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Soil biochemical properties as indices of performance and sustainability of effluent irrigation systems in New Zealand—a review

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Abstract In New Zealand, there have been a number of investigations of the effects on soil biochemical properties of land application of industrial and sewage effluents. In recent years, the rationale for determining these properties has been to ascertain if they have a potential role as early warning indicators of adverse effects of effluent irrigation on treatment sustainability and/or soil health. In this review, I summarise the findings from these studies and attempt to establish whether the data do support this role. Assessment of biochemical effects of the application of effluents to land under crops, forest, or scrub is complicated by previous land management and by site characteristics. Consequently, only investigations of effluent application onto pastoral soils have allowed an assessment of the potential value of soil biochemical properties as early-warning indicators of adverse effects. Generally, these studies have shown that effluent application has had a beneficial effect on soil properties and plant growth and this is reflected by enhanced soil biochemical activities. Where an adverse effect did occur in response to a drastic change of effluent amount and composition, soil biochemical properties were markedly reduced. However, soil chemical properties and aggregate stability were unaffected. This suggests, therefore, that there could be a role for biochemical properties as indices of performance and sustainability of land-based effluent irrigation systems. However, with most studies showing that most effluent application is beneficial, such a role may be limited to situations where the effluent is to be applied at an amount, or has a composition that has not been previously tested. The main conclusion from this review is that when irrigation schemes have been running for a number of years and are functioning well, soil biochemical properties reflect the soil health enhancements provided by the water and nutrients added. Such enhancements are generally manifested slowly and, therefore, monitoring is required over a longer duration than has occurred in several of the studies examined. Adverse effects attributable to effluent irrigation are more difficult to recognise and interpret unless a drastic change has occurred, due mainly to methodological limitations and our lack of understanding of the true meaning of what we are measuring or its relevance to soil functioning. Until our understanding improves markedly, a predictive role for these properties as an early warning of adverse effects of effluent irrigation will remain elusive.

Keywords effluent irrigation; soil biochemical properties; microbial biomass; enzyme activities; denitrification; soil health; sustainability

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INTRODUCTION

In New Zealand, land application of treated effluents from domestic and industrial sources has become an accepted and culturally desirable method of disposal of an unwanted waste, while returning valuable nutrients and organic matter to the land. Our resource management legislation (the Resource Management Act 1991 (RMA)) places an emphasis on environmental protection and on safeguarding the life-supporting capacity of, among other things, the soil. This is not merely a New Zealand initiative, as maintenance of soil quality is of international importance and is a major driver of research in many countries (Doran & Parkin 1994), including New Zealand (Schipper & Sparling 2000). Consequently, in establishing a land treatment system, it is important to ensure that the most appropriate soils are used and management practices implemented, to prevent degradation of land and excessive loss of nutrients into surface- and ground-water. Therefore, the emphasis for obtaining a resource consent under the RMA has been on assuring that: (1) the chosen site has appropriate soils and sufficient land area to adequately cope with the hydraulic load; (2) that the irrigation design minimises soil saturation and bypass flow; and (3) that losses of nutrients (especially N as nitrate) and other components of the effluent are minimised. However, apart from an acknowledgment of the potential consequences of irrigation with effluents containing high salt loading and/or having high pH (Rhoades 1972; Cameron et al. 1997; Russell et al. 1998), there has been scant recognition that more gradual soil changes will inevitably occur under intensive, long-term irrigation with nutrient- and/or organic-rich effluents, and of the issues for sustainable land management that may arise as a consequence. Soils are a product of their environment and any long-term change of physical, chemical, or biological status, induced by a large increase in water throughput and nutrient/organic-C addition, could give rise to a "new" soil with an altered capacity to cope with continued irrigation. Cook et al. (1994) found that 3 years of irrigation of a volcanic soil (Ngakuru sandy loam, an Allophanic Soil (Hewitt 1998)), under *Pinus radiata*, with secondary (2°)-treated Waipa sawmill effluent (combined industrial and domestic) resulted in a 78% decline of ponded infiltration rate, possibly attributable to clogging of soil pores. Although this decline was inconsequential for this highly permeable soil, the authors recommended that monitoring of soil hydraulic properties should be an essential part of any scheme for land treatment of wastewater. This would be especially important in situations where the initial infiltration rate and the effluent application rate were more similar. A long-term decline in soil C content could occur if the effluent is C-poor and nutrient-rich, but an increase is also possible if the effluent is C-rich. Increasing or decreasing C content could lead to changes of soil structure, porosity, and hydraulic characteristics. Of course, conversely, soil properties might change in ways that could improve soil quality and "fitness for use" through enhanced infiltration rate or elevated C and nutrient content, leading to increased microbial activity, soil fertility, and/or denitrification activity.

Most land treatment schemes include a monitoring regime to check that the operation continues to perform to the required specifications. However, the emphasis is generally on ensuring that crop health is maintained, or that ground-water and/or surface water quality are not adversely affected, i.e., that the soil continues to function as a "filter". Gradual adverse changes in other soil functions, e.g., hydraulic conductivity, leaching of nutrients, plant productivity, and structural integrity, may not be noticed until it is too late to rectify the problem without seriously compromising the continued operation of the land treatment scheme. To prevent these situations arising, we need to identify soil properties that are sensitive to such changes while they are still minor. These can, therefore, be used to predict that a change of irrigation conditions is required, to ensure that continued effluent application is sustainable in the long term and will not ultimately lead to soil degradation. Soil biological and biochemical properties have long been regarded as having an appropriate role in the assessment of soil "health" (defined as "the continued capacity of a soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" (Doran & Safley 1997)), because soil as a whole can be thought of as a living, biological entity (Quastel 1946). Agents that suppress or poison soil organisms or change the quality or quantity of organic matter can damage the functioning of the soil-plant ecosystem (Brookes & Verstraete 1989). Soil biological and biochemical properties have, therefore, been used extensively in assessment of soil changes that may arise from changing agricultural practices or as a response to soil amendments and/or pollution (e.g., Brookes 1995; Pankhurst et al. 1997; Cameron et al. 1998; Giller et al. 1998; Speir & Ross 2002). However, it is also well recognised that major problems exist in interpreting results obtained from these assessments. For example, we can only speculate on the relevance of a change of activity of a specific soil property in response to a land management effect when it is known that natural fluctuations attributable to precipitation and temperature may be at least as large (Brookes 1995; Rapport et al. 1997). Soil enzymes that exist primarily in a stabilised, extracellular state (Kiss et al. 1975) may be less sensitive to these natural fluctuations and it has been proposed that they may have a role in identifying positive or negative effects of land management practices before there are measurable changes in organic matter (Dick 1994). However, extracellular enzymes have no known role and, in addition, we measure their activity using substrates and assay conditions that are far removed from those found in soil. This means that it may be even more difficult to interpret soil enzyme results than those from assays of microbial biomass and activity (Speir & Ross 2002).

In this paper, I will review New Zealand land-based effluent treatment studies that have included assessment of soil biochemical properties, including microbial activity and biomass, nutrient dynamics, and enzyme activities. Such properties have been used in numerous international studies as indices of soil "health" and soil quality changes brought about by altering land management practices and the application of pesticides and contaminants to soil (Dick 1994; Pankhurst et al. 1997; Giller et al. 1998; Speir & Ross 2002). The predictive value of these properties, from the perspective of providing an early warning of potentially serious adverse changes in soil health and treatment sustainability in land subjected to application of industrial and sewage effluents, will be evaluated. Farm effluents, e.g., dairy shed effluent, are not included because I have not found any references that include soil biochemical properties being measured in such studies.

MEAT AND PELT PROCESSING EFFLUENTS

Ross et al. (1982) investigated the effects on soil biochemical properties of long-term border-dyke (flood) irrigation with effluent from two meat-processing plants in South Island, New Zealand. At Canterbury Frozen Meat Company's Fairton works near Ashburton, effluent had been irrigated since 1899 onto Lismore silt loam soil (a Brown Soil (Hewitt 1998)). The block of land investigated had received a mixture of main works (slaughterhouse) and fellmongery effluents (predominantly the former) since at least 1940. Typical effluent composition is shown in Table 1; note that c. 8% of the total effluent flow comprised fellmongery effluent. At Waitaki New Zealand Refrigerating Limited's works in Islington, near Christchurch, the site investigated had received effluent of similar composition for at least 20 years and irrigation was onto Waimakariri fine sandy loam (a Recent Soil (Hewitt 1998)). Both soils were freely draining, effectively preventing ponding and run-off problems

Table 1 Typical Fairton effluent composition (from Keeley & Quin 1979). COD, chemical oxygen demand; SAR, sodium adsorption ratio.

	Fellmongery ($mg\ l^{-1}$)	Slaughterhouse ($mg\ l^{-1}$)	Loading rate ($kg\ ha^{-1}\ yr^{-1}$)	Pasture requirements ($kg\ ha^{-1}\ yr^{-1}$)
pH	11.4	10.2	–	–
COD	4000	4100	–	–
Suspended solids	1800	1900	–	–
Total N	220	100	920	0*
Total S	500	50	460	20
Total P	0.5	7	65	20
Cl	2200	280	2580	0
Na	2000	230	2120	0
Ca	300	140	1290	20
Mg	10	7	65	0
SAR ($mmol^{0.5}\ l^{0.5}$)	6.0		–	–
Flow ($m^3\ day^{-1}$)	380	4500	–	–

*Assuming all N supplied by clover.

Table 2 Chemical and biochemical properties of Lismore soil irrigated with mixed slaughterhouse and fellmongery effluent or water, and of Waimakariri soil irrigated with mixed slaughterhouse and fellmongery effluent (Ross et al. 1982). *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

	Fairton (Lismore)		Winchmore (Lismore)		Islington (Waimakariri)	
	Effluent	Control	Water	Control	Effluent	Control
pH	6.3	6.2	6.0	6.2*	6.1	6.3
Total C (%)	6.8	5.6**	3.9	4.7**	3.8	4.6***
Total N (%)	0.63	0.39***	0.31	0.36**	0.35	0.36
Respiration ($mg\ C\ kg^{-1}\ h^{-1}$)	15.5	8.2***	7.9	8.1	5.9	6.2
Biomass C ($mg\ C\ kg^{-1}$)	2890	810***	1360	870**	1430	800***
Δ-Min N ($mg\ N\ kg^{-1}$)	178	36***	51	44	82	45**
Amylase ($nmol$ product $g^{-1}\ s^{-1}$)	0.35	0.21*	0.23	0.15**	0.23	0.18*
Cellulase ($pmol$ product $g^{-1}\ s^{-1}$)	64	63	61	63	68	71
Invertase ($nmol$ product $g^{-1}\ s^{-1}$)	4.21	2.70**	2.16	1.96*	3.22	1.97**
Phosphatase ($nmol$ product $g^{-1}\ s^{-1}$)	3.03	1.64***	1.75	1.46**	2.25	1.67*
Sulphatase ($pmol$ product $g^{-1}\ s^{-1}$)	1.16	0.15***	0.52	0.17*	0.41	0.15***
Urease ($nmol$ product $g^{-1}\ s^{-1}$)	5.17	0.43***	1.40	0.45*	1.68	0.49***

during irrigation (Ross et al. 1982). A non-irrigated control site was sampled at both locations and a water-only border-dyke irrigated site, together with a non-irrigated control, both on Lismore silt loam, were sampled at Winchmore Irrigation Research Station for comparison. At Winchmore, the irrigated site had received water to maintain summer soil moisture content at 20% for c. 30 years. At all three locations, the experimental plots were under permanent grass-clover pastures and all, except the Islington effluent treated sites, were grazed by sheep or cattle.

Chemical and biochemical properties of the soils, as measured in samples collected in September (early spring) 1978, are presented in Table 2. All samples were composites comprising 20 or 30 soil cores (2.5 cm diam., 0–5 cm depth). With the exception of cellulase enzyme activity in both effluent and water treatments and Δ-min N (net mineral N production over 14 days aerobic incubation at 25°C) in the water-only irrigated soil, all biochemical properties were significantly greater in the irrigated than in the control soils. This is supported by highly significant correlations ($P < 0.001$) of all biochemical properties measured, except cellulase, with soil moisture content (Ross et al. 1982). Obviously, elevated soil moisture in these normally summer-dry soils is responsible for much of the enhanced biochemical activity. This would maintain high pasture growth, which would feed back into stimulated soil biological activity.

Generally, the magnitude of the difference between irrigated and control soils was greater under effluent irrigation, and greatest in the soil (Lismore at Fairton) that had been irrigated for the longest time (Table 2). This is indicative of enhanced soil fertility derived from the effluent C and nutrients, manifest in the significantly decreased C:N ratio and significantly increased N mineralisation capacity of the effluent irrigated soils, compared with the water irrigated soil (Table 2). In addition, total P and plant-available (Olsen) P in the top 150 mm of soil from the effluent treatment area at Fairton were more than double and nearly an order of magnitude greater, respectively, than in the control soil (Keeley & Quin 1979).

In this study, the enhanced biochemical activities related directly to increased nutrient cycling and productive capability (Ross et al. 1982) and were, therefore, indicative of improved soil fertility resulting from irrigation (effluent and water). There was no visible or anecdotal evidence that adverse effects on soil structure and/or hydraulic conductivity had occurred as a result of long-term irrigation with mixed slaughterhouse and fellmongery effluent. However, not surprisingly considering the very large inputs, high proportions of the effluent components (e.g., 42% of the N and >50% of all other elements listed in Table 1, except P) were lost in drainage (Keeley & Quin 1979). In this situation, the soil may not have been adversely affected, but the effluent treatment efficiency has been compromised by the high loading rate and the type of irrigation. As might be expected, considering their relationship with soil fertility and nutrient status, biochemical properties did not give any indication that this was likely to occur.

Subsequent to this study, a new greatly enlarged pelt processing plant was built at Fairton. This led to a much greater effluent discharge and a marked change in effluent composition, most noticeably increased Na^+ content. The sodium adsorption ratio (SAR) (Russell et al. 1998) increased from a mean value of 6 in the combined effluent before the new plant was commissioned (Table 1) to generally >20 following commissioning (G. M. Keeley unpubl. data). Although the relationship between effluent SAR and exchangeable Na content in the soil is complicated by rainfall and evapotranspiration at the irrigation site (Russell et al. 1998), an effluent SAR of 20 or more would probably result in the soil exchangeable Na concentration becoming excessively high. This could ultimately lead to organic matter dissolution (Menneer et al. 2001), and/or deflocculation of clays (Russell et al. 1998), both of which could cause soil structural deterioration and result in reduced hydraulic conductivity.

In 1984, the Fairton site was sampled again and the biochemical analyses were repeated. At this time it was noted that much of the grass on the site had been killed and the bulk soil was clearly more weakly structured (Churchman & Tate 1986). In spite of these observations, the increased Na loading had not yet affected the exchange complex of the Lismore soil (fully base saturated, 84% as Ca^{2+}) and the organic C and total N contents of the soil were essentially unchanged (Table 3) (Speir et al. 1988). Macroaggregate stability was also unaffected, possibly because the method of measurement was not sufficiently sensitive (Churchman & Tate 1986). However, most soil biochemical properties were substantially lower in 1984 than in 1978 (Table 3). This indicates that microbial biomass (mineral N flush (Table 3) is a measure of microbial biomass N) and activity, and the more integrative enzyme activities, could possibly serve as early warning indicators of potentially serious adverse effects before soil chemical and physical properties show any change. However, this study did not indicate whether these biochemical tests were any more reliable indicators than much more straightforward visual observations, which also indicated that, by 1984, a serious problem had occurred at this site. It would have been very useful to have monitored biochemical properties immediately after the change of management to determine if they responded sooner than plants to the adverse conditions.

DAIRY FACTORY EFFLUENTS

Degens et al. (2000) compared samples of Horotiu silt loam, an Allophanic Soil (Hewitt 1998), near Cambridge, from adjacent dairy farms, one of which had been irrigated for 22 years with dairy factory effluent. In the top 10 cm of the soil, they found a 4-fold greater microbial biomass C content and a 50% greater basal respiration in the irrigated than in the non-irrigated soil. This particular effluent comprised cleaning materials and by-products of milk processing, including a high proportion of lactose. Substrate utilisation tests indicated that the large microbial biomass and activity in the surface soil from the irrigated farm were supported by this available C and would be unlikely to accelerate the degradation of soil organic matter (Degens et al. 2000). Indeed, it was demonstrated that there had been no loss of total C in the top 75 cm of soil, compared with adjacent non-irrigated soils.

In a further investigation on the same dairy farms, Sparling et al. (2001), also using 0–10 cm topsoil samples, measured a number of physical, chemical, and biological properties of irrigated and non-irrigated Horotiu soil and of the contrasting Te Kowhai clay loam (a Gley Soil (Hewitt 1998)). The biological properties were generally very much greater in

Table 3 Chemical and biochemical properties of the effluent-irrigated Lismore soil at Fairton before (1978) and after (1984) effluent sodicity increased (Speir et al. 1988).

Property	1978	1984
Soil pH	6.3	6.9
Organic C (%)	6.8	6.8
Total N (%)	0.63	0.67
Δ-Min N (mg kg^{-1})	178	115
Mineral N flush (mg kg^{-1})	254	182
Invertase (nmol product g^{-1} s^{-1})	4.21	2.89
Urease (nmol product g^{-1} s^{-1})	5.17	1.28
Phosphatase (nmol product g^{-1} s^{-1})	3.03	2.97
Sulphatase (nmol product g^{-1} s^{-1})	1.16	0.91

the irrigated than in the non-irrigated soils (Table 4). Microbial biomass contents in the irrigated soils were several times greater than has previously been reported for any mineral soils and comprised 7% of the total C (Sparling et al. 2001). This very high biomass and high general biological activity was again attributed to the high lactose content of the dairy factory effluent. Unsaturated hydraulic conductivity was also greater in the irrigated soils, so the changes in soil properties that have occurred can generally be considered beneficial, as they would increase the treatment of applied effluent without adversely affecting effluent application rates or pasture production (Sparling et al. 2001).

In 1991, the Tui Dairy Factory commenced irrigating their effluent onto dairy cattle grazed pastureland on Manawatu silt loam soil (a Recent Soil (Hewitt 1998)), near Pahiatua. Some mean wastewater composition data from the 1992/93 and 1993/94 seasons indicated a high pH effluent (11.4), with relatively high conductivity (1870 $\mu S\ cm^{-1}$), chemical oxygen demand (COD) (2020 $g\ m^{-3}$), NO_3-N (103 $g\ m^{-3}$), and total P (22 $g\ m^{-3}$) (G. Upchurch, Fonterra Research Centre, pers. comm.). After 3 years of irrigation, soil pH was very significantly higher in the irrigated soil, compared with an adjacent non-irrigated control (Table 5) (T. W. Speir & L. A. Schipper unpubl. data). Some biochemical properties (0–5 cm soil depth) were also significantly different in the irrigated soil (Table 5) (T. W. Speir & L. A. Schipper unpubl. data), but, unlike in the above-mentioned study of Sparling et al. (2001), some activities were lower in the irrigated soil. For the enzyme activities at least, this may have been largely attributable to the increase in soil pH. In an incubation experiment, soil phosphatase activity was shown to be reduced markedly when the soil pH was raised from 5 to 7 (Speir et al. 1992).

Table 4 Biological properties of Horotiu and Te Kowhai topsoils after 22 years' irrigation with dairy factory effluent (Sparling et al. 2001). *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

	Horotiu		Te Kowhai	
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Microbial biomass C ($mg\ cm^{-3}$)	3.7	1.3***	3.5	1.9***
Respiration ($\mu g\ C\ cm^{-3}\ h^{-1}$)	1.7	1.1**	1.9	1.4*
Mineralisable N ($\mu g\ N\ cm^{-3}$)	230	105***	200	112**
Nitrification potential ($\mu g\ N\ cm^{-3}\ h^{-1}$)	3.0	0.3**	4.2	0.09***
Denitrifying activity ($\mu g\ N\ cm^{-3}\ h^{-1}$)	4.4	0.9**	1.2	0.7

Table 5 Soil pH and biological properties of Manawatu silt loam topsoil near Pahiatua after 3 years' irrigation with dairy factory effluent. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

	Irrigated	Non-irrigated
Soil pH	7.9	6.8***
Respiration ($\mu l\ CO_2\ g^{-1}\ h^{-1}$)	12.8	10.5**
Microbial biomass C ($mg\ C\ g^{-1}$)	1.55	1.75*
Sulphatase ($nmol$ product $g^{-1}\ s^{-1}$)	0.73	0.82*
Phosphatase ($nmol$ product $g^{-1}\ s^{-1}$)	2.29	3.82**
Invertase ($nmol$ product $g^{-1}\ s^{-1}$)	4.88	5.46
Mineralisable C ($\mu l\ CO_2\ g^{-1}\ h^{-1}$)	10.5	8.8*
Mineralisable N ($\mu g\ N\ g^{-1}$)	93	75

While the above studies have shown that 22 years and 3 years of irrigation with dairy factory effluents have resulted in significant changes in soil properties, a further investigation on Taupo shallow fine sandy loam (a Pumice Soil (Hewitt 1998)) showed that 2 years' irrigation with dairy factory effluent caused no significant changes in soil biological properties (Sparling et al. 2001). This suggests that the loading rates on this site, and/or the composition of this effluent, have not yet been sufficient to induce change.

BIOGAS DIGESTER EFFLUENT

An energy farm trial was established in 1978 at Invermay Research Centre, Mosgiel, to determine whether the effluent from anaerobic digestion of crops to produce biogas (a mixture of CH_4 and CO_2 of similar composition to natural gas) could serve as a maintenance fertiliser for continuous energy farming (Speir et al. 1988; Ross et al. 1989). Three treatments were established: (1) return of digester effluent; (2) application of N, P, K, and S as mineral fertiliser; and (3) water only. All treatments received the same volume of liquid by spray irrigation and the mineral fertiliser was applied in the irrigated water. The soil (Dukes silt loam, a Pallic Soil (Hewitt 1998)) was sampled in late 1978 after ploughing and after each maize harvest of the 2-year crop rotation, i.e., in April 1979, 1981, 1983, and 1985. Before ploughing the site had been in grazed ryegrass/clover pasture for 7 years.

Soil chemical and biochemical properties (0–8 cm soil depth) are shown in Fig. 1. Soil C and N remained constant throughout the trial, indicating that 6 years of intensive cropping had not depleted soil organic matter. Cumulative crop yields were not greatly influenced by treatment, but crop nutrient contents were greatly reduced in the water-only treatment (data not shown). With the exception of respiration and invertase enzyme activity, soil biochemical properties declined, with the fertiliser treatment usually declining more than the other treatments. This overall decline probably reflects a general diminution of readily mineralisable C substrates following the transition from pasture to cropping. This has resulted in declining microbial biomass and a concomitant loss of other biochemical activities. The organic C returned in the effluent, although it may have stimulated respiration to some extent (Fig. 1), would have largely comprised intransigent organic materials resistant to the digestion process, and might not be expected to influence the decline of microbial biomass in this treatment. Soil invertase activity is strongly influenced by the extent and nature of plant cover (Ross 1976) and this would account for it behaving differently from the other activities.

Overall, returning biogas digester effluent to the land had a neutral effect on soil properties when compared with the other treatments. The declining biochemical activities were probably indicative of a shift towards a new equilibrium as a result of the conversion from grazed pasture to cropping. However, considering the extent of the decline of microbial biomass and urease activity, it must be hoped that the new equilibrium condition was reached soon after the experiment finished. In 1986, a mini-trial was set up on one of the water-only control plots. The trial comprised 20 plots variously treated with effluent, fertiliser, or water, as above, and was sampled annually from 1986 to 1989. The results of chemical and biochemical analyses have not been published because there were few significant differences between treatments (D. J. Ross pers. comm.). Within this plot, properties such as biomass C, sulphatase, and phosphatase also showed little variation between years and did not appear to be trending downwards as before, perhaps indicating that equilibrium had been attained.

SEWAGE EFFLUENTS

Ross et al. (1978) investigated the effect on soil biochemical properties of irrigating pastoral soils with 2°-treated sewage effluent. Large cores were taken from 10 North Island soils and irrigated with effluent or water for 16 months. Samples were then taken for analysis of

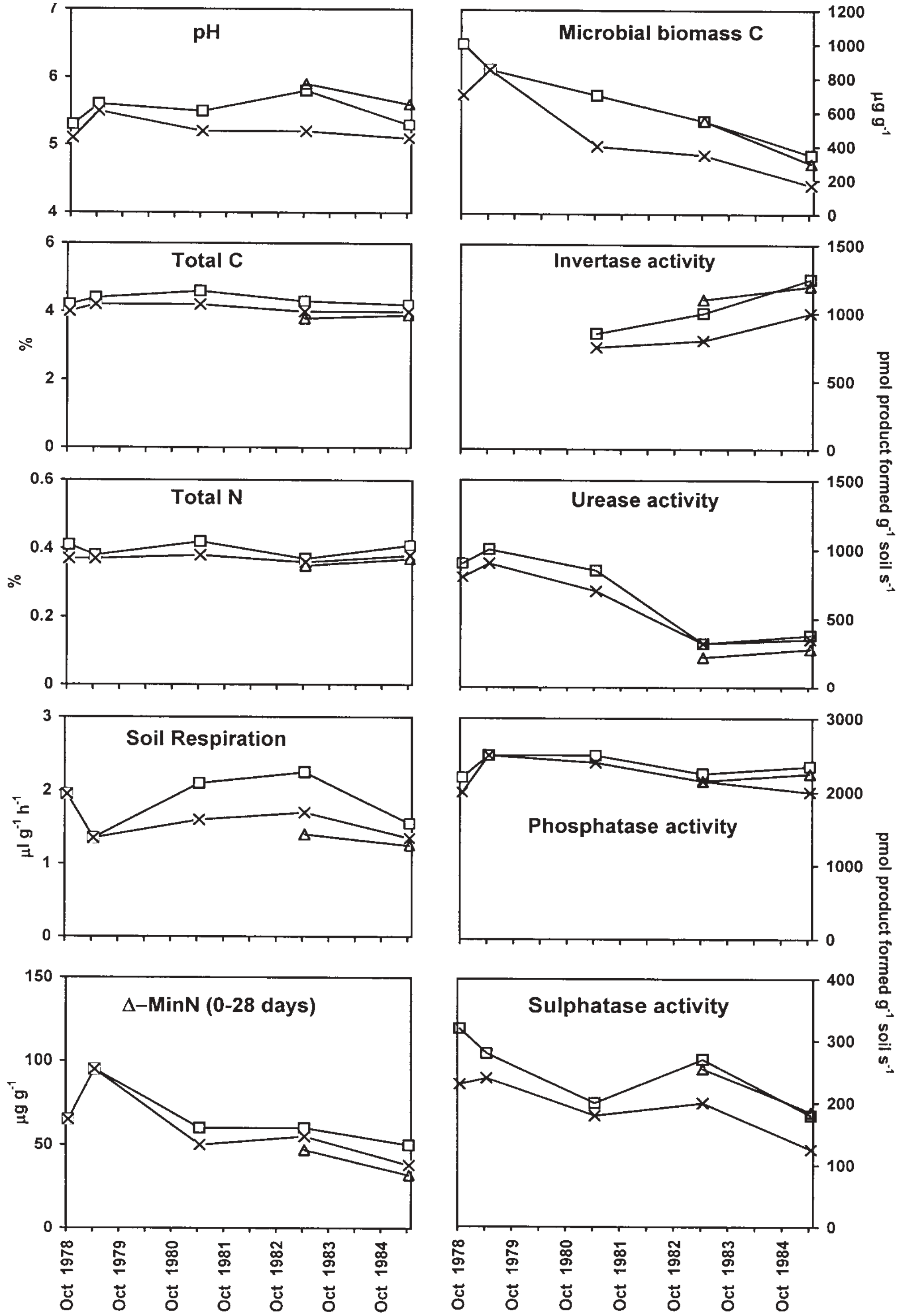

Fig. 1 Soil chemical and biochemical properties of cropped treatments irrigated with biogas digester effluent (□), inorganic fertilisers (×), and water (control) (△) (from Speir et al. 1988).

respiration, microbial biomass, and invertase, amylase, urease, phosphatase, and sulphatase enzyme activities. Differences between effluent-irrigated and water-irrigated cores of each soil were small and very rarely significant (Ross et al. 1978). In addition, there was no trend, significant or not, for higher activities to be found in the available-C enriched effluent-treated cores.

All other studies involving assessment of biochemical effects of sewage effluent on New Zealand soils have been conducted on soils under exotic forest (*Pinus radiata*) or under mixed native forest/scrub.

Rotorua City tertiary (3°)-treated sewage effluent has been spray-irrigated into Whakarewarewa Forest (*P. radiata*) since 1991 and during the early stages of the operation a trial was set up to investigate different effluent application rates. To separate the effects of effluent constituents and water loading on soil properties, water at the same loading rates was irrigated onto a small area of the forest that was not receiving effluent. At the same time, another trial was established at Waitarere, a coastal settlement north of Levin. Here, low-grade 2°-treated effluent was spray-irrigated into a mature *P. radiata* forest. The soils at the two sites were of similar texture, although of greatly different parent material: Ngakuru sandy loam, formed from volcanic tephra, and Waitarere sand (a Recent Soil (Hewitt 1998)), formed in coastal sand dunes. One purpose of these investigations was to compare the effects of irrigation with two very different sewage effluents (effluent compositions shown in Table 6) on soil biochemical properties. At both sites, soil samples were composited from 0–5 cm depth soil cores.

Schipper et al. (1996) provided a summary of the results from the Whakarewarewa trial (Table 7). A more detailed analysis of the data over the 3 years of the trial (T. W. Speir & L. A. Schipper unpubl. data, available from the author on request) mainly highlights the difficulty of sampling in a dissected and undulating terrain, and where the soils have undergone considerable disturbance from the forestry operations. For example, total C and total N increased each year in one of the control plots, and in 1994 were both nearly double the initial 1992 values. Such properties would be expected to remain relatively constant on non-irrigated areas of the forest over such a short time interval and the differences are almost certainly artefacts of sampling. The increase of total C has markedly affected the enzyme activities sulphatase and phosphatase, which normally relate strongly to soil organic C content. Indeed, all biochemical properties increased substantially in this plot over the 3 years of sampling. Consequently, although some significant effects were observed when results were averaged across the 3 years (Schipper et al. 1996) (Table 7), it is probably not

Table 6 Average composition (mg l^{-1}) of Whakarewarewa 3° effluent and Waitarere 2° effluent. Whakarewarewa data from Schipper et al. (1996). Values are means (and SDs) of 29 analyses from October 1991 to February 1994. Waitarere data are means (and SDs) of 24 analyses from August 1993 to November 1994, except for pH and suspended solids, which are means (and SDs) of 14 analyses from August 1992 to October 1993. BOD, biochemical oxygen demand.

Property	Whakarewarewa	Waitarere
pH	7.2 (0.2)	6.5 (0.4)
BOD	6.0 (1.5)	80 (20)
Suspended solids	5.5 (1.8)	170 (149)
Dissolved reactive P	3.5 (2.2)	51 (13)
Ammonium N	3.3 (2.3)	3.1 (3.4)
Nitrate N + nitrite N	6.5 (2.8)	49 (15)

Table 7 Mean soil biological and chemical properties of Whakarewarewa irrigated and control plots (effluent-irrigated, 3-year means, 1992–1994; water-irrigated, 2-year means, 1992–1993). Adapted from Schipper et al. (1996). Irrigation rates differ from those quoted in Schipper et al. (1996) as a result of updated information provided by M. Tomer, New Zealand Forest Research. LSD, least significant difference ($P < 0.05$).

Property	Units	Control	Effluent-irrigated		Water-irrigated		LSD
			64 mm week^{-1}	102 mm week^{-1}	64 mm week^{-1}	102 mm week^{-1}	
Total C	%	7.8	8.1	7.7	6.1	7.1	2.0
Total N	%	0.39	0.41	0.40	0.30	0.34	0.11
Basal respiration	mg CO_2 C kg^{-1} h^{-1}	8.53	9.49	9.94	8.21	8.11	3.19
Microbial biomass C	mg C kg^{-1}	915	872	886	887	854	109
Sulphatase	µmol kg^{-1} s^{-1}	0.62	0.59	0.61	0.52	0.47	0.18
Phosphatase	µmol kg^{-1} s^{-1}	3.36	2.65	2.77	2.62	2.63	0.57
Invertase	µmol kg^{-1} s^{-1}	1.53	2.29	2.81	1.40	1.49	0.66
Denitrification	mg N_2O-N kg^{-1} h^{-1}	0.085	0.158	0.201	0.083	0.090	0.070
Mineralisable C	mg CO_2-C kg^{-1} h^{-1}	4.15	4.27	4.41	2.93	3.06	0.88
Water-soluble C	mg C kg^{-1}	154	191	154	105	105	37
Mineralisable N	mg N kg^{-1}	57	75	104	28	19	42

acceptable to attribute them to irrigation by effluent or water. Denitrification rate and invertase activity were consistently higher in the effluent-irrigated soils and increased with increasing effluent loading rate. For denitrification, this could be attributed to the greater nitrate concentration in the soil and the inputs, although small, of C in the effluent (Schipper et al. 1996). This increase would be beneficial because it would enhance the removal of N and reduce nitrate leaching. As also shown by Barton et al. (1999), denitrification was probably not enhanced in the water-only irrigated treatments because of excessive aeration in these freely draining soils. The increase of invertase activity could be attributed to greater plant growth (primarily grasses and weeds) that occurred on the effluent irrigated plots. Schipper et al. (1996) concluded that the application of 3°-treated waste had not adversely affected the biological functioning of the soil.

At the Wairarere site, irrigation commenced in 1985 and on the sampled plots the average application rate was c. 60 mm week^{-1}. The 2°-treated effluent was greatly inferior in quality to that being applied at Whakarewarewa (Table 6) and marked differences in effects on soil properties might therefore have been expected at the two locations. In addition, effluent had been applied for 7 years when the sampling commenced, whereas application had only just commenced at Whakarewarewa. However, as at Whakarewarewa, any effects were to some extent masked by the variability found in the control plots, both within and between years. These plots contained large amounts of very decomposed branches and, due to incomplete canopy closure, there was considerable undergrowth of grass, bracken, and scrubby plants. In contrast, the long duration of nutrient- and C-rich effluent application had enhanced tree growth and canopy closure and this had resulted in much less undergrowth in the effluent-treated plots.

Three-year mean results from 0–5 cm depth samples are presented in Table 8. Total C and, perhaps surprisingly, total N were not significantly different in the effluent-treated plots than in the control plots. This could be due to movement of C and N down the soil profile, either through enhanced earthworm activity in the effluent-treated plots, or directly by leaching under the influence of the irrigation regime. To support this contention, a one-off sampling in 1994 showed that there was considerably more C located between 5 and 15 cm depth in the irrigated plots (mean 2.8%, SD 1.5%) than in the control plots (mean 0.6%, SD 0.2%) (L. A. Schipper, Landcare Research, pers. comm.).

When the Waitarere biochemical properties are compared with those at Whakarewarewa, it is immediately apparent that there are considerable differences in the responses to irrigation at the two locations (cf. Tables 7 and 8). In all 3 years, biomass C was significantly lower in the irrigated soil. Sulphatase and phosphatase activities were also generally lower under irrigation, although for sulphatase especially, this was mainly due to high enzyme activity in one of the control plots; invertase was not affected. Irrigation for 7 years with nutrient- and C-rich effluent does not appear to have stimulated general microbial activity. This is a surprising result and tends to belie visual evidence that fallen branches, stumps, and pine needle litter were more decomposed or absent on the irrigated plots. Denitrification activity was three orders of magnitude greater in irrigated than non-irrigated plots, where activity was extremely low (zero in one plot). This 2°-treated effluent would be very conducive to enhancing denitrification activity, but considering the high nitrate loading rate and the sandy texture of the soil, significant removal of N by this mechanism would seem unlikely. An interesting feature of the mineralisable C results is that they mirror, almost exactly, the phosphatase activities ($r = 0.92^{***}$, $n = 12$). Mineralisable C, CO_2 respired from re-wetted air-dried soil over 7 day's incubation (Burford & Bremner 1975), is a surrogate measure of biomass C, and these two properties would be expected to correlate highly significantly. At both Waitarere and Whakarewarewa they do ($r = 0.93^{***}$, $n = 12$, and 0.85^{***}, $n = 15$, respectively). However, only at Waitarere was there a good correlation between phosphatase activity and biomass C ($r = 0.95^{***}$, $n = 12$); at Whakarewarewa the coefficient was 0.39^{NS} ($n = 15$). This result may indicate that practically all, if not all, of the phosphatase activity in this Waitarere sand soil is located in the microbial biomass. This is a surprising result

Table 8 Three-year mean (1992–1994) soil biological and chemical properties of Waitarere irrigated and control plots.

Property	Units	Control	Effluent-irrigated
Total C	%	4.5	4.2
Total N	%	0.17	0.20
Basal respiration	mg CO_2 C $kg^{-1} h^{-1}$	2.8	2.1
Microbial biomass C	mg C kg^{-1}	763	436
Sulphatase	µmol kg^{-1} s^{-1}	0.26	0.19
Phosphatase	µmol kg^{-1} s^{-1}	3.14	2.03
Invertase	µmol kg^{-1} s^{-1}	0.79	0.83
Denitrification	mg N_2O-N $kg^{-1} h^{-1}$	0.00015	0.200
Mineralisable C	mg CO_2-C $kg^{-1} h^{-1}$	2.4	1.4
Water-soluble C	mg C kg^{-1}	158	80
Mineralisable N	mg N kg^{-1}	5.2	24

because it makes this soil an exception to the accepted wisdom that a considerable proportion of soil enzyme activity, including phosphatase, is found as a stabilised, extracellular component (Kiss et al. 1975; Skujins 1976). The increase of mineralisable N in the Waitarere irrigated plots is probably indicative of enhanced mineralising capability due to the high organic N content of the effluent and a decrease in the C:N ratio in the irrigated plots (3-year means 26 and 21 in the control and irrigated plots, respectively).

Overall, the lack of increase and probable decline of soil microbial activity in the 2°-treated effluent-irrigated Waitarere soil may be indicative that adverse changes have occurred. Why this effluent should cause this effect, when a high nutrient, high biochemical oxygen demand (BOD) dairy factory effluent greatly enhanced microbial activity and biomass (Sparling et al. 2001) (Table 4), is unknown. However, it is possible that the sewage effluent, by increasing the nutrient status of this low-fertility soil, had already caused extensive mineralisation of the litter and available soil organic matter by the time the experiment started. The irrigated soil may now contain a smaller but more active microbial population with a different composition from that in the infertile control soil. It is also possible, however, that a genuine detrimental effect has occurred, possibly caused by an unmeasured component of the effluent.

In 1995, Hutt City Council set up a trial to investigate the feasibility of spray irrigating 2°-treated sewage effluent onto steeply sloping land. The site chosen was typical of the land available for irrigation in the vicinity of the Wainuiomata sewage treatment plant, which is located in a narrow valley enclosed by steep hills. The trial site was 3.36 ha and straddled the toe-end of a ridge, with approximately equal areas on each side of the ridgeline. The hillsides have average slopes of 30° and the vertical height from valley floor to ridge crest within the trial area is 60 m. Native forest had been cleared from the hills during the latter part of the 19th century and the reverting shrubby vegetation was periodically burnt until the early 1960s. At the start of the trial, gorse (*Ulex europaeus*), bracken (*Pteridium esculentum*), and the native shrub hangehange (*Geniostoma rupestre* var. *ligustrifolium*) were dying on the drier upper and mid slopes and being replaced by native species including ponga (*Cyathea dealbata*) and mahoe (*Melicytus ramiflorus*). On the concave lower slopes, 5- to 7-m-tall, secondary-growth forest of mahoe and ponga had already replaced gorse and bracken. The soils on the trial site are predominantly Taita hill soils (Atkinson 1973; Heine 1985), classified as Ultic Soils (Hewitt 1998), and developed in weathered greywacke and a thin veneer of loess, which mantles the hills. A preliminary report had indicated that these soils were suitable for irrigation, being capable of absorbing 45 mm of applied precipitation before becoming saturated, and that irrigation could be applied at a rate of 7 mm h^{-1}.

Irrigation commenced in early June (winter) 1995 and ceased in late August 1996. Effluent was applied at a rate of 3.5–4 mm h^{-1} for 11 h on one day every week (design rate, 42 mm $week^{-1}$). Mean effluent quality over a 10-month period is shown in Table 9.

Table 9 Average composition of 2°-treated Wainuiomata effluent measured on grab samples taken on 10 occasions from June 1995 to March 1996 (Speir et al. 1999). BOD, biochemical oxygen demand.

Property	Average concentration (mg l^{-1})	Concentration range (mg l^{-1})
BOD	26	8–64
Total Kjeldahl N	47	23–115
Ammonium-N	19	7–32
Nitrate-N	11.5	5.0–19.0
Dissolved reactive P	7.2	5.3–9.1

Speir et al. (1999) measured soil physical, chemical, and biochemical properties in three plots within the trial area and a single control plot. The plots were: "Top Site", located just below the crest of the ridge; "Steep Site", on the steep mid-slope; and "Bottom Site", on the lower forested slope, within 20 m of the valley floor. These plots were representative of the dominant landscapes, with the Steep Site probably representing over 50% of the trial area. The fourth plot ("Control Site") was a non-irrigated control, up-ridge from the trial with a similar landscape position to the Top Site. Soils were sampled (composite samples each comprising 25 cores 0–5 cm depth) in early February 1995 (pre-irrigation), early February 1996 (mid-irrigation), and late January 1997 (post-irrigation).

Results of the biochemical analyses are shown in Table 10. There was a significant increase in mineralisable NH_4^+-N (Δ-Min NH_4^+-N), determined after aerobic incubation for 14 days (Ross et al. 1982), at the Top and Bottom Sites in Year 2. This property then declined markedly in the irrigated plots in Year 3, with net losses of NH_4^+-N occurring on incubation of the soils. In contrast, Δ-Min NO_3^--N had not significantly changed in Year 2, but increased markedly and significantly at the Top and Steep Sites in Year 3. These results suggest that, before irrigation commenced, the soils, with the exception of that at the Bottom Site, showed little nitrification capacity. Low rates of nitrification have been linked to low levels of inorganic P in soils (Hue & Adams 1984; Pastor et al. 1984); the Bottom Site was the only location where the soil was not P-deficient, as measured by Olsen-P concentration. The increase of Δ-Min NH_4^+-N at the irrigated sites in 1996 is probably indicative of enhanced N-mineralisation in response to nutrient and water application. There was, however, no significant enhancement of nitrification at this time, and, indeed, nitrification rate declined, although not significantly, at the Bottom Site. By 1997, however, the nitrification rate was such at all three irrigated sites that all mineralised N, and a large proportion of the NH_4^+-N, was nitrified during incubation. This could indicate that nitrifying populations take time to build up to effective levels in these previously nutrient-deficient soils. Basal respiration increased significantly in all plots, including the Control Site in Year 2, but had declined to near its initial level by Year 3. The only significant differences in substrate-induced-respiration (SIR) biomass C were at the Steep and Bottom Sites in Year 3, whereas the fumigation-extraction (FE) biomass C was always lower, usually significantly, in Year 2, but had generally recovered to near initial concentrations by Year 3. These two methods purportedly measure the same property, microbial biomass C, so such differences are difficult to explain. Phosphatase activity in Year 3 was significantly lower than in Year 1 at the Top and Steep Sites, but there were no significant changes in sulphatase activity.

Pre-irrigation soil chemical analyses showed that the Bottom Site was inherently more fertile than the other sites, undoubtedly because it received colluvium, detritus, and run-off from up-slope. Biochemical and chemical analyses during and after the irrigation period demonstrated that soil fertility had increased markedly at the Top and Steep Sites in response to effluent irrigation and that the irrigation area as a whole had an N-mineralisation capacity at least equivalent to a high fertility pasture soil (Speir et al. 1999). Apart from the Δ-Min N results, the only biochemical property that had responded to effluent irrigation was phosphatase enzyme activity. This declined at the Top and Steep Sites in response to increasing soil P content. A negative relationship between soil phosphatase and P fertility is recognised (Nannipieri et al. 1978; Speir & Cowling 1991). This is probably due to repression of enzyme synthesis rather than direct inhibition of existing enzyme activity, although inorganic P is a feedback inhibitor of phosphatase. This repression mechanism is probably responsible for the Bottom Site having a much lower phosphatase activity than the other sites, because it had a much higher native P-fertility.

Table 10 Wainuiomata effluent treatment site soil biochemical properties in 1995 (pre-irrigation), 1996 (during irrigation), and 1997 (post-irrigation) (Speir et al. 1999). 1996 and 1997 data followed by **a** are significantly ($P < 0.05$) different from the 1995 data, within each site. 1997 data followed by **b** are significantly ($P < 0.05$) different from the 1996 data, within each site.

Soil location	Year	Water content	Δ-Min NH_4^+-N	Δ-Min NO_3^--N	Basal respiration	Substrate-induced respiration biomass C	Fumigation-extraction biomass C	Phosphatase activity	Sulphatase activity
		% OD wt	(mg kg^{-1})		mg CO_2-C kg^{-1} h^{-1}	mg C kg^{-1}		µmol p-nitrophenol	kg^{-1} s^{-1}
Control Site	1995	23.7	20	0.6	6.5	1510	1980	10.3	0.41
	1996	31.1	28	1.3	10.5 **a**	1410	1540 **a**	9.8	0.35
	1997	24.5	22	13	6.4 **b**	1610	1820 **b**	10.1	0.42
Top Site	1995	30.5	–4.3	0	7.0	1370	1770	10.7	0.57
	1996	63.3 **a**	29 **a**	8.2	15.2 **a**	1150	1440 **a**	9.6	0.60
	1997	28.1 **b**	–1.9	72 **a,b**	8.0 **b**	1310	1450 **a**	8.2 **a**	0.54
Steep Site	1995	26.9	34	15	6.7	980	1590	10.0	0.43
	1996	56.4 **a**	40	10	14.9 **a**	1100	1370	9.9	0.54
	1997	18.6 **b**	–18 **b**	73 **a,b**	8.6 **b**	1590 **a,b**	1470	8.0 **a**	0.73
Bottom Site	1995	30.4	2.8	54	7.5	1040	1630	3.9	0.88
	1996	58.9 **a**	48 **a**	22	13.8 **a**	1150	1330 **a**	4.2	0.81
	1997	17.9 **b**	–18 **b**	52	5.9 **b**	1610 **a,b**	1760 **b**	4.0	0.85

One year's irrigation has obviously not been sufficient to markedly change soil microbial biomass on these plots. There was also no indication that effluent irrigation was changing soil chemistry (except for P and N status) or soil physical properties, and the water quality data indicated that effluent treatment and renovation would likely have been sustainable in the medium term at least (Speir et al. 1999).

GENERAL DISCUSSION

What do soil biochemical properties tell us about treatment sustainability and soil health?

Most of the investigations reviewed in this paper have been conducted on effluent irrigation schemes that were functioning according to specifications and where adverse effects were not observed. Generally, in pasture-based schemes where soil and site variability were not issues of concern, effluent irrigation enhanced soil biological activity and nutrient cycling. This was especially obvious under irrigation with high lactose dairy factory effluent (Degens et al. 2000; Sparling et al. 2001). This enhanced activity was not accompanied by an adverse effect on soil physical properties, and Sparling et al. (2001) demonstrated increased hydraulic conductivity in the effluent-treated soils. In the one instance where an adverse effect on plant health and soil physical properties (structural integrity) was observed (the Fairton study), an increase in effluent loading and of effluent sodicity had not affected soil chemical properties, nor had a measurable effect on aggregate stability. However, soil biochemical properties were markedly and significantly reduced (Speir et al. 1988), suggesting that such properties could have an early warning role. However, for the potential of this role to be realised, it is too late to wait for the whole irrigation site to be degraded. The effects of any untested effluent or of any drastic change of effluent quality or quantity should be tested in a small pilot trial before imposing the change on the entire site. If this is not possible, at the very least, frequent monitoring should be conducted in the early stages of establishment of the land treatment system.

When effluents are applied to crop land, or to forest or scrub land, previous land management and site effects such as topography and ground cover have a profound influence on soil biochemical properties. The generally declining activities found in the biogas digester study were also reflected in the non-effluent treatments and were due to utilisation of nutrients and residues from the previous pastoral management on this site. The inherently high fertility of the dominant soil on this site, coupled with the intransigence of the organic residues in the effluent, would have been responsible for the lack of response to effluent.

In the investigations of sewage effluent irrigation into *P. radiata* forests, previous soil disturbance has made representative sampling almost impossible. As a consequence, it was not possible to compare samples between years, and even comparisons between control and irrigated plots were of spurious value. At the Waitarere site, the control soil also was extremely infertile and had a considerable depth of decomposing pine litter, including needles, twigs, and branches. Much slower tree growth on the control area also meant that the canopy was more open than on the irrigated area. As a consequence, there was an understorey of grasses, bracken, and scrubby plants on the control plots. In addition at this site, a considerable time (7 years) had elapsed between commencement of irrigation and the start of the study. Some data from this period, over which a great deal of change had obviously occurred in the irrigated area, may have helped to explain the observed decline of the biochemical properties. Generally, the difficulties encountered in these two *P. radiata* forest studies have made it impossible to determine whether soil biochemical properties can tell us anything about treatment sustainability and soil health in forest soil land treatment schemes.

The steepland soil study was of insufficient duration for significant difference attributable to irrigation (except increased N-mineralisation and nitrification and decreased phosphatase enzyme activity) to be observed.

One important aspect of land treatment sustainability is the control of nitrate leaching. Soil biochemical properties are unlikely to provide an insight into the likelihood of excessive leaching, because nutrient-rich effluent will usually lead to enhanced activity, including N mineralisation and nitrification. However, this will be, at least to some extent, offset by enhanced denitrification and plant uptake of N. Laboratory measurements of soil biochemical activities are unlikely to indicate how the balance lies between these processes.

Perhaps the major difficulties encountered in preparing this review have been the relatively few New Zealand studies conducted that include soil biochemical properties and the extensive time period (c. 20 years) between the first and last published reports. Over such duration, methods change, properties become unfashionable, and totally new concepts and methods to investigate them appear. For this reason, it is very difficult to compare the results and draw conclusions of studies conducted decades apart. In my opinion, revisiting several of the irrigation schemes, using a common suite of biochemical methods and also a number of chemical and physical techniques, perhaps moulded on the approach of Sparling et al. (2001), would be a very valuable exercise. Perhaps my main conclusion from this review is that, when irrigation schemes have been running for a number of years and are functioning well, soil biochemical properties reflect the soil health enhancements provided by the water and nutrients added. Such enhancements are generally manifested slowly and, therefore, monitoring is required over a longer duration than has occurred in several of the studies examined in this review. Unless a drastic change has taken place, adverse effects attributable to effluent irrigation are more difficult to recognise and interpret, due mainly to methodological limitations and our lack of understanding of the true meaning of what we are measuring or its relevance to soil functioning. Until our understanding improves markedly, a predictive role for these properties as an early warning of adverse effects of effluent irrigation will remain elusive.

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