam texture with a high stone content, which increases with depth. Phosphate retention is classified as medium (36%) (Webb and Bennett 1986).

The pasture sward at this site was comprised of a well-established Perennial Ryegrass (*Lolium perenne* L.) and White Clover (*Trifolium repens* L.) mix with a minor weed component.

Four months prior to the collection of the lysimeters the site was fenced off to prevent animal access. The 24 undisturbed soil monolith lysimeters (0.5 m diameter, 0.7 m depth)

**Table 1.** Chemical properties of the soil used in the lysimeters (Wang et al. 2019).

Soil analysis <sup>a</sup>	Value	Soil analysis <sup>a</sup>	Value
pH	6.1	CEC	16 cmol <sub>c</sub> kg <sup>-1</sup>
Olsen-P	33 µg mL <sup>-1</sup>	Reserve-K	3.6 cmol <sub>c</sub> kg <sup>-1</sup>
Exch-Ca	8.1 cmol <sub>c</sub> kg <sup>-1</sup>	Sulphate-S	4 µg g <sup>-1</sup>
Exch-Mg	0.5 cmol <sub>c</sub> kg <sup>-1</sup>	Organic-C	45 g kg <sup>-1</sup>
Exch-K	0.4 cmol <sub>c</sub> kg <sup>-1</sup>	Total-N	4.0 g kg <sup>-1</sup>
Exch-Na	0.2 cmol <sub>c</sub> kg <sup>-1</sup>	Organic-S	5 µg g <sup>-1</sup>

<sup>a</sup>0–7.5 cm soil.

were collected using a well-established method of Cameron et al. (1992). Soil chemical and physical properties were analysed and are presented in Tables 1 and 2. The lysimeters were transported to Lincoln University's Field Research Centre and were installed in a purpose-built field trench with the surface of the lysimeters at the same level as the surrounding field. Plastic tubing was connected to the base of each lysimeter for leachate collection.

Each lysimeter was fitted with a rain/irrigation simulation system (RISS). This consisted of a spray nozzle (Tee Jet FL-5VC) secured to the top of each lysimeter using a metal tripod to apply water as either irrigation or simulated rain. During the summer, RISS was used to apply irrigation at regular intervals to account for evapotranspiration and to simulate normal dairy farm practices. During the winter period, the RISS was used to simulate precipitation events. Rainfall was supplemented to the 75th percentile of the amount of rainfall based on local winter rainfall records.

### **Effluent collection and treatment**

Fresh FDE was collected from the Lincoln University Demonstration Dairy Farm (LUDF) after the morning milking on 8 May 2019. The effluent produced at LUDF was from Friesian-Jersey cows (Kiwi-cross) that had grazed outdoors on a perennial ryegrass-white clover pasture mix.

300 L of the effluent was pumped into a Perspex tank and the coagulant (polyferric sulphate or PFS) was added and stirred for 2 min as described in Cameron and Di (2019). The PFS was added at a rate of 150 mg Fe L<sup>-1</sup> of effluent. After 2 h, the resulting clarified water (CW) was removed using a pump. The treated effluent (TE) was then removed. Sub-samples of each effluent type were taken for lab analysis as described in Cameron and Di (2019) and the results are shown in Table 3.

### **Treatments**

Six treatments were used with four replicates each, totalling 24 experimental units (lysimeters). The treatments were laid out in a completely randomised design. The treatments consisted of: (i) untreated farm dairy effluent (FDE) (ii) treated effluent (TE), (iii) 1:3 CW: TE mix (M), (iv) clarified water (CW), (v) clarified water spiked with 764 mg L<sup>-1</sup> NH<sub>4</sub>Cl (CW10) and (vi) water Control. CW10 simulates the clarified water being recycled numerous times to clean the dairy shed yards. The amount of N applied on a per ha basis is shown in Table 4. The six treatments were applied to the lysimeters on 8 May 2019. Each treatment was applied at a rate of 24 mm (4.71 L per lysimeter) using a jug.

**Table 2.** Physical properties of the soil used in the lysimeters (Wang et al. 2019).

Soil depth (cm)	Soil bulk density (g cm <sup>3</sup> )	Stone volume (%)	Soil porosity (%)	Soil texture
0–10	1.14	11	58	Stony ZL
10–20	1.57	30	42	Stony ZL
20–30	1.9	51	29	Stony SL
30–40	2.05	54	24	Stony S
40–60	1.96	51	27	Gravelly S

ZL, silt loam; SL, sandy loam; S, sand.

**Table 3.** Chemical and physical characteristics of the different effluent types applied to the lysimeters.

	<i>E. coli</i> (log10) (cfu 100 mL <sup>-1</sup> )	BOD (g m <sup>3</sup> )	Total-N (g m <sup>3</sup> )	NH <sub>4</sub> <sup>+</sup> -N (g m <sup>3</sup> )	NO <sub>3</sub> -N (g m <sup>3</sup> )	Total-C (g m <sup>3</sup> )	Dissolved-C (g m <sup>3</sup> )	Total-P (g m <sup>3</sup> )	DRP (g m <sup>3</sup> )	Solids (g m <sup>3</sup> )	Turbidity (NTU)	pH
FDE	5.8 b	736.7 b	114.7 b	20.5 a	0.0 a	956.7 ab	333.3 b	35.3 b	14.4 b	1266.7 b	2751.3 b	6.7 c
CW	0.9 a	131.7 a	39.7 a	33.0 a	2.6 c	90.0 a	90.3 a	0.0 a	0.0 a	4.0 a	5.5 a	4.6 a
CW10	1.2 a	118.7 a	236.7 c	233.3 c	2.6 c	93.3 a	93.3 a	0.0 a	0.0 a	3.7 a	5.1 a	4.7 b
TE	5.3 b	1123.3 c	253.3 cd	36.0 a	2.0 b	1980.0 b	89.3 a	112.0 d	0.0 a	6966.7 c	4436.7 c	4.5 a
MIX	5.4 b	1073.3 c	270.0 d	72.0 b	2.0 b	343.0 ab	91.6 a	91.3 c	0.0 a	7133.3 c	3683.3 bc	4.5 a

Notes: FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; MIX, 1:3 mix of CW:TE. Values with letter in common are not significantly different at the 5% level. *Escherichia coli* data has been log10 transformed.

**Table 4.** The concentration of N applied in each treatment ( $\text{g m}^{-3}$ ), and the equivalent concentration converted to  $\text{kg N ha}^{-1}$ .

Treatment	Total-N	
	( $\text{g m}^{-3}$ )	( $\text{kg N ha}^{-1}$ )
FDE	114.7	27.5
CW	39.7	9.5
CW10	236.7	56.8
TE	253.3	60.8
Mix	270	64.8
Control	0	0

Note: FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE.

## Sample collection

### Leachate sampling and analysis

Leachate was collected from the lysimeters after a significant rain event, or if > 300 mL of drainage water had accumulated in the collection vessel. During each collection event, the leachate volume was recorded, and subsamples were retained for analysis of Mineral-N, Total-P, DRP, Fe, and *E. coli* concentrations.

For the first four leachate collections, a sterile sampling system was used to reduce the risk of cross-contamination between sampling events. This sampling method utilised single-use sterile plastic bags which were exchanged after each sample was taken. After the first four leachate collections, the sampling method was switched to containers and sampling for *E. coli* was discontinued (because there was none detected by this stage). Subsamples used to measure Total-P, DRP and *E. coli* were kept cool (<4°C) and sent away for analysis on the day of sampling. Mineral-N and Fe samples were frozen for analysis at a later date. The last leachate sample was collected on 17 September 2019.

Mineral-N concentration was measured by using FIAstar 5000 analysers (Tecator inc., Sweden) at Lincoln University, Lincoln. To ensure analysis of samples was accurate, blank samples and inter-lab standardised samples were analysed prior to the samples and compared against their measured values. During the analysis procedure, a standardised sample was analysed and compared to every 10 samples. After 20 samples, both an internal and external standard were analysed and compared to ensure consistency.

DRP was directly measured on filtered (0.45  $\mu\text{m}$ ) leachate samples by the malachite green method (Ohno and Zibilske 1991), and Total-P was determined by digesting samples with  $\text{K}_2\text{S}_2\text{O}_8$  and NaOH (Ebina et al. 1983) followed by the malachite green colorimetry method. The concentration of *E. coli* was determined by undertaking a Colilert test (incubated at 35°C for 24 h) which gave an MPN count (Wang et al. 2019). Iron concentration in the leachate was determined using a Varian 720-ES Inductively Coupled Plasma Optical Emission Spectrometer, fitted with an SPS3 auto-sampler and ultrasonic nebuliser.

The amount of Mineral-N, phosphorus, iron and *E. coli* losses from the lysimeters were calculated by multiplying the volume of leachate by the individual concentration at each sampling event.

### ***Gas sampling and analysis***

A closed chamber method, similar to that described by Hutchinson and Mosier (1981), was used to capture GHG emissions from the lysimeters (Di and Cameron 2006; Di et al. 2007). The gas chamber consisted of a metal cylinder that was insulated with 2.5 cm thick polystyrene foam to avoid temperature changes during the sampling process. To begin gas sampling, the chamber was placed into a metal ring trough attached to the top of the lysimeter. This metal ring trough was filled with water to reduce gas exchange between the chamber and the atmosphere. At each sampling date, three samples were taken at 20-minute intervals, after which the chamber was removed. The temperature at the soil surface was taken at three 20-minute intervals throughout the sampling process.

The first gas sample was taken the day after the treatments were applied. Sampling then occurred twice weekly for the first 3 months, followed by once weekly until background levels were reached. The last sample was taken on the 29 of August 2019. On each sampling day, gas samples were collected between 1 and 2 pm, during which time the air temperature represented the daily average, and the GHG emissions were similar to the daily average (Di et al. 2007).

GHG concentration analysis was conducted by using a gas chromatograph (GC) (Model 8610C, SRI instruments, CA, USA), with an automated Gilson GX-271 autosampler (Gilson Inc., MI, USA) coupled to an electron capture detector (ECD) and flame ionisation detector (FID). Nitrous oxide was measured by ECD, whilst CH<sub>4</sub> and CO<sub>2</sub> were measured by FID (CO<sub>2</sub> was converted to CH<sub>4</sub> and then measured). The GC used three HayeSep D packed columns as the precolumn, and two of six HayeSep D as the analytical column.

Hourly GHG emissions were calculated based on the rate of increase in GHG concentration in the chamber (from 0–40 mins), corrected for temperature and the ratio of surface area to chamber volume. Daily emissions were calculated using the hourly flux, assuming that it represented the average hourly flux of the day (Hutchinson and Mosier 1981). Cumulative emissions were calculated by integrating the calculated daily GHG fluxes and linear interpolation between measurement points. The N<sub>2</sub>O emission factor (EF<sub>1</sub>) was calculated for each effluent N rate as:

$$EF_1(\%) = 100 \times (N_2O-N \text{ treatment} - N_2O-N_{\text{water}}) / \text{effluent-N}(\text{applied})$$

### ***Herbage sampling and analysis***

The pasture was harvested using electric shears when it reached approximately 200 mm in height to simulate typical dairy farm grazing practices. Residual levels were left at approximately 35 mm. Three cuts were taken over the trial period, with the last one taken on the 29 of October 2019. All the harvested herbage was removed and dried at 70 °C for 72 hrs to obtain the dry matter yield.

### ***Statistical analysis***

The leaching losses of Total-P, DRP, Mineral-N, Fe, and *E. coli* and the GHG emissions from each lysimeter were statistically analysed by conducting a one-way ANOVA using GenStat (19th edition, Lawes Agricultural Trust) to test for treatment effect significance.

*E. coli* and TP data were  $\log_{10}$  transformed, DRP and Mineral-N data were square-root transformed to meet the assumptions of ANOVA. The significant difference between treatments was determined using a Tukeys test with a significance level of 0.05.

The chemical and physical values presented in Table 3 were statistically analysed using by conducting a one-way ANOVA using GenStat (19th edition, Lawes Agricultural Trust). *E. coli*, Total-C, Solids and Turbidity were  $\log_{10}$  transformed, and DRP was square-root transformed to meet the assumptions of ANOVA.

## Results and discussion

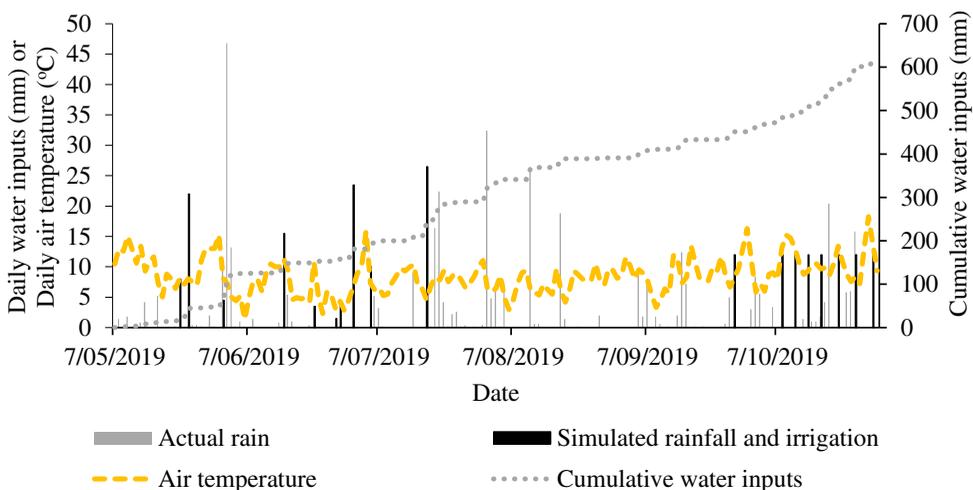
### Effluent composition

In analysing the composition of the treated and untreated effluents, it was found that CW had significantly ( $P < 0.05$ ) lower *E. coli*, biological oxygen demand (BOD), Total-N, Total-C, Total-P, DRP, Solids, turbidity and pH than the untreated FDE. Both TE and Mix had higher biological oxygen demand (BOD), Total-N, Total-P, Solids and turbidity than untreated FDE. CW10 had a higher concentration of  $\text{NH}_4$  than the other effluent types because it was spiked with ammonium chloride (Table 3).

These results follow a similar trend to those reported in Cameron and Di (2019), where both treated effluent and a mixture of treated effluent and clarified water showed lower *E. coli*, dissolved C, DRP and pH than the other effluent types.

### Climate conditions and drainage

Cumulative water inputs over the trial period (8 May 2019–29 October 2019) totalled 613.5 mm. This consisted of 399 mm of rainfall and 214.5 mm of simulated rainfall/irrigation (Figure 1). Over the leachate collection period (8 May 2019–19 September 2019) water inputs totalled 432.9 mm, of which approximately 60% was discharged as drainage.



**Figure 1.** Daily and cumulative rainfall and irrigation (including simulated rainfall), as well as daily air temperature.

This is because this trial was undertaken throughout the winter months when a large proportion of the annual drainage occurs. Average daily air temperature over the trial period was 8.5 °C, with a range of 1.3°C (6 July 2019) to 18.3°C (28 October 2019) (Figure 1).

Average cumulative drainage for each of the five effluent treatments and Control ranged from 236 mm (TE) to 277 mm (Control). In comparing the effluent treatments and Control, no significant difference was observed for average drainage after 1 d ( $P > 0.05$ ), or for average cumulative drainage ( $P > 0.05$ ) (Figure 2).

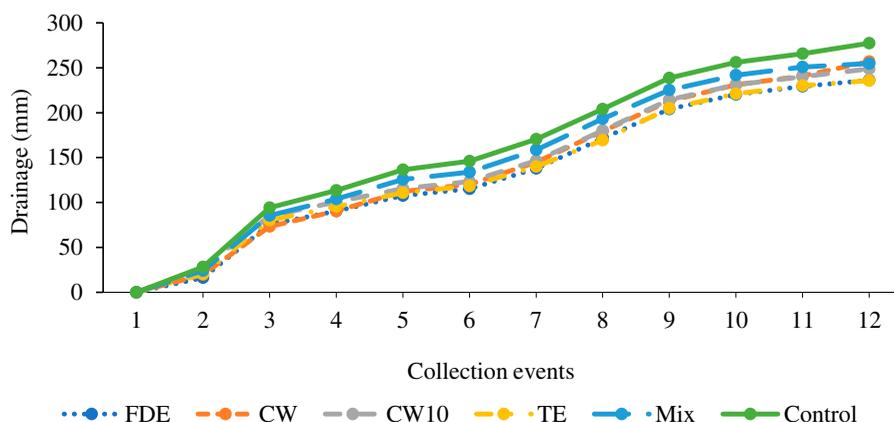
### The effect of PFS treated effluents on *E. coli* leaching losses

*E. coli* concentrations leached from the FDE treated lysimeters peaked at 10 mm of drainage, with a concentration of  $5.52 \times 10^5$  cfu 100 mL<sup>-1</sup> (Figure 3). This rapidly decreased, and after 50 mm of drainage, the *E. coli* concentrations were close to zero. Comparatively, *E. coli* concentrations under the other five treatments remained close to zero throughout the trial and no peak loss occurred (Figure 3).

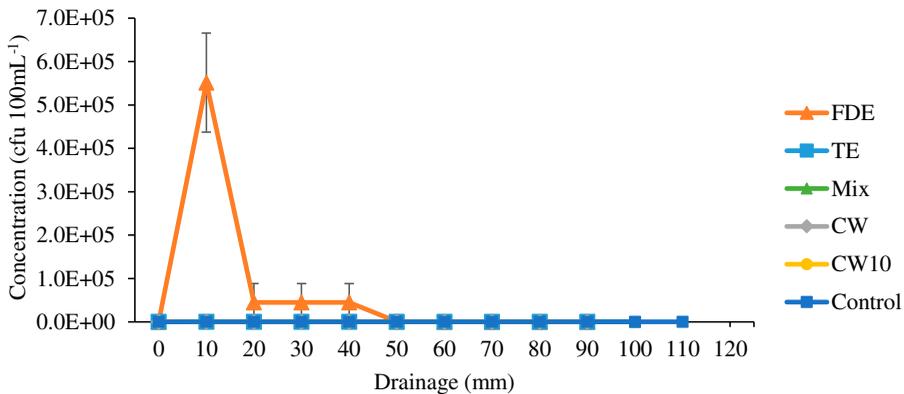
Compared to FDE, the application of PFS treated effluent and clarified water significantly ( $P < 0.05$ ) reduced *E. coli* losses by 99.97% and 99.99%, respectively (Table 5). It was also found that Mix and CW10 reduced *E. coli* losses by 99.97% and 99.99%, respectively. These reductions support those observed by Wang et al. (2019) (69% and 98% reduction for TE and Mix treatments, respectively).

The significant reduction in *E. coli* leaching losses is attributed to the reduction in *E. coli* present in TE and CW (Table 3). The reduction in *E. coli* leaching was caused by (i) the acidic nature of the PFS solution (pH < 1.0) added and (ii) the encapsulation of the bacteria within the floc. No significant difference in *E. coli* loss was observed between TE, Mix, CW, CW10 and the Control (Table 5).

The substantial reductions in *E. coli* leaching loss from PFS treated effluent could be of considerable value in reducing farm environmental impacts on water quality and help address the water quality concerns raised in the NZ government's discussion document on freshwater (MfE 2019).



**Figure 2.** Average cumulative drainage from the five treatments and Control. FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE.



**Figure 3.** Average concentration of *E. coli* in the leachate collected from the lysimeters. FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE. Y-axis values displayed in scientific notation. Error bars represent the standard error of the mean.

### The effect of PFS treated effluents on phosphorus leaching losses

Following the treatment application, Total-P concentrations under FDE peaked at 10 mm, with a concentration of 6.82 mg P L<sup>-1</sup> (Figure 4). These Total-P concentrations then decreased exponentially until background levels were reached after 90 mm of drainage. In comparison, Total-P concentrations under the other five treatments remained close to zero throughout the study.

Over the experimental period, the amount of Total-P leached from the lysimeters applied with PFS treated effluents was shown to be significantly ( $P < 0.05$ ) lower than the Total-P leached from the lysimeters treated with FDE (Table 5). No significant difference was detected between the PFS treated effluents and the Control ( $P > 0.05$ ). Total-P losses from TE and CW were calculated to be 90.4% and 86.1% lower than FDE treatment losses, respectively (Table 5).

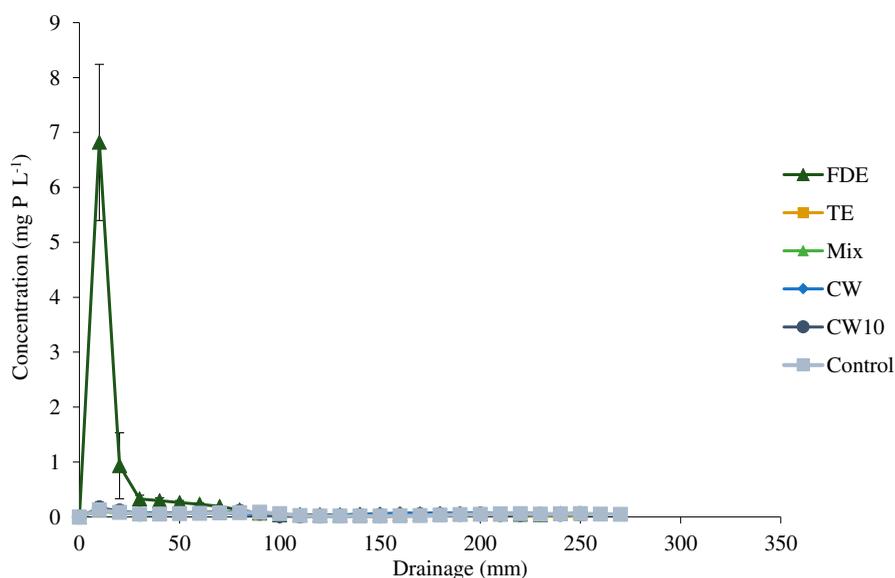
No DRP losses were detected under CW or CW10 treatments during the trial period. While DRP losses from TE and Mix treatments were significantly less than losses from FDE ( $P < 0.05$ ) with reductions of 99.5% and 98.1%, respectively, during the trial period (Table 5).

The substantial reductions in DRP and Total-P leaching losses from the treated effluents are attributed to the addition of PFS to untreated FDE prior to application.

**Table 5.** *Escherichia coli*, Total-P, DRP, Mineral-N and Iron leaching losses from the six treatments.

	<i>E. coli</i> (cfu ha <sup>-1</sup> )	Total-P (kg P ha <sup>-1</sup> )	DRP (kg P ha <sup>-1</sup> )	Mineral-N (kg N ha <sup>-1</sup> )	Iron (kg Fe ha <sup>-1</sup> )
FDE	3.5E+12 a	1.1 a	0.2 a	1.7 a	17.4 a
TE	8.8E+08 b	0.1 b	0.0 b	0.5 a	8.50 a
Mix	9.3E+08 b	0.1 b	0.0 b	2.3 a	8.30 a
CW	3.4E+08 b	0.2 b	0.0 b	1.6 a	7.70 a
CW10	1.5E+08 b	0.1 b	0.0 b	9.2 b	16.8 a
Control	4.4E+08 b	0.1 b	0.0 b	1.1 a	12.9 a

Notes: FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE. *Escherichia coli* values presented with a scientific notation. Values with a letter in common are not significantly different at the 5% level.



**Figure 4.** Average leachate Total-P concentrations collected from the lysimeters. FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE. Error bars represent the standard error of the mean.

The Fe(III) present in the added coagulant reacts with P in solution, which creates stable iron phosphate compounds (Cameron and Di 2019).

Total-P and DRP leaching losses under the FDE treatment are similar to those reported by McDowell et al. (2019), who recorded average DRP and Total-P losses over a 14-yr period of 0.316 and 1.46 kg P ha<sup>-1</sup> yr<sup>-1</sup>, respectively. McDowell et al. (2019) reported that most of the P leaching losses from a farm occurred under the effluent irrigation area.

### **The effect of PFS treated effluents on nitrogen leaching losses**

There was no significant difference in Mineral-N leaching losses between TE, Mix, CW, FDE and the Control. However, Mineral-N losses from CW10 were shown to be significantly ( $P < 0.05$ ) greater than the other treatments (Table 5). This is because CW10 was artificially spiked with ammonium-N, which was readily leached (Table 3).

Despite the application of ammonium spiked clarified water (CW10) causing the highest rate of N leaching, it did not exceed 10 kg N ha<sup>-1</sup>. Therefore, N losses from the application of effluent are relatively small compared to typical annual leaching losses from grazed dairy pasture systems (range 25–110 kg N ha<sup>-1</sup> yr<sup>-1</sup>) (Cameron et al. 2013). In addition, a smaller volume of CW would be applied to the paddock if the CW was recycled a number of times in the treatment system, compared with the untreated FDE.

### **The effect of PFS treated effluents on iron leaching losses**

There was no significant difference in iron leaching losses between treatments and the control over the trial period ( $P > 0.05$ ). Losses ranged from 7.7–17.4 kg Fe ha<sup>-1</sup> (Table 5).

Iron concentrations in the drainage water ranged from 0.05–0.46 mg Fe L<sup>-1</sup>. This is below the suggested critical iron concentration in water of 1 mg Fe L<sup>-1</sup> (Vouri 1995). For iron in water to negatively affect mayflies, concentrations would have to exceed 70 mg Fe L<sup>-1</sup>, which is over 150 times higher than the concentrations observed in this trial (Gerhardt 1994). It is important to note that iron leaching losses from the PFS treated effluents were not significantly different from the Control, or the FDE treatments, demonstrating that there is no increased risk of iron contaminating water following land application of PFS treated effluents.

A modelling exercise was conducted to estimate the effect of the land application of PFS treated effluent on the accumulation and subsequent release of iron from the soil (Table 6). The model calculated the amount of iron deposited under two scenarios: (i) where all the iron is applied to the land and (ii) where 50% of the iron precipitates out of the effluent in the storage pond, leaving 50% applied to the land. The table shows that over a year, additional iron inputs range from 0.03–0.26% of the iron present in the top 25 cm of the soil. Over a 10 yr period, total iron inputs range from approximately 0.33–2.63%. As the additions are so low, relative to the amount of iron present within the soil, it is unlikely that the application of treated effluent or clarified water would cause excessive iron build-up or leaching losses over time.

### ***The effect of PFS treated effluent on GHG emissions***

There was no significant difference in total nitrous oxide emissions over the trial period (Table 7) ( $P > 0.05$ ). Losses ranged from 0.06 kg N ha<sup>-1</sup> (CW) to 0.10 kg N ha<sup>-1</sup> (Mix).

There was no significant difference in total carbon dioxide emissions between treatments (Table 7) ( $P > 0.05$ ). Losses ranged from 3507 kg CO<sub>2</sub> ha<sup>-1</sup> (Control) to 4605 kg CO<sub>2</sub> ha<sup>-1</sup> (FDE).

Total CH<sub>4</sub> emissions did not vary significantly between treatments ( $P > 0.05$ ) and ranged from 0.4 kg CH<sub>4</sub>-C ha<sup>-1</sup> (FDE) to 0.5 kg CH<sub>4</sub>-C ha<sup>-1</sup> (Mix) (Table 7).

The similarities in total GHG emissions between all five treatments and the Control demonstrates that the application of TE and CW did not increase GHG emissions from the soil. This is supported by Wang et al. (2019) who found no difference in total GHG emissions between TE and FDE. However, Wang et al. (2019) did note that Mix emitted significantly more CO<sub>2</sub> than the Control.

The N<sub>2</sub>O emission factors (EF<sub>1</sub>) ranged from -0.33% to 0.02% (Table 7). These values are lower than those reported by Wang et al. (2019), which ranged from 0.11% for Mix to 0.36% for FDE. These values are also lower than the EF<sub>1</sub> value used in the New Zealand GHG inventory calculations (FDE EF<sub>1</sub> = 0.3%) (Van der Weerden et al. 2016). This is because nitrous oxide emissions in this trial were low, with some of the treatments emitting less N<sub>2</sub>O than the Control. It is likely that the nitrogen not lost through N<sub>2</sub>O emissions or N-leaching has been held within the soil, taken up by plants or emitted as N<sub>2</sub> gas.

### ***Pasture growth***

No significant difference in pasture growth was observed between the treatments and the Control ( $P > 0.05$ ). Over the trial period (8 May 2019–29 October 2019) pasture growth ranged from 2.0 t ha<sup>-1</sup> (Control) to 3.5 t ha<sup>-1</sup> (Mix) (Figure 5). Wang et al. (2019)

**Table 6.** Model results illustrating the amount of iron applied to land when effluent is treated with PFS ad described in this paper.

Cows (#)	Effluent (cow <sup>-1</sup> d <sup>-1</sup> ) <sup>a</sup>	PFS Fe (mg L <sup>-1</sup> effluent) <sup>b</sup>	Days in milk	Fe ppt out (%) <sup>c</sup>	Application area (ha)	Bulk density (g cm <sup>3</sup> )	Total Fe additions (kg ha <sup>-1</sup> )	Soil depth (cm)	Fe concentration in soil (%) <sup>d</sup>	Fe in soil (t ha <sup>-1</sup> )	% Fe applied of total (1 yr)	10 yr period (%)
400	100	214	270	0	20	1.25	115.6	25	1.35	43.9	0.26	2.63
400	100	214	270	0	40	1.25	57.8	25	1.35	43.9	0.13	1.32
400	100	214	270	50	20	1.25	57.8	25	1.35	43.9	0.13	1.32
400	100	214	270	50	40	1.25	28.9	25	1.35	43.9	0.07	0.66
400	70	214	270	0	20	1.25	80.9	25	1.35	43.9	0.18	1.84
400	70	214	270	0	40	1.25	40.4	25	1.35	43.9	0.09	0.92
400	70	214	270	50	20	1.25	40.4	25	1.35	43.9	0.09	0.92
400	70	214	270	50	40	1.25	20.2	25	1.35	43.9	0.05	0.46
400	50	214	270	0	20	1.25	57.8	25	1.35	43.9	0.13	1.32
400	50	214	270	0	40	1.25	28.9	25	1.35	43.9	0.07	0.66
400	50	214	270	50	20	1.25	28.9	25	1.35	43.9	0.07	0.66
400	50	214	270	50	40	1.25	14.4	25	1.35	43.9	0.03	0.33

Note: PFS Fe is the concentration of Fe used to treat the effluent. Fe ppt out is the amount of iron that precipitates onto the bottom of the effluent pond.

<sup>a</sup>Average effluent produced per cow per day is 70 L (DairyNZ 2014).

<sup>b</sup>Cameron and Di (2019).

<sup>c</sup>It has been observed that iron precipitates out of the effluent and settles to the bottom of the pond as iron sulphide (FeS).

<sup>d</sup>Fe concentration in soil was obtained from Gray and McLaren (2005).

**Table 7.** Total GHG emissions from the individual treatments, including nitrous oxide emission factor (EF<sub>1</sub>).

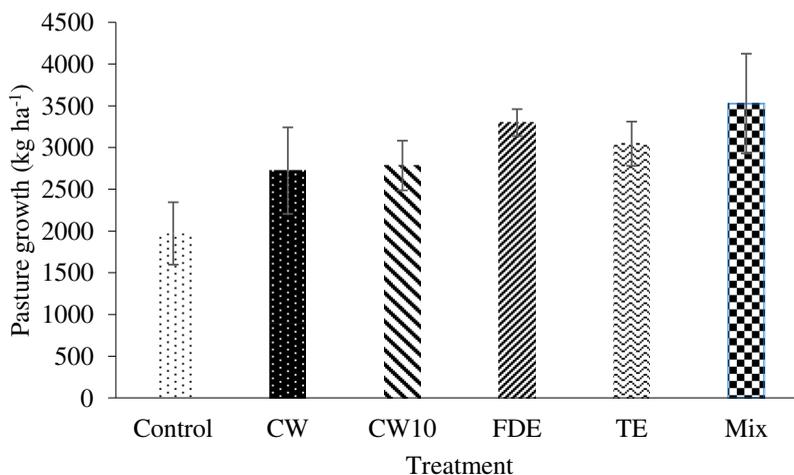
	CH <sub>4</sub> (kg CH <sub>4</sub> -C ha <sup>-1</sup> )	CO <sub>2</sub> (kg CO <sub>2</sub> -C ha <sup>-1</sup> )	N <sub>2</sub> O (kg N <sub>2</sub> O-N ha <sup>-1</sup> )	EF <sub>1</sub> (%)
FDE	0.4 a	4605.5 a	0.1 a	-0.08
TE	0.4 a	4365.9 a	0.1 a	-0.03
Mix	0.5 a	4295.8 a	0.1 a	-0.02
CW	0.4 a	3748.6 a	0.1 a	-0.33
CW10	0.4 a	4452.2 a	0.1 a	-0.00
Control	0.5 a	3507.3 a	0.1 a	-

Notes: FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE. Values with a letter in common are not significantly different at the 5% level.

came to the same conclusion, showing no significant difference in pasture growth over a 12-month period. However, the short period of measurement and the small scale of the lysimeters do not allow for an accurate comparison of pasture growth, as small variations in pasture composition or cover can influence the results.

## Conclusions

This study showed that the land application of polyferric sulphate (PFS) treated effluents significantly reduced the amount of *E. coli*, dissolved reactive P and Total-P lost through leaching, compared to untreated FDE. The reduction in *E. coli* leaching loss is the result of the acidic pH of the PFS added and the encapsulation of the *E. coli* in the flocculated sediment produced. The ferric ions added in the PFS also caused the reduction in phosphorus leaching losses, as the ferric ions react with the phosphate ions, decreasing mobility. There was no significant difference in Mineral-N leaching losses between the different effluent types and the control (except for CW10, which had additional ammonium-N added). Similarly, the land application of the PFS treated effluents and untreated FDE saw no



**Figure 5.** Average pasture growth for the five treatments and the Control over the trial period. FDE, farm dairy effluent; CW, clarified water; CW10, clarified water spiked with ammonium; TE, treated effluent; Mix, 1:3 mix of CW:TE. Error bars represent the standard error of the mean.

significant difference in the amount of greenhouse gas emissions or the amount of pasture growth between the treatments. There was also no difference in the amounts of iron lost through leaching after the land application of the PFS treated effluents compared to untreated FDE. A long-term model showed that applying PFS treated effluent to land over a 10-year period is unlikely to change iron concentrations in the soil significantly or result in excessive iron leaching.

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