

LANDFILL LEACHATE MANAGEMENT BY APPLICATION TO SHORT ROTATION WILLOW COPPICE

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SUMMARY: Two operational-scale field trials managed over 5 years were established to investigate the feasibility and sustainability of landfill leachate management by its application to plantations of short rotation willow coppice. Routine monitoring of leachate, soil, soil solution, plant tissues and drainage water allowed the fate of a number of leachate components to be determined. Crop yields were improved by leachate application, there was almost complete removal by nitrification and plant uptake of ammoniacal–nitrogen and a reduction in mass of N by 80% when the masses of applied and drained N were compared. Most of the other leachate components were held within the soil without detriment during the growing season and were released during the winter periods at lower concentrations than they were applied, following dilution by rainfall. The results suggest that the use of short rotation willow coppice for leachate management, reuse and recovery offers a cost effective and sustainable method of leachate management. The wood produced by the system may also offer an alternative income or source of renewable energy for landfill operators, since no enrichment of undesirable contaminants could be detected in the wood harvested from the system.

1. INTRODUCTION

Short rotation coppice (SRC), is an intensive silvicultural technique using fast growing tree species such as willow (*Salix*), poplar (*Populus*) and *Eucalyptus* planted at high densities (up to 25,000 trees ha⁻¹) and harvested on a much shorter rotation (3-5 years) than conventional forestry practices. The technique was developed to generate energy crops during the 1970's oil crisis, because it offered a source of renewable power. The extensive and rapidly produced root system has a large capacity for water and nutrients that may be exploited to reduce the environmental impact of leachate.

Landfill leachate management using land treatment systems has been investigated and practised in several countries including Sweden and Finland (Ettala, 1987 and Hasselgren, 1989), Canada (Gordon *et al.*, 1989), USA (Licht, 1994) and Hong Kong (Wong and Leung, 1989).

Lysimeter studies comparing the irrigation of landfill leachate and water to *Salix*, determined that leachate had a significant positive effect on yields (Alker, 1999 and Brierley *et al.*, 2001). This suggests that leachate has considerable fertiliser value and the uptake into plant tissues of leachate contaminants and water offers a method to reclaim rather than dispose of useful

resources in leachate. The use of SRC offers an advantage over food or fodder crops of avoiding any real or perceived risk of contamination of the human food chain by leachate irrigation. Controlled glasshouse, laboratory and lysimeter trials investigating leachate management using willow SRC (Alker, 1999) were followed by a short pilot scale field study where leachate was applied for a period of 6 weeks to a SRC plantation already established on the surface of a closed landfill. Encouraging results from these two investigations led to the initiation of a five-year field-scale research project (1998 – 2002). This paper summarises the technical findings of these field trials. Detailed technical results (Alker *et al.*, 2002), operational guidelines (Hallett *et al.*, 2002) and a summary of the study (Godley *et al.*, 2002) have been reported elsewhere.

2. MATERIALS AND METHODS

2.1 Field Trial Design and Operation

The study involved the establishment of two field trials at landfill sites at Hatfield (NGR 5200E 2100N) and Westmill (NGR 5350E 2160N) in Hertfordshire, UK. Willow SRC plantations were planted in May 1998 on the restored surfaces of the lined and capped landfills at both sites and were managed according to SRC best practice guidelines (FC, 2002 and IEA, 1995). The SRC plantation at Hatfield covered an area of 2.43 ha and included 2 planting densities of 12 and 24,000 trees ha⁻¹. The Westmill landfill plantation covered an area of 0.67 ha with a single planting density of 15,000 trees ha⁻¹. Both trials were separated into 6 blocks with 4 treatment plots in each block (Figure 1). Two of the blocks received either; leachate, water or no treatment (control). At Hatfield, the blocks were orientated such that field drains ran parallel to the blocks to facilitate drainage water monitoring and alternate blocks were hydrologically separated by a field drain, to minimise the migration of irrigation water between treatments.

There was no irrigation in the first year to allow the plantations to become fully established. In years 2, 3 and 4, irrigation at both sites was controlled by soil moisture. At Westmill, irrigation was initiated manually, following manual measurements of the soil moisture in each of the 24 treatment plots. At Hatfield, a datalogger based program automatically monitored 48 in-situ soil moisture probes prior to automatically initiating the irrigation system. Leachate was supplied from holding tanks at both sites, but the volume available in the tanks was not always sufficient to supply the requirements of the irrigation regime. For this reason, water meters were installed to accurately monitor the hydraulic loading rates (Table 1).

2.2 Monitoring

During the irrigation periods (May to September), leachate samples were collected at approximately monthly intervals (Table 2). Soil samples were collected before the start of leachate irrigation in 1998, after the final irrigation period in September 2001 and after the final winter period in April 2002. Stem samples were collected in January or February in 2000, 2001 and 2002, which is the typical harvest period for SRC. Leaf samples were collected; close to the start of an irrigation period at Hatfield in June 2001, near the end of an irrigation period at both sites in August 2000, just prior to leaf fall in October 2001 at both sites and at Hatfield, samples of leaf litter were collected in November 2001.

Table 1 - Annual hydraulic loading rates applied to leachate treatment blocks (mm)

	Hatfield	Westmill
1999	44.4	50.0
2000	101.2	75.0
2001	140.4	89.7

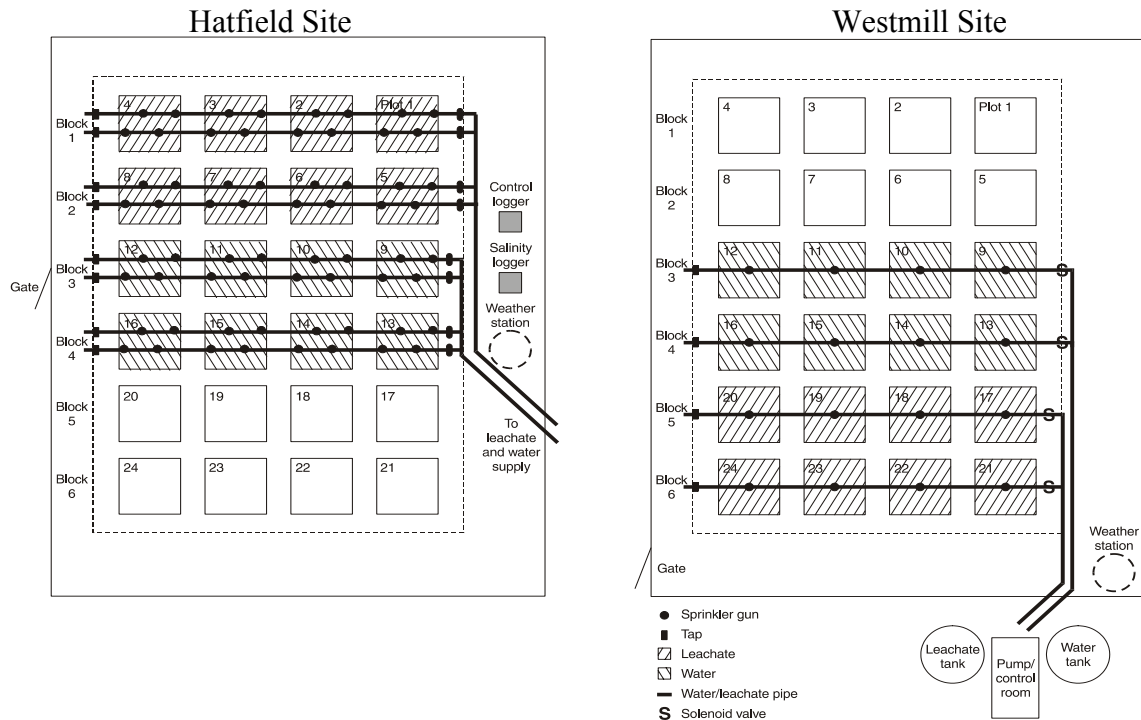


Figure 1 - Trial and irrigation system designs (not drawn to scale).

Throughout the winter periods, soil solution samples were collected from 120 ceramic cups at both sites. Field drain and drainage ditch samples were collected at Hatfield on several occasions during the trial. Soil moisture at two depths was automatically logged at hourly intervals at Hatfield and soil electrical conductivity (EC) was manually monitored at Westmill.

Samples were analysed for strategic combinations of the following chemical and physical determinands, depending on the sample type and timing: alkalinity, $\text{NH}_4\text{-N}$, As, hot water extractable and total B, 5-day biochemical oxygen demand (BOD), Ca, Cd, cation exchange capacity (CEC), water extractable and total Cl, chemical oxygen demand (COD), Cr, Cu, EC, Fe, Pb, loss on ignition at 550°C (LOI) ammonium nitrate extractable and total Mg, Hg, moisture content, total N, Ni, $\text{NO}_3\text{-N}$, sodium bicarbonate extractable and total P, pH, ammonium-nitrate extractable and total K, Na, S, SO_4 , total organic carbon (TOC), and Zn. Full details of the monitoring regimes, monitoring devices and analytical determinands are reported by Alker *et al.* (2002). All chemical and physical analyses were carried out by UKAS accredited laboratories.

A weather station was installed at both sites to monitor air and soil temperature, relative humidity, wind speed, rainfall and solar radiation. Weather data from Hatfield was used to develop a water mass balance using the WASIM model (Hess and Counsell, 2000), which was calibrated for willow SRC by Stephens *et al.* (2001). The drainage from field drains estimated using WASIM was subsequently used to estimate leaching losses from the soil of Cl and N.

3 RESULTS AND DISCUSSION

3.1 Biomass production and wood quality

The yields of leachate treated plots were 75 and 28% higher at Hatfield than unirrigated control and water treated plots respectively (Figure 2a). At Westmill, tree survival rates were lower than at Hatfield due to poor weed control in year two. Nevertheless, leachate treated plots produced 14% and 35% higher yields than control and water treated plots respectively (Figure 2b).

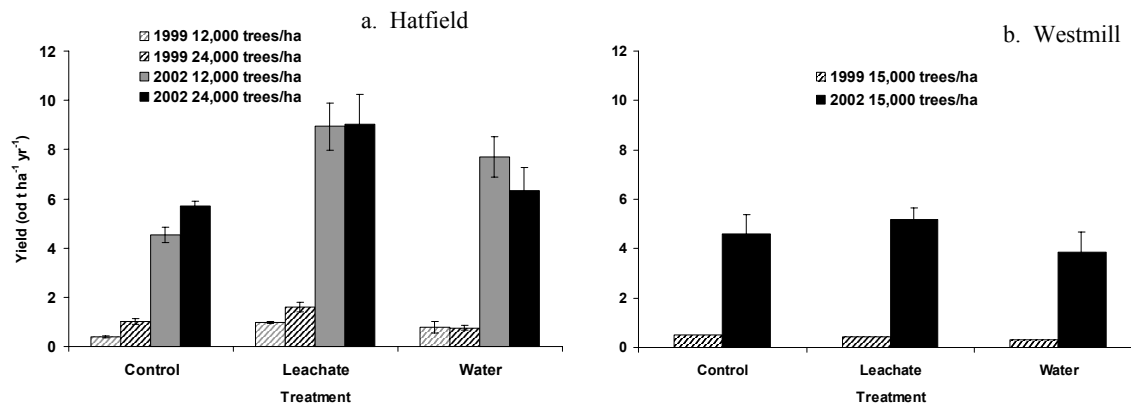


Figure 2 - Hand harvested plot yields in the first and fourth years (od = oven dry).

There was no statistically significant effect of leachate treatment on the stem tissue concentration of Cl, Na, Ca, Mg, N, P, K, Cd, Cr, Cu, Hg, Ni, Pb, Zn, Fe, As, B, S and Fe throughout the period of the trial. This suggests that utilisation of stem tissues from willow irrigated with leachate was not compromised by elevated concentrations of these elements.

Increased wood production in leachate treated trees, led to an increase in the removal from the site of leachate constituents in the harvested wood chips. For example the total N removed in wood chips at harvest was 78.6 and 141.8 kg ha⁻¹ for control and leachate treated plots respectively at Hatfield.

3.2 Fate of leachate constituents

3.2.1 Electrical conductivity and chloride

Electrical conductivity was used as a gross measure of the total dissolved salt content in soil and as an indicator of potential salinity problems. Figure 3 shows soil EC at 10 cm depth at Westmill. The mean EC of Westmill leachate was 9.4 mS cm⁻¹ and the EC of leachate treated soil increased during the irrigation period, but peaked at around 4 mS cm⁻¹, classifying the soil as slightly saline (USDA, 2002). This was within the tolerance of *Salix alba* and *Salix nigra* species, which tolerate up to 6 mS cm⁻¹ (Swift, 1997) and suggests that existing soil moisture and rainfall had diluted the soil solution salt content even during the summer, when soil moisture levels are relatively low. Shortly after the cessation of leachate application, the soil EC decreased to levels found within water and control soils, indicating that rainfall leached dissolved salts from the soil during the winter.

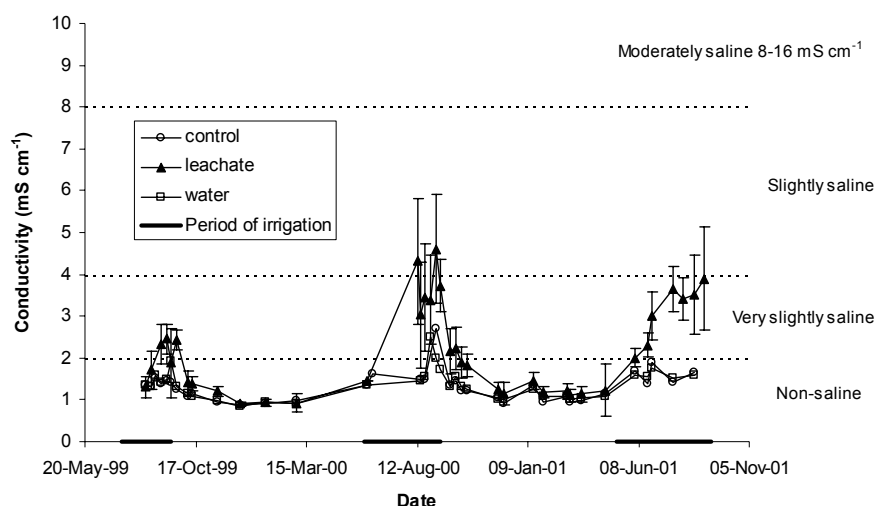


Figure 3 - Soil electrical conductivity at Westmill and soil salinity classifications (USDA, 2002).

Table 2 - Mean concentration of key components in Hatfield and Westmill leachates between 1998 and 2001.

Determinand	Units	Hatfield	Westmill
NO ₃ -N	mg l ⁻¹	0.56	1.31
NH ₄ -N	mg l ⁻¹	85.7	214
pH		7.28	7.53
EC	mS cm ⁻¹	5.03	9.38
Cl	mg l ⁻¹	889	2154
Na	mg l ⁻¹	549	1463
Mg	mg l ⁻¹	107	134
Ca	mg l ⁻¹	372	251
BOD	mg O l ⁻¹	44.2	127
K	mg l ⁻¹	123	274

Soil solution chloride at both sites followed a similar pattern to soil EC measurements at Westmill. The levels peaked at the end of the irrigation period, but were largely below the concentration of applied leachate (see Figure 4). The only exception was for a 3 week period following the cessation of leachate application at Westmill in 2002, when the pore water concentrations exceeded the mean leachate concentration by a maximum of 450 mg Cl l⁻¹. After winter flushing, there was no significant difference in the total or water extractable Cl between leachate treated and control soils at either site. Water from the field drains flowing from leachate treated plots contained Cl concentrations (mean of 206 mg l⁻¹) which were on average 53% lower than the concentration in soil pore water. Water in the drainage ditch was diluted still further, such that water at the ditch outlet contained a mean Cl concentration of 77.1 mg l⁻¹, which was substantially lower than the environmental quality standard (EQS) for chloride of 250 mg l⁻¹.

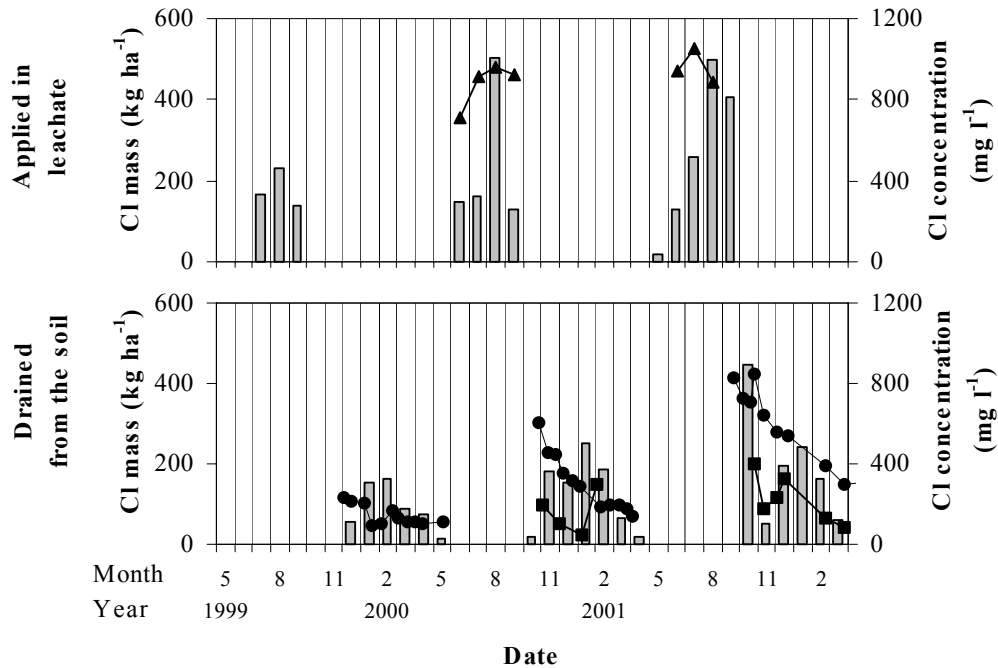


Figure 4 - Hatfield Cl budget. Upper plot represents Cl mass (bars) and concentration (\blacktriangle) applied in leachate. Lower plot represents Cl mass draining from field drains (bars), concentration in soil pore water (\bullet) and concentration in field drain water (\blacksquare).

At Hatfield, the total mass of Cl applied to the leachate treated areas over the duration of the trial was 2784 kg ha⁻¹. Chloride added in leachate was stored in the soil during the summer months, when there was no drainage from the site. Leachate irrigation accounted for just 11% of the hydraulic load, with rainfall accounting for the remaining 89%. During the winter periods (October to April) the stored Cl mixed with rainwater and was slowly released in a diluted form from the soil. By the end of each winter period, at least 88% of the Cl that had been applied during the previous irrigation period had been drained from the soil.

Drainage of Cl from the soil into field drains was estimated using concentration data and modelled drainage volumes to be 2574 kg ha⁻¹, accounting for 92% of the Cl applied. Uptake of Cl into harvested wood chips accounted for 15.3 kg ha⁻¹, less than 1% of the applied Cl.

3.2.2 Cations Na, Ca, Mg, K.

The loading rates of the plant essential cations, K, Mg and Ca, from applied leachate accounted for between 2 and 13% of the mass of these elements contained within the top 25 cm of soil, before leachate irrigation began (Table 3). After leachate application, there was no statistically significant difference ($P > 0.05$) in the total K, Mg and Ca soil concentrations between leachate and control plots, but ammonium nitrate extractable concentrations of K and Mg (the plant-available fractions) were significantly increased ($P < 0.05$) in leachate treated soils. For example, control and water irrigated soils contained 0.023 to 0.036 mg g⁻¹ extractable Mg, indicating that most of the soil Mg was not available for plant uptake and the soil was approaching Mg deficient status, according to MAFF (1998) soil classifications. Leachate application raised the extractable Mg to between 0.047 and 0.116 mg g⁻¹ improving the plant available Mg status of the soil, without significantly increasing the total Mg of the soil. A similar effect was observed for Mg at Westmill and K at both sites.

The total soil sodium concentration was significantly increased in the leachate treated plots compared to control and water treated plots at both sites in response to the relatively high Na

loading rate (Table 3). Control and water irrigated soil contained Na concentrations in the range 50 to 90 mg kg⁻¹ in April 2002 at both sites (see for example Figure 5). Typical soil Na concentrations of 230 to 8050 mg kg⁻¹ are reported for UK soils (Wild, 1988). Therefore Hatfield and Westmill soils were naturally low in Na concentrations. The range of Na soil concentrations in leachate treated soil at Hatfield in September 2001 shortly after leachate application had ceased was 300 to 400 mg kg⁻¹. Sodium is not an essential element for most plants but can be adsorbed by plants to concentrations of 1.5 to 9.9 mg g⁻¹ (Wild, 1988). In addition, few toxic effects of sodium have been documented (Knudsen *et al.*, 1982), so the elevation of sodium by leachate application is unlikely to have any beneficial or detrimental effects on plant growth. After the winter period, soil sodium concentrations at both sites had decreased to between 120 and 260 mg kg⁻¹ which was within the range of pre-treatment levels (10 to 320 mg kg⁻¹), suggesting that applied Na was also leached from the soil during the winter.

Table 3. Potassium, Mg, Ca and Na in soil, leachate and harvested wood chips

Site		K	Mg	Ca	Na
Hatfield	Mass in 0-25 cm depth of soil (kg ha ⁻¹)	7623	7161	13361	642
	Mass applied to treatment plots (kg ha ⁻¹)	496	431	1499	2212
	Proportion of soil mass applied in leachate %	7	6	11	345
	Mass removed in harvested wood (kg ha ⁻¹)	42	6.5	80	<3.9
Westmill	Mass in 0-25 cm depth of soil (kg ha ⁻¹)	5993	4520	35337	434
	Mass applied to treatment plots (kg ha ⁻¹)	784	390	687	3950
	Proportion of soil mass applied in leachate %	13	9	2	910
	Mass removed in harvested wood (kg ha ⁻¹)	22	3.5	46	2.3

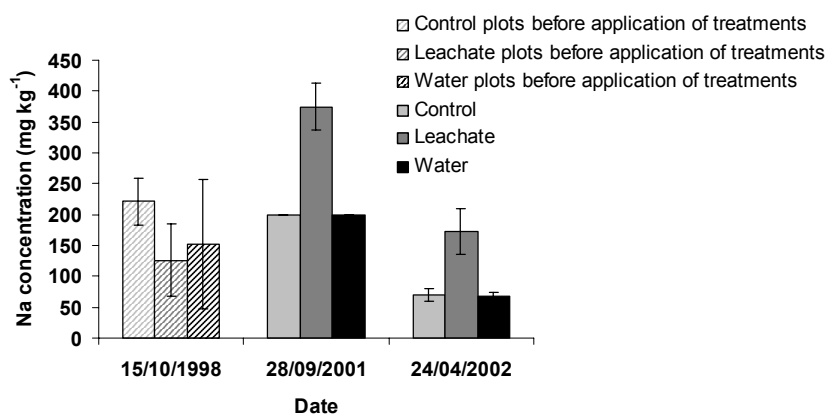


Figure 5. Soil sodium concentrations.

The mass of K, Mg, Ca and Na in harvested wood chips accounted for 8.4 (2.8), 1.5 (0.9), 5.3 (6.7) and <0.2 (0.06) % of the masses applied in leachate at Hatfield and Westmill (in brackets) respectively. Therefore plant uptake was not a significant removal mechanism for these leachate components. However, the improved nutritional soil status brought about by leachate additions of K, Mg and Ca, may have contributed to increased yields in leachate treated plots and hence increased plant uptake of other leachate components compared to controls.

3.2.3 Nitrogen

Over 99% of the N applied in leachate was as $\text{NH}_4\text{-N}$, however there was no statistically significant effect ($P > 0.05$) of leachate application on the $\text{NH}_4\text{-N}$ concentration of soil at either site. The $\text{NO}_3\text{-N}$ soil concentrations were significantly higher in leachate treated plots compared to control and water plots ($P < 0.05$), suggesting that leachate $\text{NH}_4\text{-N}$ was readily nitrified to $\text{NO}_3\text{-N}$ in the soil.

Initial pore water samples were collected from both sites in 1998 prior to the application of treatments. At Hatfield the $\text{NO}_3\text{-N}$ concentration of pore water ranged from 4 to 42 mg l^{-1} (mean of 28.8 mg l^{-1}). These values represent the existing $\text{NO}_3\text{-N}$ present in the soil, derived from the ploughed in and previously fertilised crop of winter wheat. The concentrations of $\text{NO}_3\text{-N}$ had decreased for all treatments by winter 1999/2000 to less than 8 mg l^{-1} despite the application in leachate of 41 kg N ha^{-1} (Figure 6). Plant uptake, denitrification and leaching had depleted soil $\text{NO}_3\text{-N}$ supplies during this time and the application of 44 mm of leachate in 1999 was insufficient to balance those losses. Nitrate pore water concentrations in the water and control plots remained low throughout the remainder of the trial, not exceeding 8 mg l^{-1} on any occasion after 1998. The soil $\text{NO}_3\text{-N}$ concentration in leachate treated plots also remained low in 2000/2001, despite the application of 96 kg N ha^{-1} in applied leachate. For a short period directly after the 2001 irrigation period, which applied 214 kg N ha^{-1} , pore water $\text{NO}_3\text{-N}$ concentrations in the leachate treated blocks were at levels similar to those observed in 1998, prior to treatment application. The maximum pore water $\text{NO}_3\text{-N}$ concentration was 45 mg l^{-1} on 20/09/01. At Westmill, a similar pattern was observed but the higher N loading rate in 2001 (294 kg ha^{-1}) resulted in a higher peak pore water $\text{NO}_3\text{-N}$ concentration of 95 mg l^{-1} . As was the case for Cl, peak mineral N ($\text{NO}_3\text{-N}$ plus $\text{NH}_4\text{-N}$) pore water concentrations were considerably lower than the mineral N concentration in applied leachate (Table 2). This was due in part to dilution, but unlike Cl, was also a function of plant uptake.

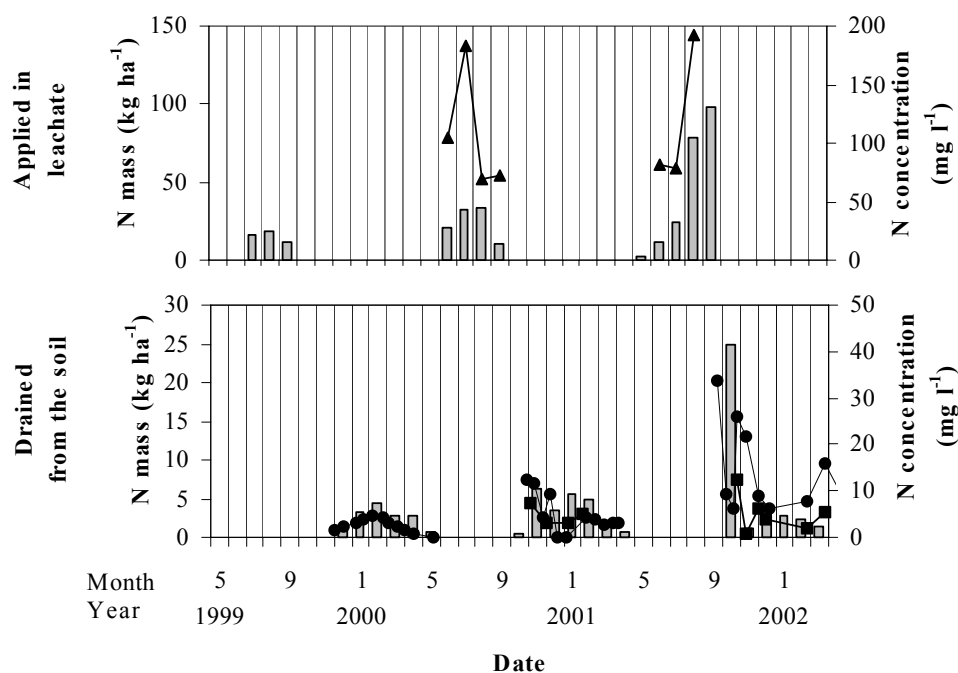


Figure 6. Hatfield N budget. Upper plot represents N mass (bars) and concentration (\blacktriangle) applied in leachate. Lower plot represents N mass draining from field drains (bars), concentration in soil pore water (\bullet) and concentration in field drain water (\blacksquare).

An N mass balance using data from Hatfield, indicated that 41% of the mass of N applied was accounted for in machine harvested stem material, while only 21% of the N applied was drained from the site. The amount unaccounted for by drainage or offtake was 132 kg ha⁻¹. Of this, 52.5 kg ha⁻¹ remained within the standing stem material or was dropped to the ground during the harvesting process (calculated using the difference between machine and hand harvested yields). Between 63 and 84 kg ha⁻¹ was stored in leaf litter and a further 3.9 kg ha⁻¹ was added to the soil N pool. Other potential losses from the system include ammonium volatilisation and denitrification, but these were not directly measured.

Therefore approximately 79% of the applied N was removed from the leachate. This is equivalent to the best biological NH₄-N removal systems such as 2 stage nitrification and denitrification systems, which often require addition of a carbon source and involve sludge production. Approximately half of the N removed was stored within the system, primarily as organic N in plant tissues. This will be released as mineral N over time, potentially decreasing the efficiency of the system. The contribution of these releases is not currently well understood and more research is recommended to assess the long-term effects of nutrient recycling in the system. However the proportion of N applied that was leached from the site decreased each year from 35 to 25 to 17%, despite annual increases in the N loading rate. This may reflect increasing yields, as the crop became established and if this is the case, even higher offtakes may be possible as yields increase in the second and third harvest rotations.

3.2.4 Heavy metals

The loading rates of heavy metals to the soil were insignificant compared to the masses held within the top 25 cm of soil (Table 4). Mean annual heavy metal loading rates were in most cases one or two orders of magnitude lower than the proposed limits for sewage sludge application to soil (CEC, 2000). As a result, it was not possible to detect any statistically significant effects of leachate application on soil, plant tissue or water heavy metal concentrations.

Table 4 - Heavy metals in leachate and loading rates compared to the proposed Sludge Directive limits (CEC, 2000)

	Mean concentration (mg l ⁻¹)	Total loading over 3 years (g ha ⁻¹)	Mass in 0-25cm depth of soil (g ha ⁻¹)	Mean annual loading (g ha ⁻¹ yr ⁻¹)	Proposed limit values from draft Sludge Directive. (g ha ⁻¹ yr ⁻¹)
Arsenic	0.0035	30.7	28548	10.2	
Lead	0.037	321.7	112998	107.2	2250
Mercury	0.0004	3.2	424	1.1	30
Chromium	0.035	307.1	96346	102.4	3000
Copper	0.011	92.1	79085	30.7	3000
Nickel	0.009	79.0	50018	26.3	900
Zinc	0.032	281	168566	94	7500
Cadmium	0.004	38.0	1052	12.7	30

A common concern associated with land-based treatment of landfill leachate is the potential contamination of soil by heavy metals. However the heavy metal concentrations of UK landfill leachates are often relatively low. A review of 30 UK leachates concluded that the heavy metal concentrations were within the typical range for sewage discharged to sewer from residential properties (Robinson, 1995). Assuming that a 'typical' UK landfill leachate contains the heavy

metal concentration equal to the mean value of the 30 leachate samples analysed by Robinson (1995); in excess of 3000 m³ of leachate per hectare per year (300 mm yr⁻¹) could be applied before the proposed Sludge Directive limits are exceeded. Leachate loading rates are therefore more likely to be limited by the Cl, Na, N and dissolved salt contents than by the heavy metal content of the leachate.

4. CONCLUSIONS

Operational-scale field trials of leachate management by application to willow SRC allowed the following conclusions to be drawn:

- Leachate management by application to willow SRC is feasible at the hydraulic and chemical loadings used in this trial,
- Dilution of leachate occurred in the soil from existing soil moisture and rainfall. This means that the soil both diluted and acted as a buffer to protect downstream receiving systems from shock loads,
- Leachate treatment by willow SRC resulted in almost complete NH₄-N removal from leachate by a combination of nitrification and plant uptake,
- The N removal from the leachate was high and matched the best biological treatment system. But N stored in plant tissue may subsequently be released from the system, potentially reducing the N removal efficacy in the long term and
- The heavy metals in the leachates tested were low and did not accumulate in soils to which leachate was applied.

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