

A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality

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Abstract Dairy farming is the largest agricultural industry in New Zealand, contributing 20% of export earnings but providing a challenge for the environmentally acceptable treatment of wastes from dairy farms. Nutrient-rich farm-dairy effluent (FDE), which consists of cattle excreta diluted with wash-down water, is a by-product of dairy cattle spending time in yards, feed-pads, and the farm dairy. Traditionally, FDE has been treated in standard two-pond systems and then discharged into a receiving fresh water stream. Changes brought about primarily due to the Resource Management Act 1991 have meant that most regional councils now prefer dairy farms to land treat their FDE. This allows the water and nutrients applied to land in FDE to be utilised by the soil-plant system.

Research on the effects of land-treating FDE, and its affects on water quality, has shown that between 2 and 20% of the nitrogen (N) and phosphorus (P) applied in FDE is leached through the soil profile.

In all studies, the measured concentration of N and P in drainage water was higher than the ecological limits considered likely to stimulate unwanted aquatic weed growth. Gaps in the current research have been identified with respect to the application of FDE to artificially drained soils, and the lack of research that has taken place with long term application of FDE to land and at appropriate farm scale with realistic rates of application. Whilst the land treatment of FDE represents a huge improvement on the loss of nutrients discharged to fresh water compared with standard two-pond systems, there is room for improvement in the management of FDE land-treatment systems. In particular, it is necessary to prevent the direct discharge of partially treated FDE by taking into account soil physical properties and soil moisture status. Scheduling effluent irrigations based on soil moisture deficits results in a considerable decrease in nutrient loss and may result in a zero loss of raw or partially treated effluent due to direct drainage.

Keywords farm-dairy effluent; land treatment; nitrogen; phosphorus; water quality; spray irrigation; pathogens

INTRODUCTION

The period between 1993 and 2003 was one of remarkable expansion and growth for the dairy industry in New Zealand, the country's largest export earner (Statistics New Zealand 2000). In this 10-year period, national dairy cow numbers increased by 44%, from 2.6 to 3.74 million cows. Likewise, stocking rate increased from 2.5 to 2.6 cows hectare⁻¹. By 2003 the total effective land area grazed by milking cows had increased to 1.5 million hectares (Livestock Improvement Corporation 2003). These increases in cow numbers, stocking rate and total area in dairy farming generated greater volumes of farm-dairy effluent (FDE) requiring treatment. Poorly-operated effluent treatment systems (two-pond or land application), particularly in areas newly converted to dairying, began to have visible

impacts on surface-water and ground-water quality (Monaghan et al. 2002b).

To estimate the quantities of FDE being generated, the following approximations can be used. Dairy cows spend approximately 2 h per day over the milking season in the farm dairy or yards (i.e., effluent collecting areas) (Cameron & Trenouth 1999). If it is assumed that they deposit excreta at a constant rate over a 24-h period, then approximately 10% of their excreta will be deposited within the farm dairy and yards. Cameron & Trenouth (1999) state that this percentage ranges from 5 to 15% and depends greatly on cattle management practices. Following milking, the yards are washed down with high-pressure hoses using approximately 50 litres of water $\text{cow}^{-1} \text{day}^{-1}$ (Vanderholm 1984). The resulting wash-down water contains a diluted mix of cattle faeces and urine, along with any chemical that may have been used to wash down the milking plant.

The physical, chemical, and biological characteristics of FDE are highly variable and change within and between farms due to contrasting management of storm water, feed pads, wash-down waters, chemicals, age and breed of herd, and stock management whilst in the yards (Heatley 1996; Longhurst et al. 2000). The average composition of FDE comprises 8% excreta, 4% teat washing, and 86% wash-down water (Longhurst et al. 2000). FDE has a pH of approximately 8 (Heatley 1996). The solid content of FDE from over 63 sites ranged from 0.04 to 5.3%, with an average of 0.9% (Longhurst et al. 2000). Longhurst et al. (2000) also reported mean nitrogen (N) and phosphorus (P) concentrations for raw FDE, from a number of different research trials, to be 269 mg N litre^{-1} (range 181–506) and 69 mg P litre^{-1} (range 21–82). Using the average concentrations, this suggests that, relative to the 1993 situation, there is now approximately an extra 16 million cubic metres of FDE in New Zealand per year, containing 4300 tonnes of N and 1100 tonnes of P, requiring treatment.

Historically, the common form of treatment for FDE has been the two-pond system combining both an anaerobic and facultative pond (Sukias et al. 2001). In the first pond, organic matter in the effluent is digested by anaerobic fermentation, a mixture of partially digested faeces and “carried-in soil” settles out of suspension and accumulates at the bottom of the pond as sludge. The second pond, which is a facultative pond, is usually larger in surface area and shallower. The bottom layer continues to act as an anaerobic treatment whilst the top layer of the pond provides an aerobic treatment.

The combination of an aerobic and anaerobic pond efficiently removes sediment and biological oxygen demand (BOD), but high concentrations of nutrients remain (Hickey et al. 1989; Ledgard et al. 1996; Longhurst et al. 2000; Sukias et al. 2001; Craggs et al. 2003). Longhurst et al. (2000) reported that effluent discharging from a standard two-pond system to surface waters has approximate concentrations of 91 mg N litre^{-1} and 23 mg P litre^{-1} . Although the two-pond treated effluent represents a significant improvement compared with the nutrient concentrations of raw FDE, the concentrations of N and P in two-pond treated FDE are still three and two orders of magnitude greater than the levels (0.1 mg N litre^{-1} or 0.1 mg P litre^{-1}) considered likely to promote aquatic weed growth (MfE 1992).

With the introduction of the Resource Management Act (RMA) in New Zealand in 1991, the two-pond treatment system, with discharge to a stream, began to be phased out by regulatory authorities and is now regarded as a discretionary activity by most regional councils whereby councils retain discretion over all aspects of a consent and all applications for a consent are generally publicly notified (Parminter 1995; Heatley 1996; Cameron & Trenouth 1999). The RMA provided regional councils with the legislative control to prevent adverse environmental impacts such as discharge of nutrient-rich effluent from two-pond systems. Furthermore, the RMA stated that regional councils must recognise and provide for Maori spiritual and cultural values. Maori advocate that wastes should not be disposed of in water but returned to the land (Cameron & Trenouth 1999). Land application of FDE, taken from either an existing two-pond system or directly from a sump holding the daily wash-down of FDE, became the preferred treatment option for many of the regional councils in the 1990s (Environment Waikato 1994; Parminter 1995; Heatley 1996).

Whereas the impacts of land disposal of industrial and municipal wastes have been widely researched and reviewed (e.g., Cameron et al. 1997) and an understanding developed of what constitutes best and poor management practices, research on FDE application to land and the long-term impacts on soil chemical and biophysical quality are less common and have not been extensively reviewed.

The objective of this publication is not to provide a review of the processes involved in the treatment of effluents when applied to soil, because publications such as Cameron et al. (1997) and Bond (1998) have already extensively reviewed the technical and environmental issues associated with land treatment

of effluents. This publication aims to review published data on the land treatment of FDE in a New Zealand context with particular reference to the effectiveness of nutrient removal and implications for water quality.

SYSTEM DESIGN

The aim of land application of effluents is to utilise the soil/plant system to absorb, filter, and break-down all waste components of applied effluent, so as to minimise the risk of high nutrient loads and harmful micro-organisms leaching or draining into sources of fresh water (Cameron et al. 1997; Bond 1998; Brewer et al. 1999; Tillman & Surapaneni 2002). Land treatment allows FDE to be considered a fertiliser resource that supplies N, P, and K as well as trace elements Ca, Mg, and Na to the land in a liquid form (Hart & Speir 1992; Parminter 1995; Heatley 1996; Longhurst et al. 2000). Effluent can represent a 10–12% saving of a farm's annual fertiliser requirements; however, because FDE is not a balanced fertiliser, additional applications of P are usually required (Ledgard et al. 1996; Longhurst et al. 2000).

The source of FDE for land application is either stored effluent, which may have been partially treated, or effluent which has come directly from the yard via a sump that collects daily wash-down liquid. Such effluent is raw with no treatment and little or no settling. Storage facilities vary in size from those with the capability to hold a few days' production of effluent through to those that are able to store upwards of 2 months' effluent. Many farmers are able to use existing two-pond systems to partially treat and store very large volumes of FDE.

Small, self-propelled travelling irrigators are commonly used to apply FDE to land in New Zealand. These irrigators are generally low maintenance and have a range of operating speeds and, hence, are able to apply effluent at a variety of depths (Heatley 1996). Contract vehicle spreaders can be used to periodically draw FDE from a pond or storage facility and then apply to chosen paddocks. However, the one-off nature of such applications dictates that application rates may need to be high. Slurry stirrers can also be used to remove accumulated sludge from the bottom of ponds and apply it in the same manner (Heatley 1996). Flood irrigation can be used on free-draining soils to apply FDE via furrows and borders. Efficient surface coverage requires a well-graded land surface. Land flooding of FDE can be added to

existing border-dyke operations and can therefore be a low cost method of application, however the risk of environmental pollution is high (Heatley 1996). The soil injection method, commonly used in Europe involving the placement of effluent directly into the soil opened up with disks or tines, is not regularly used in New Zealand (Heatley 1996).

Land application of FDE in New Zealand is controlled by regional councils, who determine whether this is considered a permitted (no consent required), controlled (consent required but granted if all appropriate conditions are met), or discretionary activity (consent declined or granted at the discretion of the council). Farmers have to comply with a number of conditions stipulated by their local regional council. Conditions vary between councils but usually take into account hydraulic and nitrogen loading, proximity to waterways, neighbouring properties, and system design and maintenance. All of the regional councils rely, to some extent, on outcome-focused rules which specify that land applications should not cause effluent to enter surface water and that application depths should be set accordingly to meet this requirement (Cameron & Trenouth 1999).

The minimum area of land to be set aside for applications of FDE is usually 3–5 ha per 100 cows or no less than 10% of the total farm area. This minimum area is set by the maximum permissible annual N loading, commonly 150–200 kg N ha⁻¹ yr⁻¹ (Environment Waikato 1994; Heatley 1996; Cameron & Trenouth 1999). Selvarajah (1996) builds a case for a maximum annual effluent N loading rate of 150 kg N ha⁻¹ based on soil mineral N budgeting. He estimated that most Waikato soils would require FDE at a rate of approximately 60 kg N ha⁻¹ yr⁻¹ to meet the annual soil mineral N deficit plus another 15 kg N ha⁻¹ yr⁻¹ to replace volatilisation and denitrification mineral N losses from the applied effluent. This equates to 75 kg N ha⁻¹. Assuming that 50% of total FDE N is in the mineral N form, then FDE at the rate of 150 kg N ha⁻¹ yr⁻¹ is required to alleviate the annual mineral N deficit. However, in the long term it was noted that increased N leaching losses could be experienced due to increased mineralisation of N from the increases in the soil organic N pool.

Some regional councils do not specify either a maximum daily or per application depth, however many have adopted a range between 15–25 mm (Heatley 1996). The Dairying for the Environment Committee (Heatley 1996) recommends a maximum application rate of 10–30 mm h⁻¹ depending upon soil type.

PASTURE GROWTH RESPONSE

Application of FDE to pastures below optimum fertility (particularly those low in N) can cause marked increases in pasture yield. The nutrients taken up by the extra pasture growth can be considered to be part of the land treatment effect, temporarily associating nutrients with carbon in a non-leachable pool.

An effluent pasture growth study was carried out by Goold (1980) from 1972–76 in the Northland region, near Whangarei, on Waikare clay. Four treatments were set up: control, water-only and two application rates of raw FDE (12 and 6 mm every 21 days) irrigated from a sump. Prior to the application of FDE the site was of high fertility (Truog P level of 80). Substantial increases in annual herbage yield were measured under FDE addition (27% for the low FDE application rate and 43% for the higher rate). This increase in pasture growth was attributed to N input from the FDE as the water-only treatment provided no increase in yield compared with the control treatment and the soil already had a high P status. Average nutrient loadings from the low rate of FDE treatment were 156 kg N, 46 kg P, and 348 kg K ha⁻¹ yr⁻¹. The high rate of K input from the high rate of effluent treatment resulted in a significant ($P < 0.05$) increase in soil levels of K.

Roach et al. (2001) reported on two pasture growth trials in the regions of Taranaki and the Waikato that received applications of FDE on dairy grazed pasture. The fertility status (Olsen P) was not reported for either trial sites. FDE applications increased pasture yield of all three treatments by up to 17% and was equal to the yield increases gained by the equivalent urea N loading. Such a result suggests that there is more N available for plant uptake than the 50% available mineral N in FDE assumed by Selvarajah (1996). This could be a likely result of mineralisation of N from organic N applied previously in FDE. Measures of pasture nutrient composition indicated that levels of K had increased considerably under high rates of effluent application. Similar results were obtained in the Waikato trial where increased pasture growth as a result of FDE application ranged from 7% (75 kg ha⁻¹ yr⁻¹) to 24% (375 kg ha⁻¹ yr⁻¹).

Changes in pasture growth rates and nutrient concentration were also noted by Bolan et al. (2004) when FDE was applied to a high fertility perennial rye grass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture (Olsen P 25–30 mg P ml⁻¹) at the No. 4 dairy unit of Massey University. FDE (aerobic pond) with N, P, K, Ca, and Mg concentrations of 135, 22.1, 231, 15.2, and 11.5 mg litre⁻¹, respectively,

was applied for a 6-month period at rates of 0, 150, and 200 kg N ha⁻¹. Pasture dry matter yield increased with an increasing rate of FDE application. The dry matter response ranged from 4.1 to 7.2 kg dry matter kg⁻¹ N applied, which was approximately 60% of that achieved with a similar rate of N applied as urea. The concentration of N and K also increased with an increasing rate of FDE application. Analysis of the soil at the end of the trial indicated that increases in the rate of effluent application had decreased the content of exchangeable Ca and Mg in the soil. This was a consequence of the high K loading and leaching of anions, presumably including nitrate. To minimise this accelerated leaching, the rate and frequency of FDE application should not produce a K loading rate that exceeds the maintenance K requirement of the nitrogen-stimulated, increased pasture production.

CONTAMINATION OF SURFACE WATER BY PATHOGENS IN FDE

FDE contains varying concentrations of faecal micro-organisms which originate from dairy cattle excreta. Dairy cattle are asymptomatic carriers of micro-organisms capable of causing gastroenteritis in humans, including *Giardia*, *Cryptosporidium*, and two thermophilic *Campylobacter* subspecies, *C. jejuni* and *C. coli* that are responsible for almost all human cases of campylobacteriosis. When raw or partially treated FDE reaches fresh-water bodies, micro-organisms potentially within the FDE have the capability of contaminating the water as a drinking source (Donnison & Heatley 1996; Ross 2003). *Campylobacter jejuni* is the principle bacterial hazard for recreational water users or those drinking untreated water (McBride et al. 2002).

Aislabie et al. (2001) investigated the movement of bacterial indicators through lysimeters containing four differently structured Waikato soil types. FDE was applied at 50 mm h⁻¹ followed by simulated rainfall at 5–10 mm h⁻¹ until one pore volume of leachate had been collected. The two free-draining soils (Waihou and Atiamuri) with a uniform porous structure which encouraged matrix flow of water, transported considerably fewer microbes than the coarse-structured, poorly drained soils (Te Kowhai and Netherton) which exhibited preferential bypass flow of drainage through large macropores. The public health impact of such microbe contamination depends on the destination of the drainage water (ground versus surface water bodies).

McLeod et al. (2003) compared the movement of faecal coliforms with a chemical tracer (bromide) in a free-draining and poorly drained soil in the Southland region. A volume of 25 mm FDE spiked with a bacteriophage was applied to soil lysimeters followed by one pore volume of rainfall at 5 mm h^{-1} . It was found that phage movement peaked early in the flow (approximately 0.15 pore volume) and then tailed off, indicating bypass flow through larger macropores. The bromide tracer moved more uniformly through the soil, entering more of the micropore system profile (matrix flow), and the concentration peaked at approximately 0.5–0.8 pore volume. The results indicated that the rapid transmission of faecal microbes to surface or ground waters could occur when FDE was applied to soils with the potential for larger amounts of bypass flow such as those with installed mole and pipe drainage.

More recently, Donnison & Ross (2003) have reported the occurrence of *Campylobacter jejuni* in water exiting mole and pipe drainage system soils in West Otago. It was found that on the occasions when preferential flow (also termed bypass flow) of raw, spray-irrigated, FDE occurred through the mole and pipe network, the concentrations of campylobacter were similar to those in the applied effluent (10^5 campylobacter 100 ml^{-1}).

NUTRIENT LEACHING LOSSES RESULTING FROM APPLICATION OF FDE

For a land treatment system to be sustainable it must be efficient in both the storage of effluent in the soil and the subsequent uptake of plant nutrients applied in the effluent. The longer the effluent resides in the soil's active root zone, the greater the opportunity for the soil to physically filter the effluent whilst absorbing nutrients and making them available to plants. Most of the research related to nutrient dynamics under land treatment of FDE has focused on quantifying aspects of nutrient movement, in particular leaching losses. Such losses can be measured in the direct drainage of untreated or partially treated effluent, immediately following irrigation events or in the drainage that occurs in the succeeding winter. The studies are reported below.

Research conducted by Macgregor et al. (1979) on a mole and tile drained Tokomaru silt loam at Massey University's No. 4 dairy farm found that approximately 90% of N and 98% of P from partially treated FDE was retained by the soil system. However, nutrient losses were prevalent at times

when soil moisture conditions permitted the rapid movement of effluent through the subsurface drainage. The permanent pasture site was spray irrigated with 20–30 mm of pond-treated FDE every 10–15 days throughout the lactation season. The authors found that when cumulative evaporation usually exceeded cumulative rainfall, no drainage resulted from spray irrigations of FDE. When the soil was close to or at field capacity, up to 30% of the applied effluent volume drained through the mole and pipe network. Annual nutrient inputs of $1125 \text{ kg N ha}^{-1}$ and 125 kg P ha^{-1} were added as FDE. The measured annual nutrient losses were a total of 150 kg N ha^{-1} and 1.6 kg P ha^{-1} . Of the nutrients lost, $90 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and $0.6 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ exited in winter drainage. Drainage losses from a grazed pasture system without added FDE were $30 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and $0.1 \text{ kg P ha}^{-1} \text{ yr}^{-1}$.

At the same research site, Cooke et al. (1979) found that the quantity of effluent preferentially exiting the soil as drainage was strongly related to soil and climatic conditions. Under saturated soil moisture conditions, when effluent irrigations coincided with natural rainfall (47 mm), they measured 78 mm of drainage following an application of 30 mm of FDE. Under summer conditions, 18 mm of drainage was recovered from an application of 24 mm of FDE when there was a soil water deficit of 6 mm. A total of three irrigation events were intensively monitored and nutrient inputs and drainage losses characterised. Analyses of nutrient loss in the drainage found that the soil was more efficient at removing particulate forms than dissolved forms. The presence of strongly sorbed anions such as P in drainage provided evidence that some untreated FDE drained via preferential flow pathways. Approximately 20% of both the N and P spray irrigated onto land was leached through the mole and tile drainage system during the drainage events.

Further research investigating an improved method for the land treatment of FDE (deferred irrigation, application only when a suitable soil water deficit exists) was also established on a mole and pipe drained Tokomaru silt loam at the No. 4 dairy farm of Massey University (Houlbrooke et al. 2003). Winter drainage following the summer applications of FDE using the deferred irrigation criteria resulted in no increase in leaching losses of $\text{NO}_3^- \text{-N}$ (Fig. 1). There was a 3.3 kg N ha^{-1} increase in total N lost in winter drainage from soils receiving summer applications of FDE. This represented 3.5% of the N applied in effluent. Farm-dairy effluent application also resulted in greater concentrations of dissolved

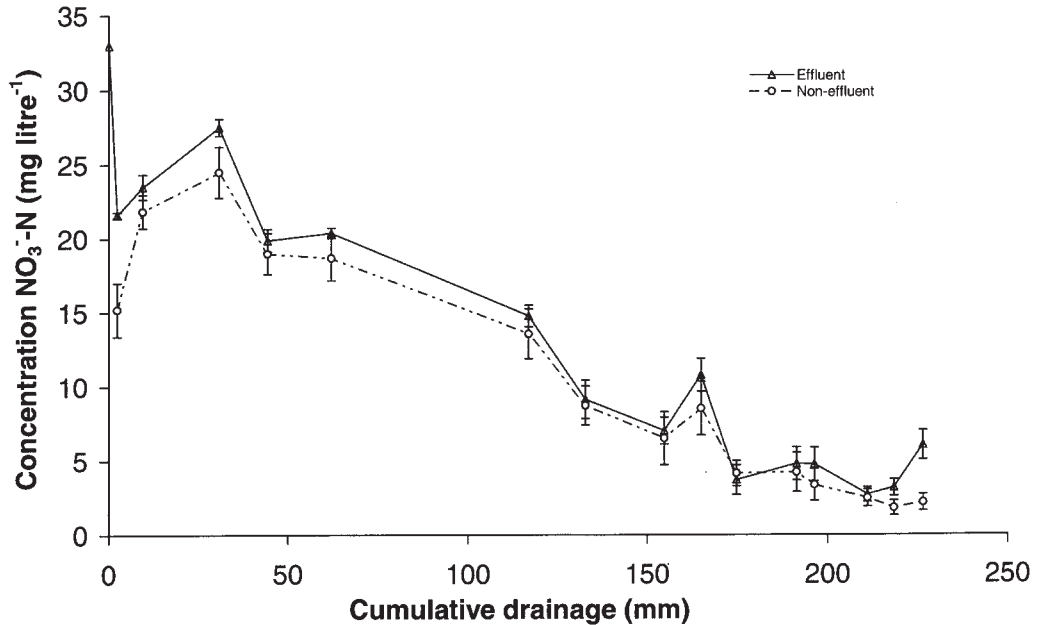


Fig. 1 The trends in drainage NO₃⁻-N concentration with total amount of accumulated drainage, in both the non-effluent and effluent plots. Error bars represent one standard error (from Houlbrooke et al. 2003).

inorganic P being leached throughout the winter drainage period (Fig. 2). However, the annual loss of total P (0.52 kg ha⁻¹) equated to approximately only 3% of the P applied in summer applications of effluent.

Longhurst et al. (1999) applied raw FDE at six loading rates of N (ranging from 0 to 375 kg N ha⁻¹ yr⁻¹) to ungrazed pastures on a well-drained Horotiu silt loam at the No. 1 Dairy Unit at Ruakura, Hamilton. FDE was applied 17 times, at 4–7-day intervals, from January to April 1997. Pasture yield over a year was found to have increased by up to 24% above the control. The efficiency of N use decreased with increasing FDE loading rates. At 75 kg N ha⁻¹, equivalent N recovery by plant uptake was 85%, however, at the 375 kg N ha⁻¹ rate the rate of N recovery was only 40%. Nitrate-N (NO₃⁻-N) leachate was collected using ceramic cup collectors during the subsequent winter drainage period (5 June–3 October), which was dryer than average (only 80% of the expected annual 1200 mm rainfall for 1997). The average concentration of leachate in winter drainage from the 375 kg N ha⁻¹ treatment was 0.76 versus 0.42 mg NO₃⁻-N litre⁻¹ from the control, with a calculated NO₃⁻-N loss of 2.1 and 1.2 kg N ha⁻¹. This would appear to be very low and is partly attributable to the absence of any cattle-grazing effects

eliminating the leaching from urine patches and the low volume of winter drainage.

A laboratory incubation was undertaken by Barkle et al. (2001) using Te Kowhai silt loam to investigate soil immobilisation and mineralisation of N from a standard (302 mg N litre⁻¹) and high (1011 mg N litre⁻¹) rate of FDE application. The high application concentration was achieved by the addition of extra faeces and urine to ensure that substantial microbial growth resulted. At the standard rate of FDE addition, net N immobilisation persisted throughout the period of the experiment; however, at the high rate of FDE application, net N mineralisation occurred after day 113.

Barkle et al. (2000) used lysimeters to investigate the rate at which soil organic matter was mineralised from raw FDE applied to an ungrazed Te Kowhai silt loam soil. The authors suggest that due to increased N mineralisation from the accumulating soil organic matter, N fertilisation should be decreased on FDE application sites. It was found that FDE application to land could only be sustained in terms of N leaching when the supply of inorganic N was continually matched by pasture uptake. However, a constraint to substituting FDE N for fertiliser N is that increased available N is most needed in winter and early spring when climate conditions do not

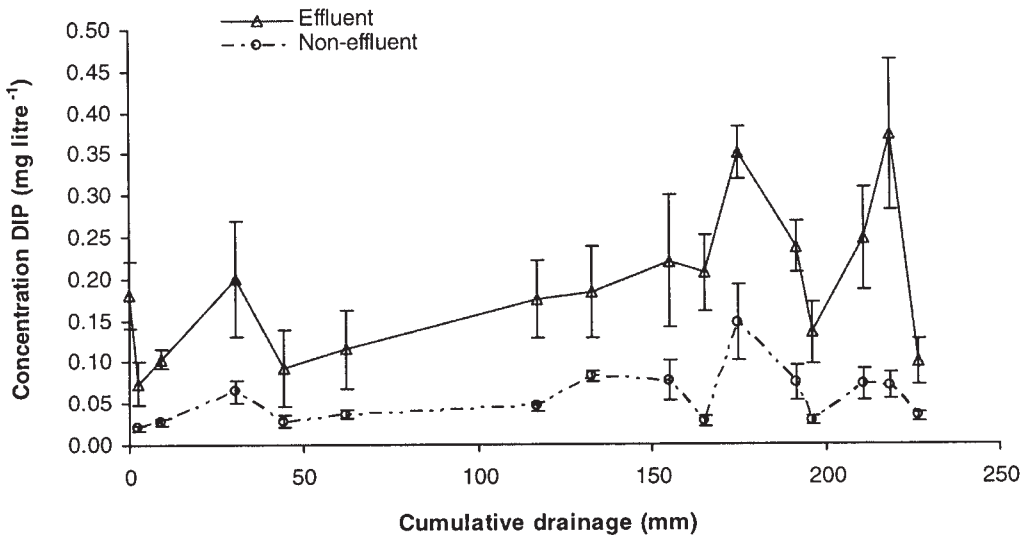


Fig. 2 The impacts of effluent irrigation on dissolved inorganic P (DIP) concentrations. Error bars represent one standard error (Houlbrooke et al. 2003).

favour rapid N mineralisation. At this time N-boosted pasture growth is required to meet increasing feed requirements at the start of lactation. With FDE application, although the organic-N pool is increased, the larger pool may not increase N availability due to lack of mineralisation during the critical time for pasture requirements.

Roach et al. (2001) applied urea and pond-treated FDE to an Egmont brown loam at rates of 100, 200, and 400 kg N ha⁻¹ yr⁻¹ to grazed dairy pastures near Hawera, in the Taranaki region. Eight, monthly applications were made from September to April. NO₃⁻-N leaching from any direct FDE drainage and winter drainage was measured using ceramic cup samplers in conjunction with lysimeters and showed that the three treatments had average NO₃⁻-N concentrations of 7, 8, and 20 mg N litre⁻¹ which resulted in annual N losses of 18, 20, and 50 kg N ha⁻¹ yr⁻¹.

A lysimeter study was established by Singleton et al. (2001) on a Te Kowhai silt loam soil on the No. 1 Dairy Unit at Ruakura, Hamilton, to investigate N leaching of FDE when drainage is managed by controlling the water table. The treatments used were raw FDE and water. The lysimeters were irrigated weekly with raw FDE at a very low instantaneous application rate of 4 mm h⁻¹ (less than the saturated hydraulic conductivity) to minimise the loss of raw effluent via preferential flow. A weekly total of

17 mm of FDE was applied which corresponded to approximately half the water-holding capacity of the top 20 cm of the soil profile. Drainage was managed using a weir to maintain the water table at depths of 25, 50, or 75 cm below the soil surface. In the first season, a total of 511 kg N ha⁻¹ yr⁻¹ was applied as FDE, and leaching losses of approximately 33 kg N ha⁻¹ were measured. In the medium (50 cm) and high (25 cm) water table treatments, these losses under FDE application were approximately double those receiving the equivalent amount of water only. In the second season, the loading rate of FDE was increased to 1518 kg N ha⁻¹ yr⁻¹ and a total of 131 kg N ha⁻¹ was leached from the soil, approximately 100 kg more than the equivalent water-only treatment. The high water table (25 cm below soil surface) treatment resulted in less N being leached in a nitrate-N form (but a higher organic-N loss) than the lower water table treatments; this was believed to be attributable to the likely enhanced denitrification resulting from the higher water table.

A number of lysimeter studies have been reported from Lincoln University on free draining soils looking at the impacts of dairy farm practices (including the applications of FDE and urea) on NO₃⁻-N and NH₄⁺-N leaching losses. Di et al. (1998) applied a total of 400 kg N as raw FDE by either flood irrigation or spray irrigation over two split irrigations on a Templeton fine sandy loam soil. Throughout the

length of the trial (December 1995–March 1997) a total of 799 and 359 mm of drainage was collected from the flood irrigation and spray irrigation treatments. After the first application, neither treatment had concentrations of nitrate-N in drainage any higher than the control (<1 mg N litre⁻¹). It was suggested that low nitrate-N concentrations in the summer should be expected as a result of microbial immobilisation of mineral N, denitrification during irrigation, and plant uptake. Raw FDE has only a very low NO₃⁻-N concentration and FDE moving through soil macropore systems and recovered as drainage water will carry little nitrate-N despite having a large total-N concentration. Following the second FDE application (May 1996), the nitrate-N concentration in drainage from the spray irrigation and flood irrigation treatments increased to 17 and 10 mg N litre⁻¹. The lower concentration measured in drainage from the flood irrigation treatment was attributed to an increased denitrification loss occurring after this method of applying FDE. NO₃⁻-N losses at the 400 kg N ha⁻¹ yr⁻¹ application rate were lower for FDE than from N fertiliser, indicating less mineralisation and nitrification of FDE-N.

Silva et al. (1999) applied raw FDE at 200 or 400 kg N ha⁻¹ yr⁻¹ in four split applications to a Templeton fine sandy loam soil either with or without 1000 kg N ha⁻¹ of added urine (believed to be the approximate loading of N in a urine patch). A total of 1328 mm of water was applied as either rainfall or irrigation and resulted in the collection of 410 mm of drainage. Without urine, the total NO₃⁻-N leaching loss was 6.3 and 10 kg N ha⁻¹ from the 200 and 400 kg N ha⁻¹ yr⁻¹ treatments. This represented a 2.5–3.2% annual loss of the N originally applied as FDE. When urine was applied to the lysimeters, the calculated paddock loss, taking into account the likely relative proportion of urine and non-urine patches, was 46.5 kg N ha⁻¹ as NO₃⁻-N from the 200 kg N ha⁻¹ treatment (14% of the N applied as urine plus FDE) whilst the 400 kg N ha⁻¹ treatment had a lower loss of 35.8 kg N ha⁻¹ (10% of the total N applied as both urine and FDE).

Di & Cameron (2002) also flood irrigated a Lismore stony silt loam soil with raw FDE at total loading rates of 200 and 400 kg N ha⁻¹ yr⁻¹ over four split applications from April 1998 to March 2000. A total water input (irrigations and rainfall) of 1400 mm for year 1 and 1700 mm for year 2 resulted in 610 and 880 mm of drainage. Peak drainage concentrations of NO₃⁻-N following applications of FDE were 21.3 and 34.2 mg N litre⁻¹ for the 200 and 400 kg N ha⁻¹ yr⁻¹ treatments. The annual loss of NO₃⁻-N

was considerably different between the 2 years that the experiment was conducted. Year 1 had losses of 55 and 78.3 kg N ha⁻¹ for the 200 and 400 kg N treatments, whilst year 2 had much smaller losses of 7.6 and 18.7 kg N ha⁻¹ for the 200 and 400 kg N treatments. These losses represent approximately 10% for year 1 and 2.5% for year 2 of the total N originally applied as FDE. Interestingly, smaller NO₃⁻-N losses were measured in the second year despite the fact that year 2 had a greater cumulative drainage of water than year 1. The difference in NO₃⁻-N losses between years was explained by the effects of initial pasture renovation at the beginning of the trial causing a release of mineral-N through the mineralisation of organic-N in decaying plants.

Cameron et al. (1999) reviewed a number of different effluent research trials completed at Lincoln University and concluded that the rate at which FDE is applied to land influences the quantity and therefore risk of N leaching. Results were reported showing peak drainage water concentrations of 10–18 mg N litre⁻¹ (depending on irrigation conditions) when FDE was applied in two split applications of 200 kg N ha⁻¹ yr⁻¹. The peak concentration was, however, decreased to 4 mg N litre⁻¹ when the FDE was applied in four split applications of 100 kg N ha⁻¹ yr⁻¹.

An investigation of the status of soil physical and chemical properties following 6 years of raw FDE applications was reported from a Wairarapa dairy farm under long term dairy pasture by Hawke & Summers (2003). No changes in soil physical properties (saturated hydraulic conductivity, porosity and bulk density) were found. A significant increase in total Kjeldahl-N and cations (K⁺, Na²⁺, Ca²⁺, Mg²⁺) was measured in the top 10 cm of soil. Olsen P levels increased from 56 to 76 µg P g⁻¹ in a soil that has a low P retention. It was deemed that pasture nutrient requirements could be sustained using FDE. It was, however, noted that the C:N ratio had dropped from 28:1 to 20:1, and that the change in soil N dynamics may have long-term implications for mineral N leaching.

Roygard et al. (2001) investigated the effectiveness of several different tree species at removing mineral-N from soils that were receiving applications of pond-treated FDE. A bare ground treatment was used as a control. The research involved a lysimeter study using a Manawatu fine sandy loam soil receiving weekly applications of FDE at a rate of 21.5 mm per application throughout the entire lactation season. The total quantity of N applied in the FDE over the season was 236 kg N ha⁻¹. Average

NO_3^- -N concentrations of leachate collected from the lysimeter were higher than the New Zealand drinking water standard ($11.3 \text{ mg N litre}^{-1}$) for all treatments. However, NO_3^- -N concentration in the drainage from two of the tree species (*Eucalyptus nitens* and *Salix kinuyangi*) (26 and $19 \text{ mg N litre}^{-1}$ respectively) was significantly lower than the bare soil treatment ($40 \text{ mg N litre}^{-1}$). It was found that tree species varied in evapotranspiration rates and their ability to take up N. The deciduous tree species *S. kinuyangi* maintained the lowest N leachate concentration prior to harvest. The lysimeters restricted the root zone laterally but not the canopy, so the projected canopy area exceeded the soil surface area for the root zone and subsequently affected the drainage rates.

IMPLICATIONS FOR WATER QUALITY

The consensus view of the research cited above is that land treatment of FDE to trap nutrients in soil is relatively effective, with only 2–20% of the nutrients applied in the FDE being transported to fresh water bodies either as immediate drainage or as nutrient leaching from FDE-applied soils. This represents a considerable reduction of the quantity of nutrients that discharge from a two-pond system directly into receiving fresh water bodies. However, in many cases, particularly those with very high loading rates of FDE where there was an increased likelihood of preferential flow of partially treated FDE, the concentration of NO_3^- -N being leached was above the New Zealand drinking water standard ($11.3 \text{ mg N litre}^{-1}$). This has particular implications for FDE application to free-draining soils whose drainage waters recharge regional aquifer systems that commonly provide drinking water to rural communities. The health risk posed by drinking water that is high in nitrate is greater for babies and young children who may be prone to the blood disorder called methaemoglobinaemia. The result of such a disorder is a reduction in the oxygen-carrying capacity of the blood stream; hence the condition is often known as “blue baby syndrome”. The health risk of drinking microbial contaminated water can be more severe on human health than that of water high in nitrate, potentially causing severe gastroenteritis. In particular this can be an issue in rural water supplies which are commonly untreated.

In all the reported studies, the concentrations of N and P (if measured) were higher than the levels ($0.1 \text{ mg N litre}^{-1}$ and $0.1 \text{ mg P litre}^{-1}$) considered

likely to promote aquatic weed growth (MfE 1992). Such high levels of N and P are likely to encourage algal blooms and aquatic plant growth that deplete oxygen levels in the water, resulting in a decrease in biodiversity in the stream (Bond 1998; Cameron & Trenouth 1999).

The Resource Management Act (1991) states that effluent application to land should not have any adverse effect on aquatic life (Parminter 1995; Cameron & Trenouth 1999). It appears that standard dairy farming practices of cattle grazing (leaching from urine patches) and fertiliser applications is more responsible (particularly at a farm scale) than is land application of FDE for elevated levels of nutrients leached into groundwater systems, streams, and lakes (Silva et al. 1999; Di & Cameron 2002; Monaghan et al. 2002a; Houlbrooke et al. 2003). Of most importance is the careful management of land treatment systems to prevent the direct discharge of raw or only partially treated effluents.

CONSIDERATIONS FOR IMPROVED FDE LAND APPLICATION

A number of areas can be identified where there are shortcomings with the current management of FDE application to land. Goold (1980), Roach et al. (2001), and Bolan et al. (2004) reported high levels of potassium (K) in both soil and pastures following long-term applications of FDE to land. Longhurst et al. (2000) reported, in a survey of FDE characteristics, that the concentration of K was usually 80% of the concentration of N. The typical concentration range of N and K found in ryegrass pasture is 2–4% and 1–3% (McLaren & Cameron 1996). Nitrogen is commonly used to determine the maximum nutrient loading to land (often $150\text{--}200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). At such rates K will be applied to the soil at loadings of $120\text{--}160 \text{ kg ha}^{-1} \text{ yr}^{-1}$, which is far in excess of the $50\text{--}90 \text{ kg K ha}^{-1} \text{ yr}^{-1}$ required for maintenance of K reserves in the soil. When K is applied to soil at far greater than maintenance requirements, the resulting high K levels in pasture and decrease in calcium and magnesium can induce metabolic disorders in dairy cows, particularly milk fever (hypocalcaemia) and ryegrass staggers (hypomagnesaemia) (Roach et al. 2001; Tillman & Surapaneni 2002).

Soil physical characteristics have a considerable impact on the effectiveness of any land treatment system for FDE as the continuity of macropores can have a considerable effect on the preferential flow of water, particularly in soils with mole and pipe

drainage. Preferential flow of water (and nutrients) occurs through natural soil macropores such as continuous cracks and earth-worm channels (McLay et al. 1991). Furthermore, when mole and pipe drainage has been installed to ameliorate poor drainage, large macropores are created above the ripped mole channel which promote drainage by by-pass flow. Drainage by-passes a great deal of the soil matrix, exiting the mole system through the pipe drain (Kladivko et al. 1991; Kohler et al. 2001).

The soil moisture status of the land receiving application must be considered because during periods when rainfall exceeds evapotranspiration (usually May to October) soil water is at, or close to, field capacity and water may move freely through the soil profile. As both Cooke et al. (1979) and Macgregor et al. (1979) reported, applications of FDE at times of low soil moisture deficit resulted in large quantities of drainage and hence nutrient losses.

The large range of nutrient losses reported for applications of FDE has less to do with the initial nutrient content of the effluent (pond versus sump) and is likely to be related to the quantity of effluent applied, the management of effluent, and soil moisture condition at the time of effluent application (Table 1). Many of the research trials reported above applied effluent in a number of split applications across the drier summer months, hence minimising the direct losses of effluent. No trials have reported the common practice of irrigating FDE daily throughout the lactation season (August–May) from a small wash-down sump at the farm dairy. Such a practice inevitably involves applying FDE to the

soil at times when there is little or no soil moisture deficit, such as early spring and late autumn. The range of percentage losses reported suggests that management of effluent, particularly with regard to the soil moisture status at the time of application, may play a large part in determining the likelihood of nutrients from FDE directly draining, or being retained in the soil profile. In many cases the research reported has applied FDE at extremely high rates of N application, far in excess of the 150–200 kg N ha⁻¹ commonly stipulated by regional councils in New Zealand. It could be argued that there is a need for more research to be undertaken under more realistic farm conditions for the application of FDE.

Recent research by both Monaghan & Smith (2004) and Houlbrooke et al. (2004) has investigated improved methods for land applying effluent to artificially drained soils. FDE should not be applied to soil based simply on its theoretical ability to absorb nitrogen. Effluent applications should be made with regard to current soil moisture status and soil physical characteristics such as soil structure and hydraulic properties. Both research trials found that applications must be applied only at times of suitable soil moisture deficit to avoid the preferential flow of applied FDE and hence the direct drainage of partially treated effluent that is likely to have a significant adverse impact on the receiving water bodies. Adequate pond storage is required to hold FDE at times during the lactation season such as early spring when the soil is commonly close to or at field capacity with low soil water deficit. Such

Table 1 Amount of N loss from a range of different applications, rates, and forms of farm dairy effluent (FDE).

Source	FDE source	FDE rate (kg N ha ⁻¹ yr ⁻¹)	Application criteria	% applied N lost
Macgregor et al. (1979) ^a	Pond	1125	20–30 mm every 10–15 days	10
Di et al. (1998) ^b	Raw	400	2 × 200 kg N ha ⁻¹	7
Silva et al. (1999) ^b	Raw	200	4 × 50 kg N ha ⁻¹	2.5
Silva et al. (1999) ^b	Raw	400	4 × 100 kg N ha ⁻¹	3.2
Roach et al. (2001) ^c	Pond	100	Monthly at 12.5 kg N ha ⁻¹	18
Roach et al. (2001) ^c	Pond	200	Monthly at 25 kg N ha ⁻¹	10
Roach et al. (2001) ^c	Pond	400	Monthly at 50 kg N ha ⁻¹	12.5
Singleton et al. (2001) ^d	Raw	511	17 mm applied weekly	7
Singleton et al. (2001) ^d	Raw	1518	17 mm applied weekly	9
Houlbrooke et al. (2003) ^a	Pond	95	7 applications of c. 9 mm	3.5

^aTokomaru silt loam; ^bTempleton fine sandy loam; ^cEgmont brown loam; ^dTe Kowhai silt loam.

a system has been called “deferred irrigation” by Houlbrooke et al. (2004) and has been successful in minimising nutrient losses as a result of the direct drainage of partially treated FDE and in many cases has eliminated them altogether.

It has been identified that there was a lack of research in New Zealand carried out under realistic farm conditions, in particular with regards to the sometimes excessive N and P loadings used. Furthermore it could be argued that there has been a lack of research at a farm scale and even to some extent at a paddock scale from dedicated long-term effluent blocks within a farm dairy. There is a need for more data to be collected at the farm scale from such blocks on the impacts of long term irrigation of FDE on nutrient leaching and pasture quality and its potential associated animal health impacts. To date there has been a lack of research published on the extra difficulties associated with land treating poorly drained soils that have had artificial drainage such as mole and pipe installed, although there has been some recent research on this carried out in both the Manawatu and Otago regions. Improved strategies are required to assist farmers to land treat FDE in a sustainable manner.

SUMMARY

Traditionally FDE has been treated in standard two-pond systems and then discharged into receiving fresh water streams. Changes brought about primarily due to the RMA of 1991 meant that most regional councils now prefer the land treatment of the FDE. Conditions under the resource consent process often stipulate maximum N loading rates and hydraulic application rates and an effects based clause. FDE is often applied to land by way of small travelling irrigators and is utilised by the soil-plant system for its water and nutrients. Historical research on the effects of land treating FDE on water quality showed that between 2–20% of the N and P applied as FDE is directly leached through the soil profile, therefore entering receiving fresh water bodies. In all cases, the concentrations of leachate in drainage waters were higher than the ecological limits considered likely to stimulate unwanted aquatic weed growth, however this is also true of non-irrigated, grazed dairy pastures.

Whilst the land treatment of FDE represents a huge improvement on the loss of nutrients discharged to fresh water from standard two-pond

systems, there is still room for improvement in the management of FDE land treatment systems. It has been identified that the applications of FDE at times of zero, or very small, soil water deficit, such as those moisture conditions found in early and late lactation are more likely to result in the direct drainage of only partially treated effluent. Furthermore, free-draining soils and soils with artificial drainage may be prone to the rapid movement of applied effluent by the process of preferential flow through large macropores. Improvement in the management of land applications can be made to prevent the direct discharge of partially treated FDE by taking into account soil physical properties and soil moisture status and by having the capability to store FDE for extended periods when soil moisture conditions are unsuitable for application.

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