RESPONSE OF SHORT ROTATION FORESTRY TO DAIRY FARM-POND EFFLUENT IRRIGATION

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ABSTRACT

A growing concern to protect the environment has prompted Regional Councils in New Zealand to monitor compliance under the Resource Management Act (1991) covering the discharge of wastewater into waterways. To meet the desired standards, application of wastewater onto high dry matter producing short vegetation forests offers opportunity for the beneficial use of nutrients while renovating the wastewater.

A field trial was established near Palmerston North to determine the response of nine Salix clones and one Eucalyptus short rotation forest (SRF) species to dairy farm effluent irrigation and to determine their water and nutrient uptake potential. A micro sprinkler irrigation system was designed to operate at 100 kPa and supply each plot of 16 trees with either 7.5 mm, 15 mm, or 30 mm of dairy farm effluent every two weeks. Twenty-four applications were made covering two growing seasons with a break over winter. A control treatment of 7.5 mm of water + 187.5 kg N ha^{-1} $year^{-1}$ was included, being equivalent to the nitrogen addition from the lowest effluent application rate. The three SRF species, *Salix matsudana x alba* (NZ 1295), *Salix kinuyanagi* (PN 386) and *Eucalyptus nitens* were selected for more detailed analysis than the other seven Salix clones. This included the measurement of evapotranspiration rates and a pot trial to determine the tolerance level of seedlings to higher levels of effluent application. Application of up to 90 mm of effluent per fortnight increased the biomass production and nutrient accumulation of potted PN 386 and *E. nitens*, whereas the NZ 1295 produced optimum biomass and accumulation of nutrients at 60 mm of effluent application per fortnight.

At the end of the first growing season, the above ground biomass of the ten tree species in the field trial was assessed using a non-destructive method followed by a destructive harvest at the end of the second growing season. Dry matter production in these short rotation forest crops varied with species and clones and with the amount of dairy farm-

pond effluent applied. *Salix* NZ 1296, PN 386 and NZ 1295 irrigated with the highest application rate of 30 mm of effluent per fortnight produced the highest biomass yields of 37.91, 37.87 and 37.58 ODt ha^{-1} $year^{-1}$ respectively. NZ 1296 irrigated with 30 mm of effluent per fortnight accumulated 196 kg N ha^{-1} $year^{-1}$, 37.6 kg P ha^{-1} $year^{-1}$, and 103.6 kg Mg ha^{-1} $year^{-1}$ in its above ground biomass. *E. nitens* irrigated with 15 mm of effluent per fortnight produced a comparable above ground oven dry biomass yield of 36.33 ODt ha^{-1} $year^{-1}$ and accumulated the highest amount of potassium and calcium in its above ground biomass giving 145.4 and 148.1 kg ha^{-1} $year^{-1}$, respectively.

Transpiration monitoring during the second growing season using a heat pulse technique showed that under the highest application rate (30 mm per fortnight) on a cloud-free day, 15 month old NZ 1295 trees each transpired the highest cumulative amount of 6.38 mm day^{-1} compared to 2.71 mm day^{-1} for trees irrigated at the lowest rate (7.5 mm per fortnight).

Results of this study overall suggest that increasing the rate of effluent irrigation will increase the soil pH, nitrates and exchangeable potassium, calcium and magnesium concentrations throughout the soil profile. Total nitrogen and total phosphorus levels decreased throughout the soil profile after the second growing season. The cation exchange capacity of the soil decreased with increased rate of effluent after the second growing season.

The soil-SRF treatment system renovated the nutrients in the effluent. The soil-*E. nitens* treatment system renovated the highest percentage of total nitrogen (17.2 t ha^{-1} m^{-1} depth) equivalent to 96.45% of total nitrogen supplied by both the soil and the 30 mm of effluent applied per fortnight. The soil-PN 386 treatment system renovated the highest percentage of total phosphorus (6.4 t ha^{-1} m^{-1} depth) equivalent to 92.72% of the total phosphorus available in the soil and supplied by the 7.5 mm of effluent treatment. The soil-NZ 1295 treatment system renovated the highest percentage of potassium (99.5%),

calcium (98.74%) and magnesium (95.63%) supplied by both the soil and the 30 mm of effluent treatment.

The capacity of the three SRF species to renovate total nitrogen, phosphorus and potassium from the effluent decreased with increasing rates of application. PN 386 irrigated at 7.5 mm of effluent renovated the highest percentage of 99.45% of total nitrogen (114.25 kg ha^{-1} over two growing seasons) and 79.18% of total phosphorus (35.60 kg ha^{-1} over two growing seasons). The amounts of calcium and magnesium renovated by the SRF species were more than the amount supplied by even the highest rate of effluent (30 mm per fortnight).

Salix PN 386, NZ 1295 and *E. nitens* are recommended SRF species to grow in a land treatment scheme for dairy farm pond-effluent when applied at a rate of 30 mm per fortnight over the growing period on to a silt loam soil. Pot trials showed higher volumes of effluent renovation on to PN 386 and *E. nitens* may be applicable when applied up to 90 mm of effluent per fortnight but further evaluation is needed before this can be recommended.

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CHAPTER 1

INTRODUCTION

Many dairy farms treat the dairy shed washings in anaerobic/aerobic ponds before discharge of the treated effluent to pasture or waterways. This system can still have a large impact on receiving waterways as the effluent contains relatively high levels of nutrients and pollutants which threaten the environment once discharged or allowed to percolate into the ground water (Mason, 1994). Potassium and nitrogen contents of dairy farm-pond effluent is particularly higher compared with sewage effluent.

A growing concern to protect the environment has prompted regional councils in New Zealand to monitor compliance under the Resource Management Act (1991) covering the discharge of wastewater into waterways. To meet the desired standards, application of wastewater onto high dry matter producing short rotation forests (SRF) offers opportunity for the beneficial use of nutrients while renovating the wastewater (Barton et. al, 1989).

Irrigation of land with dairy farm-pond effluent is one of the alternatives to discharge and a soil-SRF treatment system has the potential to effectively treat the effluent when applied at a regulated hydraulic loading rate. The soil particles can filter suspended solids and can fix dissolved components in the effluent by adsorption, ion exchange or precipitation. Micro-organisms in the soil can transform and stabilise the nutrients from the wastewater. The growth of SRF species on treatment site can enhance absorption and utilise nutrients from the wastewater for growth and production. The SRF root system can also help improve the infiltration capacity of the soil.

SRF crops like willows and eucalyptus are fast growing species and are known to produce high dry matter. Sims et. al (1992) recommended coppice willows to be ideal attachment for land treatment of wastewaters due to its fibrous root system that has the ability to utilise large quantity of water and nutrients. Barton (1989) emphasised the potential use of coppice eucalyptus for wastewater treatment being able to accumulate high amounts of nitrogen. These SRF species has also the potential to provide non-polluting sources of renewable energy while renovating waste waters.

Aside from preventing the possible risk of ground water contamination and eutrophication of waterways, it is desirable to recycle nutrients from wastewater wherever feasible to support sustainable crop production. Hence, it is the purpose of this study to investigate the performance of short rotation forest species, *salix* and *eucalyptus* as part of a land treatment scheme for dairy farm-pond effluent.

Specifically, this study aimed to:

- identify suitable SRF species for dairy farm-pond effluent irrigation;
- quantify the level of dairy farm-pond effluent irrigation suitable for the production of SRF species;
- determine the effect of dairy farm-pond effluent to the physical and chemical properties of soils;
- quantify the amount of waste nutrients from dairy farm-pond effluent renovated by the SRF species;
- quantify the amount of nutrients renovated by the soil-SRF system that were supplied by the soil and the effluent and;
- determine the evapotranspiration of SRF species when irrigated with varying rates of dairy farm-pond effluent.

An overview of previous work is given in chapter two of the thesis.

The responses of ten species to different rates of dairy farm-pond effluent irrigation and water + nitrogen in terms of biomass production and nutrient accumulation were evaluated (chapter 3). The three most suitable species or clones of SRF trees for treating dairy farm-pond effluent irrigation were identified and the level of irrigation that produced optimal biomass production and nutrient uptake and accumulation into the biomass was determined.

The effects of applying different rates of dairy farm-pond effluent to the physical and chemical properties of the soil were discussed in chapter 4. Samples were analysed before treatment began and after harvesting the trees at two years old.

The portion of waste nutrients in the dairy farm-pond effluent applied at the various application rates that was renovated by the SRF trees and filtered by the soil matrix over the two growing periods was quantified (chapter 5).

The effect of dairy farm-pond effluent irrigation on the evapo-transpiration of the three selected species was monitored during a short period of the growing season and is reported in chapter 6.

Finally, the responses of seedling of the three selected SRF species to particularly high rates of dairy farm-pond effluent irrigation were determined in a pot trial described in chapter 7. The maximum irrigation level of dairy farm-pond effluent irrigation that was tolerated by each of the three SRF species in terms of maximum growth, biomass production and nutrient accumulation was determined.

The results of these studies were brought together in concluding section (chapter 8) and practical recommendations made along with suggestions for further studies.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Waste effluents can be regarded as a valuable source of water and nutrients rather than a disposal problem for agricultural production. Land application of secondary treated waste effluents can provide an economic and environmentally acceptable method of disposal. The nutrients present offer opportunity to increase the productivity of crops and to ameliorate and reclaim degraded land. Application especially during periods of soil moisture deficit aid irrigation and will increase crop production.

Organic wastes such as farm slurries and sewage sludge are widely used in agriculture as sources of nutrients and organic matter. The nutrients contained in most organic waste effluents, particularly nitrogen (N), phosphorus (P) and potassium (K), provide soil nutrient supplements necessary for crop production. These effluents can be used to offset the cost of using inorganic fertilisers. However, the presence of hazardous substance like toxic organic chemicals, heavy metals, pathogens, salts and extreme pH values in waste effluents are constraints on its reuse or for application to land.

The use of waste effluents to irrigate crops not in the food chain such as SRF species grown for energy purposes is environmentally safe. Regular harvesting and transporting the SRF species off site is a means of avoiding overloading the soil-SRF treatment system since nutrients are continually removed.

2.2 Short Rotation Forestry (SRF)

2.2.1 Importance of SRF trees

Fast growth and high biomass production of plants are essential considerations for the success of short rotation forestry if to be used as a source of renewable energy and/or for fibre.

Short rotation forests are grown in much shorter periods than traditional forest, these being normally 2 to 10 years between rotations. This involves the establishment of closely spaced plantations and harvesting of trees at short rotation periods on a regular basis in order to produce maximum growth under certain production regimes. When the trees are harvested some species can "coppice" or regrow from the same stump eliminating the need for replanting or re-establishment of the plantation (Lowe et al., 1994). This technique aims to increase the production of woody biomass for fibre and fuels and minimise the cost. It also reduces the regeneration of forest by repeated harvesting of vigorous coppice growth over several cutting cycles.

Under New Zealand conditions, *Eucalyptus* species and *Salix* species can be successfully grown and harvested on 3 year and 1 year short rotation periods, respectively. Campbell (1991) identified several species of fast growing *Eucalyptus* species that could be suitable for use as pulpwood and as a non-polluting source of energy. Willows can be chipped and manufactured into briquettes for use as energy source for the production of high valued crops during the winter. These trees can also be used for soil conservation practices because of their fibrous root system (Sims, et al., 1991) and ability to survive in wet sites.

Other benefits can be derived from the production of SRF trees when used as fuel to displace coal, oil or gas (Southeastern Regional Biomass Energy Program, 1995). These include:

- Reductions in air emissions of sulphur oxide and nitrous oxide;
- Reductions in a net air emissions of carbon dioxide;
- Introduction of a new crop to farmers;
- Reduced soil erosion;
- Reduced runoff of pesticides, herbicides and nutrients;
- Less contamination of groundwater with nitrates, pesticides and herbicides;
- Improved soil physical properties resulting both in better infiltration of rainwater, improved rain hydrology and higher crop productivity;
- Increased storage of carbon above and below ground level; and
- Increased variety of microorganisms, mammals, birds and other wildlife.

Short rotation forests can be more advantageous than traditional forests in terms of ecological perspectives such as land use, landscape, wild habitat and waste management (Nielsen, 1992).

- Land use: The establishment of SRF can be less demanding and more extensive land use prevails compared with other crops. The permanent rooting system and lack of tillage allow for good recycling of nutrients, diminishing the need for commercial fertiliser and the risk of nutrient leaching.
- Landscape: SRF trees can add to the scenic and refreshing views of green vegetation.
- Wild life habitat: SRF tree plantations offer good shelter to birds and animals. Trees provide resting and nesting habitat and encourage supplies of insects and earthworms which are important sources of food for birds. To some extent, deer and hares frequently browse under willows which is encouraged in European countries.
- Waste management: SRF plantations is not included in the food chain, limiting the chance of heavy metals and pathogens to be ingested by humans and other grazing animals. Perennial energy crops like willows and eucalyptus have the further

advantage of taking up nutrients over a longer period, thus limiting the leaching of nutrients. These features make SRF trees attractive for waste effluent treatment as a means of wastewater purification.

2.2.2 Nutrition of SRF trees

Trees normally contains up to 60% water in the fresh weight of biomass. The remainder is the dry matter consisting mainly of carbon, oxygen and hydrogen. SRF trees, like other plants, grow and build up their biomass with the sufficient supply of 16 essential elements to complete their life cycle (Ericson et al., 1993). The elements required by the trees are grouped into:

- Macro-nutrients - carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg) and
- Micronutrients - iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl) and boron (B).

The SRF nutrient requirement and balance is comparable to arable crops. The demand of a SRF plantation for nutrients is at peak during the expansion of its canopy. The rapid growth rate and frequency of harvesting of these trees suggest high nutrient requirement for productive management. The relatively high productivity of SRF trees in terms of tonnes/hectare/year, and the substantial removal of nutrients in regularly harvested biomass, suggest that the addition of nutrients would be beneficial to maintain crop yield (Riddell-Black, 1995). Trees managed on short rotation periods are thought to be able to take up and store nutrients in excess of their requirements. These nutrients are stored in the stem biomass of trees during the winter (Miller, 1989a; Riddell-Black, 1995).

The repetitive harvesting cycle of SRF trees would suggest that nutrients taken up by the crops from the soil will result in soil nutrient depletion. Updegraff et al. (1990), concluded that relatively high rates of uptake during production of SRF trees maintained NH_4^+ and NO_3^- pools at low levels, minimising N exports to the atmosphere and environment. To replenish any depleted nutrients taken up by the trees, nutritional management is an essential approach to the fertility of soil for the successful production of biomass. Ways to replenish the depleted nutrients in the soil include growing nitrogen-fixing crops, adding inorganic fertiliser, or application of agricultural wastes (i.e., dairy farm-pond effluent or municipal sewage effluent).

The draw back of using inorganic fertilisers are the cost and the acidifying effect on the soil. In New Zealand, dairy farm-pond waste effluent is abundant as the result of widespread dairy production industry. This effluent is rich in nutrients like N, P and K that can sustain and increase biomass production of SRF trees. The use of dairy farm-pond effluent for SRF biomass production offers an inexpensive and environmentally appropriate disposal method.

Among the nutrients required for SRF production, nitrogen triggers the emergence of leaves and development of canopy. The unavailability of nitrogen will most likely limit the growth of trees (Hansen et al., 1988 and Rytter, 1990). As the canopy reaches full development, there is a decreasing demand for nitrogen since nutrients begin to recycle from litter fall (Guo, 1999). This condition suggests that there is a lower N nutrient requirement in the stem biomass of SRF trees. Several studies have been conducted to determine the effect of N application on the biomass production of SRF trees (Stewart et al., 1988; Rytter, 1990; Updegraff, 1990; Ericson, 1992 and Riddell-Black, 1995). Restricted supplies of nutrients and their inaccessibility to trees will result in poor health, appearance and reduce biomass yields. Constrained supplies of N and P nutrients to SRF trees will increase biomass partitioning below ground level to enable roots to explore the soil volume in search of nutrients for biomass production. Ericson et al. (1992) disclosed that a shortage of K, Mg, Fe and Mn primarily affects the processes associated with carbon fixation and assimilation, decreasing the carbohydrates in the plant tissue. Low production of carbohydrates in plants inhibits root growth and impairs the ability of the plant to take up sufficient nutrients.

Hytonen (1995) disclosed that application of N increased the three-year biomass yield of willows by 1.5-2.7 times compared with unfertilised trees and that addition of both N and P nutrients increased the concentrations of corresponding extractable nutrients in the soil as well as in the foliage. Plants subjected to luxury uptake of growth limiting nutrients may allocate more of those resources to existing foliage, increasing the photosynthesis capacity of the trees.

Frison (1992) mentioned that nutrients needed by SRF trees can vary as a function of soil fertility and clone requirements. However, basic fertilisation before planting can be useful for the establishment of trees depending on the nutrient level of the soil. SRF trees are among the fastest and highest producers of biomass when treated optimally with nutrient and water (Perttu, 1987, 1988, 1991; Christersson, 1992 and Sennerby-Forsse et al., 1992). Table 2.1.2 shows the optimal proportions of nutrient compounds to achieve maximum willow production under Swedish condition.

Table 2.1. Optimal proportion by weight of the essential mineral nutrient compounds in a fertiliser for achieving maximum willow production.

Macronutrient	Proportion	Micronutrient	Proportion
Nitrogen	100	Iron	0.6
Potassium	72	Manganese	0.4
Phosphorus	14	Boron	0.1
Magnesium	8.5	Zinc	0.06
Calcium	7	Copper	0.03
Sulphur	9	Molybdenum	0.007
		Chlorine	0.003
		Sodium	0.003

Source: Ericsson, 1981

2.2.3 Effluents as a source of nutrients for SRF trees

Secondary treated dairy-farm pond effluent is rich in nutrients particularly, N, P, K, Ca, and Mg (Bolan, 1996; Mason, 1996). The treated effluent contains 110 g of total nitrogen m^{-3}, most of it as ammoniacal-nitrogen (95 g m^{-3}), 24 g of total phosphorus m^{-3}, 168 g of total potassium m^{-3}, 23 g of total calcium m^{-3} and 14 g of total magnesium m^{-3}. The application of this effluent on to SRF trees makes it attractive to farmers in order to reduce application of inorganic fertiliser. The use of this effluent would also eliminate the fear of metal accumulation in the plant tissues and acidification of the soil which can result from inorganic fertiliser use. The effluent does not only provide a valuable resource of nutrients but also irrigation water requirements for maximum crop growth and production. Dairy farm-pond effluent can sustain production of crops as can other organic sources. For example Riddell-Black (1995) indicated the fertiliser value of sewage sludge application to short rotation coppice crops.

The disposal of dairy farm-pond effluent is regulated by the RMA (1991). The permitted level of application of nitrogen on to soil varies with each region in New Zealand. This is due to insufficient knowledge of processes being available at present rather than due to regional differences. Generally, the rate of application of effluent should not exceed or match the nutrient uptake capacity of the trees, hence application of 200 to 250 kg N ha^{-1} $year^{-1}$ is recommended as being sufficient to sustain the growth and biomass production without the potential risk or hazard or risk of nutrient leaching (Overcash and Pal, 1979). The Council of European Communities (1991) promulgated the European Council Directive 91(676)EEC requiring Member States to implement the allowable maximum rate of total nitrogen application to 210 kg $ha^{-1}year^{-1}$ for the first four years and reducing to 170 kg ha^{-1} $year^{-1}$ for succeeding years. Excessive loading of N on to cereals can cause crop lodging and excessive vegetative growth. Excess nitrates in forage crops may result in excess nitrates ingested in animals and production of nitrous oxide gases following ensiling. Nitrates in the plants when ingested by animals may be converted to nitrite which, following absorption, may react with haemoglobin to cause methemoglobinemia or cyanosis. This results in the inability of the haemoglobin to transport oxygen and can result in suffocation of the animal (Black et al., 1984).

In agricultural crop production, basal application of fertiliser is essential and is a standard component of crop management practice. Agren (1984) pointed out the importance of applying fertiliser to crops before depletion of soil nutrients occurs. The maintenance of a balanced nutrient status of a plantation by fertiliser application may prolong the life of the plantation through maintaining productivity, and thus delaying the need to replant (Riddell-Black, 1995).

The nutrient requirement of willows (*Salix spp.*) for maximum production can be matched to the nutrient content of secondary treated dairy farm-pond effluent as related to nitrogen. The figures in table 2.2 suggest that the nutrients in the effluent fulfils the N and K nutrient requirement of willows. However, only 30% of P, 70% of Ca and 90% of Mg nutrient requirement of the crop is met by the application of effluent. The information presented in the table suggests the suitability of dairy farm-pond effluent as a valuable resource of nutrients for SRF biomass production.

Table 2.2 The proportions of the five main nutrients related to nitrogen in secondary treated dairy farm-pond effluent compared to the nutrient requirement of willows (*Salix spp.*) to give maximum production.

Nutrients	Nutrient Requirement of Willows**	Nutrient in the Effluent***
Nitrogen	100	100
Phosphorus	14	5
Potassium	72	150
Calcium	7	5
Magnesium	9	8

**Perttu, 1993
***Computations based on Bolan et al., 1996

Dairy farm-pond effluent may be applied at different times during the growing season. However the optimum utilisation of the nutrients contained in the effluent may be derived when applied in spring at the beginning of the growth of the trees. Buds break and early expansion of leaf is fuelled by nutrients translocated from the stems and roots of trees (Miller, 1989a). The timing of effluent application was not considered in this study, there being an equivalent application made every two weeks through out the growing season (section 3.2)

2.3 Sources of waste effluents

Waste effluents contain materials and contaminants that can pollute natural waters when discharge into streams or bodies of water. The nutrients in the effluent can cause eutrophication and promote growth of unwanted algal blooms.

There is a wide range of chemical composition and biological characteristics between effluents from domestic, industrial and agricultural wastes (Table 2.3). They also vary with time and the treatment employed. Predominant sources of waste effluents are derived from dairy sheds, milk processing factories, piggeries, poultry farms, meat processing plants, wool scours, feedlots, vegetable and fruit processing plants, paper and printing operations, textile plants, metal industries and sewage treatment plants (Hart and Spear, 1992 and McLaren and Smith, 1996).

2.3.1 Sewage wastes

Sewage wastes are normally collected from households, commercial institutions and industrial operations. They contain solids, organic materials, nutrients, superfactants (detergents) and pathogenic organisms like bacteria, viruses and parasites. The significant concentration of nutrients in this waste, particularly nitrogen (N) and phosphorus (P) make it a potential resource for soil fertiliser and conditioner (Bledsoe, 1981, Henry and Cole, 1983 and Cole et al., 1986). In some localities treated sewage is

Table 2.3 Characteristics of various wastewater effluents (concentration expressed as mg/L, except pH units)

Parameter	Piggery effluent[1]	Dairy shed effluent[2]	Feedlot effluent[3]	Cheese factory effluent[4]	Milk/ butter factory effluent[4]	Whey effluent[4]	Meat processing effluent[5]	Winery effluent[6]	Cannery effluent[7]	Municipal sewage effluent[8]	Fellmongery[9]	Hide processing[9]	Secondary tannery effluent[10]	Silage effluent[11]
PH	8.1-8.8[a]	8	-	4.5-6	10-12	4.5	8.4[d]	3.4-9.4	-	6.8-9.6	11.4	9-10	7.6	-
BOD_5	176	3200	6000	8000	1500	48000	20-1500	2000-3000	550	15-100[e]	-	-	30	-
COD	886	954[b]	-	-	-	-	80-3000	-	1190		4000	3100-3400	410	60000
TSS	358	2400	15200	-	-	-	20-2000	600-700	425	15-100[e]	1800	2150	120	60000
TN	230	187	900	200	70	1510	-	20-36	28		-	-	135	23000
TKN	213	176[b]	-	-	-	-	40-240		-	1.5-25.1	-	-	130	
NH_4	170	84	-	-	-	-	5-220		0.7	0-12	-	-	115	
NO_3	17	5[c]	-	-	-	-	0-160	0.1	0.3	0-10.1	-	-	5	
TP	65	26	150	100	35	365	5-30	5-6.6	6	2.2-8.5	-	-	1.6	1000
K	162	200	106	160	13	1560	20-150	100	24	12.9-18.3	50	-	-	4000
Ca	3	22[c]	146	95	8	610	3-250	44	45	10.7-18.3	300	-	340	
Mg	10	27	1865	14	1	80	3-10	8	4	5.3-11.7	10	-	36	
Na	112	119	478	380	560	440	50-250	70	47	83.1-122.7	2000	-	2700	
SO_4	-	-	-	-	-	-	-	-	40		-	-	-	
Cl	-	180	-	-	-	-	-	5	66	45.7-72.9	-	-	3430	

Additional data to the main references were provided as shown:

[a]Vanderholme, 1984, [b] Mason, 1994, [c]Bolan et al., 1996, [d]Tipler et al., 1996, [e]Black et al., 1984, [1]Lowe, 1993, [2]Wrigley, 1994, [3]Bowmer and Laut, 1992, [4]Barnet et al., 1994, [5]van Oostrom, 1994, [6]Carnus Wang, 1998, [7]Tedaldi and Loehr, 1990, [8]Myers, et al., 1994, [9]Lieffering, 1995, [10]Carnus and Mason, 1994, [11]Vanderholm,1984

seen as a valuable resource for land irrigation (Department of Health, 1992). However, Cameron et al. (1997) reported the concentration of nutrients varied considerably between sewage wastes which makes it difficult to establish standard treatment operations for sewage waste effluent disposal.

Sewage waste can be disposed of in a variety of ways, provided it is treated to meet the standard requirement or quality for the intended use. Treatment removes undesirable constituents such as solids, pathogens and other contaminants and is undertaken to protect public health and to maintain the aesthetic quality of the environment (Black et al., 1984).

The reduction or removal of noxious substances from waste effluent before recycling the effluent back to the environment is necessary to meet the desired standards of treated effluent. This process utilises a combination of physical separation and aerobic or anaerobic biological treatment. Sewage sludge (solid material) is retained and the treated water (sewage effluent) is drained off.

The quality of wastewater is dependent on the treatment provided, the operating strategy employed and the characteristics of the raw sewage. It is observed that treated wastewaters exhibit wide variations in quality. McLaren and Smith (1996) differentiated treated sewage effluent from normal 'clean' water in the following ways:

- Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of the effluent is higher. Treatment of the wastewater may reduce the BOD and COD, but the level of reduction depends on the intensity of the treatment.
- Inorganic concentrations are higher in wastewater particularly sodium, chloride and bicarbonates. These ions cause an increase in the total dissolved salt content (salinity) and sodicity (sodium content) of the wastewater and are generally not removed during treatment, except for some precipitation as carbonates.
- Effluents contain higher concentrations of macronutrients, especially N and P.

- The concentration of trace elements may also be higher as a result of addition of industrial wastewater to the sewer. Trace elements required by plants such as boron (B), copper (Cu), manganese (Mn), molybdenum (Mo) and zinc (Zn) may be present in excessive and possibly toxic concentrations. Other elements such as cadmium (Cd), lead (Pb), nickel (Ni) and mercury (Hg) may also contribute to the toxic hazard of the effluent.

Pathogenic microorganisms are present, although their concentration is reduced during the treatment process. About 600,000 faecal coliforms per 100 ml are found in secondary treated domestic sewage effluents in New Zealand. If treatment plants have disinfecting facilities, then faecal coliforms can be reduced to about 8000 per 100 ml (Hauber, 1995).

2.3.2 Industrial waste effluents

Industrial waste effluents include wastewaters produced or generated as a result of any manufacturing process , mining, trade or business related activities. This includes wastes from metal manufacturing or processing, plastic manufacturing, wine manufacturing, glass processing or manufacturing, tannery operations, pulp and paper mills, printing, textile manufacturing, fertiliser works, oil exploration and production sites and food processing. The disposal of these types of wastes is a concern particularly in maintaining the high quality of waterways whether for recreation or future use.

Since the chemical composition and biological properties of industrial effluents widely varies depending on the type of industry involved (Table 2.1) it is difficult to draft standard guidelines for their reuse and disposal. Waste effluents from factories in particular tend to be treated before disposal. However, many nutrients, metals and organic compounds remain in significant amounts after treatment. Although N and P in these wastes are useful for crop production, application on to land can be detrimental where toxic metals, organo-chemical compounds, high levels of salt and extreme pH are also present.

For example, waste effluents from pulp and paper milling industries contain metals, high amount of cations and a range of toxic organic compounds whereas tannery effluents contain toxic chemical elements and compounds such as chromium, aluminium, polyphenolics and aldehydes (Carnus and Mason 1994). Chapman (1996) reported that winery wastewater can be high in organic carbon, relatively low in nitrogen and phosphorus and moderately high in salts and acidity. Harding (1986) stated that each type of industrial waste has different properties. Because of the diverse chemical and biological nature of these wastes, each specify type of waste requires special precautions and considerations for treatment and disposal.

2.3.3 Agricultural waste effluents

Agriculture contributes a major part of the New Zealand economy. Dairy farming alone provided the country with an earnings of NZ$2,605 million in 1989, averaging about 14.7% of the export earnings (New Zealand Official Yearbook, 1990). The New Zealand Statistics (1993) estimated an area of 17.5 million ha of agricultural land, which is about 64% of the total land area of the country. The biggest proportion is used for animal grazing for about 8 million cattle and 55 million sheep in 1991. There is also a large number of pigs, poultry and other livestock raised. From these agricultural production and processing industries, about 530,000 tones of wastes was generated in 1991 (CAE, 1992). Cooper and Russell (1982) also estimated that the pollution level made by the meat processing industry alone is equivalent to the level produced by 3.5 million human population.

Agricultural wastes are valuable sources of nutrients and organic matter that can support crop production and ameliorate the soil. Vanderholme (1984) concluded that recycling, reprocessing and utilisation of agricultural wastes in a positive manner offer the possibility of beneficial use rather than simply disposal or relocation. In New Zealand, the estimated fertiliser value of dairy shed effluent, pig slurry and poultry manure amounted to NZ $36 million per year Bolan et al., 1997). The multiple discharge of effluent from dairy sheds represents a potentially large impact on receiving water quality and related adverse effects on the in-stream habitat. Although dairy oxidation ponds have been extensively used in New Zealand to treat the effluent, it still contains relatively high levels of ammonia, phosphorus, potassium, faecal coliforms, pathogenic bacteria and suspended solids that threaten the "green-clean image" of the environment if discharged to water-ways or allowed to percolate into the ground water.

Animal waste commonly refers to manure with added water, bedding soil, hair or spilled feed. It is a highly variable material with its properties dependent on several factors such as animal age and species, type of ration, production practices and environment. Other agricultural wastes may also be a mixture of several components.

There are eleven different types of pollutants referred to, or implied by standards in the Resource Management Act (1991), either in sections 70 or 107 on water quality classes (Third schedule):

- oxygen-demanding substances- which consume oxygen in receiving waters and thus affect aquatic life;
- suspended solid materials- which can settle in receiving waters causing noxious sludge and oxygen-depletion (and are also light-attenuating and may cause visual degradation- items 10-11 below;
- infectious microbiota which cause disease in man or domestic animals acids and bases- causing undesirable pH changes in waters;
- heat- causing thermal stress to aquatic life;
- toxic materials- that poison aquatic life (or people or domestic animals);
- nutrients- which promote nuisance plant growth in receiving waters;
- malodorous substances- causing "objectionable" odours to emanate from water;

- tainting substances- making water or fish flesh unpalatable;
- light-attenuating materials- which change optical properties (colour and clarity) to receiving waters so affecting the habitat for aquatic life and use by people;
- unsightly materials visually degrading floating, settling or suspended solids or immiscible liquid materials (e.g. grease, litter items and surfactants).

The pollutants listed above (except heat, acids and bases) are usually found in lagoons treating wastewaters from piggeries and dairy sheds.

2.4 Treatment of waste effluents

Waste management is a major concern of society. Recent concerns by the public and governmental agencies about non-point and point source surface and groundwater pollution have resulted in stricter regulations and concerted efforts to evaluate practices that will minimise water pollution. Untreated effluent is not allowed to be discharged directly into waterways and to some degree is prohibited from being spread on to land if it causes odour nuisance. In New Zealand, several waste effluent treatment strategies have been developed to remedy the problem of environmental pollution.

2.4.1 Physical treatment of waste effluent

Physical treatment of waste effluent involves the separation of solids and suspended particles from the liquid part of the effluent. This treatment reduces the rate of sludge build up in lagoons, wear on pumps and rapid reduction of the BOD (biological oxygen demand) concentration in effluent before disposal or reuse.

There are two basic methods of physical separation of waste effluent. One uses the difference in density between the particulate matter and the liquid using settling basins

2.4.2 Chemical treatment of waste effluent

Chemical treatment of waste effluent consists of adding chemicals to enhance treatment characteristics, such as settling of solids by pH correction (ARMCANZ and ANZECC, 1995).

2.4.3 Biological treatment of waste effluent

In New Zealand, agricultural, sewage and industrial waste effluents are often treated biologically using two pond systems (lagoon systems). This system is used to enhance the breakdown of volatile organic pollutants. The lagoon system is designed to take into account the quantity, quality and intermittent generation of effluents. It consists of anaerobic pond (first pond) and aerobic pond (second pond). The anaerobic pond carries out the treatment of waste effluent in the absence of oxygen which can effectively treat the initial strength of the effluent. The aerobic pond requires dissolved oxygen to further breakdown the effluent coming from the first pond into a more stable and less offensive form.

Traditionally, anaerobic effluent treated in the aerobic ponds was discharged directly into the farm drainage system, streams or rivers, but there has been rising concerns on the treatment and disposal of waste effluent produced by the market driven dairy farming industry.

Dairy stabilisation ponds built to standards and guidelines (MAF, 1985) have been commonly used by dairy farmers. The pond system was assessed as the best practical option for waste treatment (MAF, 1994) because of the following reasons (Dairying and the Environment Committee, 1996):

- A low cost system.
- Relatively simple in design and straightforward to install.

- A low cost system.
- Relatively simple in design and straightforward to install.
- Low in maintenance requirements.
- Adaptive as herd size changes.
- Able to readily fit into a larger effluent treatment system as an initial treatment.
- Effective when operating optimally. Treatment can reduce the concentration of nutrients and pathogenic microorganisms in effluent and decrease the risk of nuisance odours.

Unfortunately, reports on the performance of pond systems in New Zealand show they are often not meeting the standard requirement of treated effluent for discharging into waterways. The cold climatic condition is one of the reasons for the unsatisfactory performance of the pond system. In addition the average lighting of the whole water column in the ponds is too low to sustain phytoplankton growth (Davis-Colley et al., 1993). The Taranaki Regional Council (1995) also raised the fact that many older pond systems are receiving wastes from herds larger than for which the pond was designed. Incorrect design and management of pond systems are also factors that result in substandard treatment of dairy shed effluent. As a consequence, the pond effluent, when discharged directly to the waterways, introduces contaminants resulting in the following (Hickey et al., 1989; Taranaki Regional Council, 1995; Dairying and the Environment Committee, 1996):

- Removal of much less than 95% BOD_5. Design guidelines for dairy shed ponds should achieve 80% of BOD_5. However, in practice, they appear to be achieving only about 40-50% removal on average (Warburton, 1983; MAF, 1994 and Mason, 1994).
- Subsequent river deoxygenation with accompanying adverse effects on aquatic life. The low BOD_5 removal might be due to restricted supply of oxygen in the pond as indicated by limited biomass of algae. Mason (1994) presented in his study that the BOD is associated with the suspended solids (SS) fractions of wastewaters and the

continuous removal of the latter will substantially improve the effluent quality in terms of BOD level.

- High suspended solids in discharged effluent, causing nuisance algal and plant growth in waterways.
- Variable and sometimes unacceptable pathogenic microorganism levels in the discharged effluent, making the receiving water unsuitable for bathing and sometimes for stock watering.
- High concentrations of ammonia in discharges, with accompanying adverse effects on aquatic life. Ammonia in particular concerns regional councils as it is toxic to fish. Therefore the ammonia concentration in the effluent requires a very high dilution rate to eliminate this effect. Limited oxygen supply in the pond restricts the nitrification of ammonia-N.

New awareness of the environmental impacts of contaminants in dairy waste effluent and also the optical effect of effluent constituents has raised awareness that the traditional pond system should be upgraded to achieve a more sustainable waste effluent management practice.

A number of approaches to pond modifications and incorporation of supplementary treatment attachments were investigated to achieve improved standards of treated dairy shed effluent to better protect the environment. These include the use of *Pinus radiata* bark mixed with fluidised bed boiler ash to absorbed the bulk of ammonium from the dairy farm-pond effluent (Bolan et al., 1996); the use of natural New Zealand zeoliotes to remove NH_4-N in wastewater (Nguyen, 1996); and the use of "add-ins" and "add-ons" (Sukias et al., 1996):

- Add-ins - (like mechanical aeration and baffling) added to existing pond facilities.

- Add-ons - added to unchanged existing pond facilities, such as construction of shallow maturation ponds, rock filters, overland flow beds, constructed wetlands, rotating biological reactor and land application.
- Redesigned/configured pond facilities such as increasing pond size, provision of inlet and outlet structures, construction of shallow depth ponds, biofilm attachment to surfaces and the use of multiple ponds.
- Alternative process of treatment such as land treatment and wetland treatment.

2.4.3.1 Land application of waste effluents

The growing concern of protecting the environment and promoting the "green-clean-image" of New Zealand has prompted the regional councils to monitor compliance with the Resource management Act (1991) conditions covering the discharge of wastewater to waterways. The only way to avoid prosecution and penalties in disposing dairy shed pond effluent is to employ extra treatment technologies. Land application of waste is one such potential and inexpensive extra wastewater treatment technology.

Land treatment involves the application of waste effluents to the land as a convenient means of disposal. The soil acts as a living filter in terms of treating the waste effluent. The waste effluent undergoes several stages when applied to soil (Dairying and the Environment Committee, 1996).

- Suspended solids and microorganisms are filtered out between soil particles.
- Nutrients (e.g. nitrogen, phosphorus and potassium) are retained by the soil through sorption.
- Organic materials are broken down by the soil microorganisms.

Another feature of land treatment is the incorporation of vegetation. If waste effluent is applied to the vegetation, microorganisms and plants have the ability to remove or uptake nutrients as part of their nutrient requirement.

There are two concerns towards application of waste effluent on to land: disposing the effluent without regard to maximising the use of nutrients; and utilising the nutrients in the effluent as a fertiliser for crop production. Generally, land application provides the most efficient means of recycling valuable water, along with the nutrient and organic components of the effluent (ARMCANZ and ANZECC, 1995).

The discharge of waste effluent, particularly dairy-farm pond effluent onto land is an alternative disposal to discharge to waterways. Because effluent is rich in nutrients, it is a valuable resource that can be used or recycled for productive use. The objective of land application of secondary treated effluent is to utilise the chemical, physical and biological properties of the soil and plants to assimilate the waste components without adversely affecting the soil quality or causing contaminants to be released to water or to the atmosphere. Land treatment or land disposal of waste effluent is promoted as a more sustainable alternative to point discharges because nutrients are returned to the soil and plants. Cameron et al., (1996) reported that plant growth on the land treatment site is a key feature of the treatment system as it removes nutrients and water from the waste.

This was further documented by Labrecque et al., (1995) when Salix species were used as filters for the purification of sludge wastewater as well as for biomass production. Nielsen (1994) also reported that the incorporation of short rotation forestry trees such as poplars and willows in a land treatment scheme is advantageous because these trees have

- longer growing seasons and deeper longer lasting rooting systems that can utilise more efficiently the pulses of mineralised nutrients from the waste effluent and

- high evapotranspiration so are able to utilise wastewater for growth. Schultz et al, (1995) also confirmed that fast-growing trees added to a land treatment scheme reduced the nitrate-N concentrations of the wastewater from 12 mg/l to 2mg/l.

2.4.3.2 Wetlands systems

Constructed wetlands and natural wetlands are another form of biological treatment of waste effluent making use of constructed shallow ponds termed wetlands. This treatment is easy to manage without involving substantial capital and running cost. Studies have shown that wetlands can significantly reduce the BOD_5 and SS levels of pond discharges (Taranaki Regional Council, 1995). Wetlands are effective environments for denitrification and can be used in combination with mechanical aeration of oxidation ponds. The inclusion of plant system in the wetlands is an efficient feature of stripping nutrient from the waste effluent through plant uptake or assimilation but was not considered further in this study.

2.5 Health effects associated with wastewater treatment, disposal and reuse

Waste effluents must be applied to land in a way that does not cause a nuisance nor endanger health. The use of waste effluent should not increase the risk of disease from pathogens. Toxic elements from the waste effluents should not be allowed to enter into the food chain to eliminate the danger of toxic ingestion by animals or humans.

Treatment of waste effluents and their disposal is controlled by the legislative obligations of the Health Act, 1956, the Building Act, 1991 and the Resource Management Act, 1991. Standards were promulgated for land disposal of waste effluent with the intention to protect the public health in New Zealand in accordance with the social, climatic, economic conditions and aspirations of every citizen. The utilisation of waste effluents on to land is in accordance with the Maori cultural values and practices, in particular with regard to the use of natural water resources. Health issues associated with wastewater treatment, disposal and reuse is highly documented. One example is the environmental occurrence of Cryptosporidium in wastewater, treated wastewater, surface water and ground waters as reviewed by Rose (1997). In another incident, wastewater from oyster-harvesting vessels was identified as the probable source of oyster-associated viral gastro-enteritis outbreaks in Louisiana, USA, during the winter season (Farley et al., 1997).

Paul et al. (1997) indicated that subsurface disposal of wastewater can contribute to the degradation of water quality. This occurred when wastewater is injected into the porous limestone bedrock. Bacteriophages and viral tracers were evident in a simulated injection well and in an active disposal well. Another model (Shival et al.,1997) validated data confirming the outbreak of cholera epidemic as a result of direct consumption of vegetables irrigated with wastewater. Carcinogenic effects to human were also established when wastewater was treated with chlorine compounds. Chlorinated by-products of wastewater treatment that are discharged to surface water and enter into the drinking supply was highly correlated with the high incidence of waterborne cancer diseases (Doyle, et al., 1997).

It was also reported that the major source of exposure to chloroform is related to chlorination of wastewater entering the water supplies and occurs by ingestion of drinking water, inhalation or skin absorption as a result of other uses of chlorinated water at home (Wallace, 1997). Clinical findings established a high rate of cognitive deficits of patients with central nervous system dysfunction attributable to exposure to wellwater that was treated with trichloromethylene (White et al., 1997).

In a centre-pivot sprinkler irrigation system applying municipal sewage effluent, the number of microbial organisms increased with increasing amount of manure in the effluent (Magid et al., 1996). This indicates a probable incidence of spreading microbial diseases among people and animals living nearby areas affected with the disposal of the effluent.

Recreational water contaminated with waste effluent may be higher than previously expected. In a white-water rafting expedition in flooded rivers, some participants were diagnosed with unknown strain of febrile illness that was transmitted by Leptospirosis that come from the contaminated water (Reisberg et al., 1997).

The application of effluent to land planted with SRF species, if properly designed and managed can reduce the possibility of adverse effects on human health.

2.6 Resource Management Act (RMA) 1991

The statutory framework for managing water quality and restricting discharges to water in New Zealand is the Resource Management Act, 1991. The purpose of the act is to promote sustainable management of natural and physical resources. It relies on safeguarding the environment by avoiding and mitigating any adverse effects of activities on the environment. The RMA (1991) stipulates considerations of Maori spiritual and cultural aspirations for natural waters with respect to discharge of waste effluents. Section 15 of the Act requires every person who discharges contaminants into water to obtain a discharge permit from the regional council unless the discharge is specifically allowed by a rule in the regional plan or by regulations. The RMA (1991) is implemented by the regional councils of New Zealand. Each council has the authority to control discharges of contaminants on to land, water and air.

Section 70 of the Act prescribes that a regional council cannot make a rule in a plan that allows as Permitted Activity any discharge that would, after reasonable mixing in the receiving water produce any of the following effects:

- The production of any conspicuous oil or grease films, scums or foams, or floatable or suspended materials:
- Any conspicuous change in the colour or visual clarity:
- Any emission of objectionable odour:
- The rendering of fresh water unsuitable for consumption by farm animals:

- Any significant adverse effect on aquatic life.

Each region has set up a standard of disposal to surface water which varies with respect to regions. The standards governing the disposal of wastewater is presented in table 2.4 Each regional council have a set of specified standard parameters for the disposal of wastewater. Table 2.4 is a range of different standards adopted by different regional councils in New Zealand.

Table 2.4 Summary of standards in New Zealand in the disposal of wastewater to surface water as prescribed by regional councils and governed under the RMA (1991).

Parameter	Range of Standards
Treatment requirement	• Two pond system (anaerobic- aerobic), barrier ditch or effluent quality specified • Discharges of untreated wastewater or treatment by physical process only are prohibited
BOD_5	• Effluent quality $\leq$ 100 g m^{-3} (unfiltered) • Receiving water $\leq$ 2 g m^{-3} (dissolved carbonaceous)
SS	• Effluent quality - 100 - 150 g m^{-3} • Receiving water $\leq$ 5 g m^{-3}
Ammonia	• Receiving water $\leq$ 0.7 g m^{-3} at temperature $\leq$ 15°C • Receiving water $\geq$ 0.8 g m^{-3} at temperature > 15°C • Receiving water $\leq$ 0.7 g m^{-3} • Receiving water $\leq$ 0.8 with unionised fraction $\leq$ 0.02 g m^{-3} • Effluent quality $\leq$ 75 g m^{-3} (median)
Phosphorus	• Receiving water $\leq$ 0.01 g m^{-3} • Receiving water $\leq$ 0.015 g m^{-3}
Other considerations	• Receiving water -Section 107 plus discretion to impose additional conditions -No unacceptable impacts -Temperature change $\leq$ 3°C -Dissolved O_2 > 80% saturated concentration -No undesirable biological growths -Change in horizontal visibility $\leq$ 30% -Change in hue $\leq$ 10 (Munsell points) -Change in euphotic depth $\leq$ 20% -Limits on enterococci -Particulate organic matter -Dissolved reactive phosphorus • Effluent quality -Mean turbidity $\leq$ 60 NTU -Seven day mean annual low flow can provide 100:1 min dilution capacity -Faecal coliforms either $\leq$ 200 per 100ml or $\leq$1000 per 100 ml depending on use

Source: Forsyth, 1996

In New Zealand, the requirements for discharges of dairy shed and piggery wastewater to surface water is governed by the standards set by Regional Council and Unitary Authority Requirement for Discharges to Water under the RMA (1991).

The discharge of agricultural wastewater, like the dairy farm-pond effluent should meet the standards for effluent quality or receiving water quality as prescribed by the RMA (1991). These standards must not be less than the minimum standards set.

Discharges to land and water can be categorised as a Permitted Activity, Controlled, Discretionary, Non-Complying and Prohibited Activities according to the nature and scale of effects likely to be generated by the discharge.

In some other regions in New Zealand, Section 107 of the RMA, 1991 alone is used as the standard for the disposal of wastewater to surface water. Additional discretions can be imposed depending on each region.

2.7 Effects of land application of waste effluents to plants and trees

Land application of wastewater onto high dry matter producing vegetation not included in the food chain is a promising extra treatment technology. This offers opportunity for the beneficial use of nutrients while renovating the wastewater to a high degree. Barton et al. (1989) mentioned that crop uptake and subsequent harvest of energy crops can renovate nitrogen from wastewater. This is supported by the study of Frederick et al (1985) which shows that energy crops such as *Acacia dealbata* and *Eucalyptus regnans* can achieve an average uptake of 77 and 277 kg N/ha/annum over eight years, respectively. Other considerations include the relative ability of a vegetation to provide economic and environmental benefit. As an example, an eight year old *E. regnans* (based on above ground biomass) can provide of 33.5 TJ/ha of energy (Frederick et al, 1985). Given these considerations, the choice of SRF/soil system for wastewater treatment has the potential to:

- provide non-polluting source of energy;
- offset the CO^2 production from dairy farm effluent;
- renovate/filter dairy farm-pond effluent that will contribute to the local groundwater level;
- give potential utilisation of nutrients for production and
- provide potential resources for pulpwood and woodchip production..

Aside from preventing the possible risk of groundwater contamination, it is desirable to recycle nutrients wherever feasible, to support production of plants for food and fibre. Its reuse also represents energy conservation by cutting the energy demand for fertiliser manufacture and application.

2.7.1 The potential of short rotation forestry (SRF) for a landbased treatment scheme

High dry matter productivity of SRF crops is an essential criterion in a land based treatment scheme (George et al, 1986). Using this criterion, it is anticipated that the SRF crops can rapidly take up large amounts of nutrients. The extent of biomass production normally predicts the amount of nutrients to be assimilated by crops. There is no reason to expect that SRF plantations will give rise to any major environmental hazard from a nutritional point of view, provided the rate and timing of effluent application is adjusted to the nutrient delivery of the soil and uptake capacity of the plants.

Harvesting of the SRF crops is an additional process that will strengthen the durability of a landbased treatment scheme since the nutrients can be relocated away from the disposal site (Barton et al, 1989).

It is anticipated that the use of SRF crops for wastewater disposal will be accepted by the public, knowing that these crops are not included in the food chain. Added bonuses of SRF production is its potential for pulpwood and woodchip production. Lucrative export potential markets for SRF products exist since projected annual deficit of hardwood pulp log and woodchip are expected to grow as much as 2 million m^3 by the year 2000 (Asian Development Bank as cited by Rogerson, 1992).

2.7.2 SRF biomass production

Campbell (1991) identified several species of fast growing SRF crops as a non-polluting source of renewable energy. *Eucalyptus nitens* was one of the most promising having the ability to produce 36 oven dry tonnes/ha/annum of above ground biomass when grown in small plots (Frederick et al, 1986; Campbell, 1991). Its high wood density of 414 kg/m^3 makes *E. nitens* suitable for energy and pulpwood production (Campbell, 1991). Furthermore, *E. nitens* is a frost and cold tolerant crop and performs well on hill country exposed to severe summer drying (Hathaway & Sheppard, 1986), making this crop a potential all year round nutrient and wastewater assimilator.

Salix kinuyanagi rank second to *E. nitens* of the ten species compared, however its low wood density of 320 kg/m^3 makes it less suitable for energy wood production (Campbell, 1992). *Salix viminalis* and *Salix dasyclados* had been successfully grown in Sweden and Denmark as energy crops (Untregger and Ledin, 1992). In New Zealand *Salix* species are predominantly used for soil conservation practices because of their fibrous root system (Sims et al, 1991) and ability to survive in wet sites. These deciduous trees become dormant during the winter and the absence of plant activity could restrict their use in land treatment schemes.

2.7.3 SRF nutrient accumulation and evapotranspiration

Many studies have been conducted showing the beneficial effects of waste and wastewater application to plants. The nutrient and water component of waste effluents directly satisfy the nutrient and moisture need of the crop for maximum crop production.

Choudhary et al. (1996) reviewed the use of pig manure in crop production with emphasis on its effect on crop yield and composition. Pig manure application was reported to be effective in increasing the yields of cereals, legumes, oilseeds, vegetables and pastures and in increasing plant nutrient concentrations, especially nitrogen, phosphorus and potassium. In most agricultural crop production, basal application.
In eucalyptus and pines irrigated with sewage effluent for two years, Myers et al. (1994) reported that the rate of N accumulation in the trees was about 10 times greater than the rate of P accumulation, and that eucalyptus accumulated more nutrients than pines because of faster early growth rates. However, nutrient accumulation capacity in the eucalyptus decreased after canopy closure. This would be the time to harvest the trees in order to remove most of the nutrients from the site.

One of the important factors in achieving large increases in agricultural crop production is the mineral nutrient status of the plants (Ericsson et al, 1993). However, the nutrient requirement of plants vary depending on other factors, such as plant genera, length of vegetative stage, moisture and climatic regime of the area.

Environmental considerations with regard to nutrient requirements of SRF crops entails no hazard from nutritional point of view. The dense mat root system of SRF crops are efficient nutrient assimilators (Sopper, 1979). Leakage of wastewater when irrigated or applied on to SRF crops should pose no threat at normal loading rates, since SRF crops are known to intercept large amount of water. For example in Sweden (Table 2.5, Cienciala et al, 1994) the total transpiration of irrigated spruce for a period of 149 days was 3014 kg of water/tree compared to 2144 kg of water/tree for non irrigated trees. The presence of moisture or
Water can influence the amount of uptake of nutrients by plants. Rytter (1994) described in his study that daily irrigation of grey alders fertilised with about 2117 kgN/ha for seven years resulted in the enhanced nutrient status of the trees, thereby high nutrient concentrations in the litter produced

It was also noted by Sims et al. (1994) that roots of SRF crops irrigated with effluent at the rate of 200 mm/week at the Richmond meatworks Oringi, New Zealand are situated mainly in the top 400 mm of the soil layer while trees without effluent gave more even distribution of roots down to 800 mm of the soil column. Sims et al (1994) stated that the roots systems of the effluent irrigated trees may have adapted and amassed close to the soil surface in order to benefit from the water and nutrients flowing on or near the soil surface. It is anticipated that the fast growth observed in SRF crops and the high biomass dry matter production will result in enhanced nutrients levels in all parts of the trees.

Table 2.5 Total transpiration and total dry matter increment of spruce trees

Parameter	Irrigated	Control	Drought
Total transpiration (kg/tree)	3014	2144	1212
Total dry matter increment (kg/tree)	15.1	10	5.6

Cienciala, 1994
Calculation was performed for a continuous period of 149 days
Transpiration data was collected from Spring to Autumn for 24-year old spruce trees

Holmes and Colville (1979) showed evidence that forest use more water than grassland and this led the selection of a crop factor of 1.5 needed for the empirical estimate of tree evapotranspiration (i. e. 1.5 X pan evaporation) under the Wodonga (Australia) climatic condition. Morris and Wehner (1987) showed that high water use of irrigated eucalyptus is influenced by the dense canopy and architecture. These factors allow absorption of more energy for evaporation. Unrestricted availability of soil water owing to frequent irrigation and hence virtually no moisture stress; an arid climate conducive to high rates of plant transpiration when soil moisture is readily available, and possibly enhanced transpiration resulting from the changes in plant morphology induced by nutrient rich effluent were shown to be further advantages.

Several species of eucalyptus, willows and poplars have shown good potential for biomass production in New Zealand. Most often, the foliar nutrient concentrations of SRF crops are used as a baseline in assessing the need for fertiliser or nutritional amendments. However, it is recommended to look into the total nutrient requirement of each SRF crops. Table 2.6 shows the nutrient concentration of leaves (% of dry matter) of SRF crops grown at different stands and conditions. *Acacia dealbata*, followed by *Salix alba* are shown to be good potential nutrient strippers because of their nutrient concentrations in their leaves.

The foliage nutrient concentrations of SRF crops presented in table 2.6 are indicative of the crops' abilities to use nutrients from effluent. It is expected that these SRF crops will substantially exhibit their uptake when subjected to high loading of nutrients (Cromer et al, 1976).

Table 2.6 Foliage nutrient concentration of unfertilised SRF crops at different age of stands

SRF Crops	Age*	N	P	K	References
		(g/kg dry basis)			
A.dealbata	8	37.8	1.62	9.3	Frederick et al 1985
E. regnans	8	16.1	1.48	7.4	Frederick et al 1985
E. nitens	5	15.0	1.10	6.0	Frederick et al 1986
S. alba	5	26.2	2.31	6.4	Krstinic et al 1986
Hybrid Poplar	4	5.0	0.80	4.4	Wittwer et al 1980

*Age of trees when nutrient analysis was undertaken

Table 2.7 shows the biomass production and relative nutrient assimilation capacity of fertilised and unfertilised *E. globulus*. Added is the expected positive growth and biomass production response of SRF crops to unlimited supply of nutrients.

Table 2.7 Biomass and nutrient concentration of 4-year-old *E. globulus*

Treatments	Biomass[1] tonnes/ha	Nitrogen[2] kg/ha/y	Phosphorus[2] kg/ha/y
Unfertilised	1.6	6.6	0.4
Fertilised[3]	7.6	23.02	2.32

[1]Oven dry weight in the above ground components Cromer et al, 1976

[2]Nutrient uptake in the above ground components [3]202 kgN/ha and 90 kgP/ha

There was a dramatic response of *E. globulus* in terms of biomass production and nutrient uptake when fertilised with 202 kgN/ha and 90 kgP/ha from the date of planting till the age of 15 months (Cromer et al., 1976). Nutrients losses were evident in this study, which might have leached through the ground water, were volatilised, or locked up in the soil. However, such losses were not quantitatively evaluated.

Luxury uptake may interfere with the availability of other nutrients which might result in an unfavourable crop response. Baier (1992) presented evidence that very high levels of K become limiting to plant growth because of the interaction with Ca^{++}, Mg^{++} and (sometimes) H^{+}. Bonneau (1992) observed Norway spruce and white fir to be deficient in Mg if the Mg/K ratio was below 2. Likewise, white fir becomes K deficient if the Mg/K ratio is higher than 2. Hofmann and Muller as cited by Bonneau (1992) stated the K/Ca ratio is important, for example, a K/Ca ratio of 2 gave taller trees of Norway spruce compared with K/Ca ratio of 1.2.

At this point, everything is not known about the needs for fertilisation in forestry. Nutrient needs and nutrient deficiencies are usually defined in terms of foliar nutrient analysis. Application of nutrients must be made at the maximum safe capacity for plants to uptake without the fear of contributing more than the allowable level of nutrient contaminants to the groundwater. For example the nitrate-nitrogen (USEPA, 1976) level should be no more than 10 mgN/l and K level should be no more than 12 mgK/l with a guide of 10 mgK/l for drinking water (Johnston et al, 1992).

A major avenue of nutrient loss from plants is through litterfall. It is a major contributor to nutrient mass loading when considering the design of waste or fertiliser application to trees. Chapin (1991) mentioned that nutrient loss in litter is strongly influenced by litter's nutrient concentration, which is determined by the tissue concentration in live leaves and the degree to which nutrients are resorbed into the woody biomass before leaf fall. Table 2.5.5 shows the amounts of nutrients and biomass in litterfall and stemwood from an SRF crop in Wodonga, Australia (Stewart et al, 1988). *E. saligna*, had the highest nutrient levels in its stemwood and the lowest nutrient levels in its litterfall, and is thus a good potential SRF crop for land treatment.

Ericsson et al (1993) further support the fact that fertilised and irrigated stands of a two year old Salix viminalis plantations showed enhanced nutrition condition in leaves and leaf litter than untreated plants in Sweden.

Table 2.8. Stemwood and litterfall biomass (oven dry tonnes/ha/y) and nutrient content (kg/ha/y) of 4-year old SRF crops irrigated with municipal effluent

	P. radiata	Poplar 65/31	*E. saligna*
Stemwood			
N kg/ha/y	27.36	31.24	54.5
P kg/ha/y	5.13	14.2	10.9
K kg/ha/y	41.04	45.44	59.95
Litterfall			
N kg/ha/y	101.68	146.64	57.12
P kg/ha/y	9.84	24.96	4.2
K kg/ha/y	46.74	89.7	22.26
Biomass			
Stemwood t/ha/y	17.1	28.4	54.5
Litterfall t/ha/y	8.2	7.8	4.2

Computations based on Stewart et al (1988) data

Nutrient removal of SRF crops is also influenced by the age of trees when harvested for utilisation. Untregger (1992) presented evidence (Table 2.9) on the nutrient concentrations of a cloned willow (4/68T) at different ages. He disclosed a decreasing rate of 50% for P, 40% for N and 35% for K for 8-year-old willows when compared to 2-year-old willows. Harvesting can be done when canopy closure is reached for willows since accumulation of nutrients decreased.

Table 2.9 Nutrient contents of a cloned basket willow (4/68T)

Nutrients	2 years	4 years	8 years
N %	0.616	0.543	0.382
P %	0.0896	0.0688	0.0496
K %	0.195	0.157	0.127
Ca %	0.61	0.61	0.61
Mg %	0.0584	0.0663	0.0621
S %	0.06	0.06	0.06

Data taken from Untregger (1992)

O'Connell and Grove (1993) further disclosed that trees fertilised with 200 kgN/hectare/year resulted in 30% more N in the litterfall than in the control. Those applied with P at 200 kgP/hectare/year over three years resulted in 50% to 100% more P in the litterfall than the control. Moreover, Ca concentrations increased from 1.75% to 1.91% with increasing rates of P fertiliser, while K concentrations increased with increasing rates of P and N fertilisers. Table 2.5. 7 shows that 3 year-old E. diversicolor fertilised with N and P had higher nutrient levels in their litterfall than the 5-year-old trees.

SRF crops when irrigated with dairy shed oxidation pond effluent will assimilate and utilise the nutrients and wastewater for growth and biomass production.

Table 2.10 Comparison of the N and P contents (kg/ha/y) in the total litterfall of a 3 -year old and 5- year-old regrowth E. diversicolor treated with N and P fertilisers

	P_o-N_o	P_{200}-N_o	N_{200}-P_o	N_{200}-P_{200}
Nitrogen				
3 years	9.93	11.83	14.1	17.07
5 years	6.16	6.16	8.3	7.26
Phosphorus				
3 years	0.34	0.63	0.42	0.81
5 years	0.20	0.26	0.218	0.29

Data taken from O'Connell and Grove (1993)

2.7.4 Performance of SRF crops irrigated with municipal and industrial wastewaters

Several studies have been conducted in assessing the performance of SRF crops when irrigated with municipal sewage effluent and meatworks wastewaters. Each type of effluent varies in biochemical composition and this suggests varying the rates of application to SRF crops. For example dairy shed oxidation pond effluent typically contains 100 gN/m^3 of ammonium-nitrogen (Mason, 1994) compared to municipal sewage effluent which contains 20 gN/m^3 (Stewart et al, 1988). Since dairy shed effluent quality may vary significantly when compared to other wastewaters, its application to SRF must be properly documented to avoid the threat of environmental pollution.

In Australia, several tree crops were irrigated with municipal effluent as a part of a landbased disposal scheme for wastewater (Stewart et al, 1988). Response of trees irrigated with 1347 mm of municipal sewage effluent over 4 years is presented in Table 2.11.

Table 2.11 Biomass production* and mean nutrient concentration** of 4-year old trees irrigated with municipal effluent

Trees	Biomass t/ha/y	Nitrogen kg/ha/y	Phosphorus kg/ha/y	Potassium kg/ha/y
Poplar 65/31	11.65	63.25	14.75	49.33
P. radiata	10.43	63.25	6.5	51.77
E saligna	20.95	61.04	9.75	70.92
River she-oak	12.3	101.25	13.25	70.70

Stewart et al (1988)

E. saligna, responded well in terms of biomass production (Stewart et al, 1988). Although it had the lowest nitrogen concentration among the trees planted, its high rate of biomass production suggests a higher nutrient stripping capacity than the poplar and *P. radiata* trees.

George et al (1986) stressed the consideration of high dry matter productivity of a crop and not the rate of nutrient uptake when selecting a crop to give maximum nutrient removal from

the disposal site. Table 2.11 shows the performance of E. botryoides irrigated with 20 mm of meat processing wastewater per week over the control crop (Barton et al., 1991).
The difference in biomass production and foliage nutrient concentrations of irrigated E. botryoides compared to the control could be due to the nutrient effect, the irrigation effect or both.

Table 2.12 Biomass production and foliage nutrient concentration of 2.8-year-old *E. botryoides* irrigated with meat processing wastewater

Treatment	Biomass (tonnes/ha/y)	N%	P%	K%
Irrigated with 20mm/week of effluent	19.77	3.28	0.200	0.960
No irrigation	8.4	2.61	0.140	0.801

Barton et al. (1991)

2.7.5 SRF crops vs. pasture

In New Zealand, several studies have been conducted showing the performance of pasture as part of a land treatment. Cameron et al, (1993) disclosed that effluent flood irrigated pasture can capture 44% of applied nitrogen. Nitrogen loss through denitrification and the amount remaining in the soil were found to be 28% and 20% of the applied N, respectively.

A crop rotation schedule of rye grass in the winter and coastal bermuda grass in the summer demonstrated a 67% N nutrient recovery efficiency from the application of municipal waste effluent (USEPA, 1976). The unaccounted amount of N either leached out through the groundwater, was volatilised or remained as residual N. For phosphorus, 18 % of the effluent content was recovered by the crops.

Both pasture and SRF crops are potential filters for wastewater and harvesting these crops gives the opportunity to relocate unwanted nutrients away from the disposal site. However, when pasture crops are grazed by livestock, nutrients are returned to the disposal site via animal excrement, thus adding mass loading to the disposal site. Cutting the pasture and removal as hay or silage would overcome this problem.

Table 2.13, shows the N and P nutrients uptake of trees and grasses. The trees showed reasonable rates of nutrients removal, although some grasses were relatively higher in their uptake of nutrients. However, the use of SRF crops for land treatment can offer greater economic value depending on local market for fuelwood and pulpwood.

Holmes and Colville, (1979) mentioned that evapotranspiration varies with respect to crops, and that SRF crops transpire more than grassland. In Australia, Stewart et al (1988) selected a crop factor between 1.4 to 1.9 (multiplied by pan evaporation) to estimate the tree evapotranspiration, whereas in South Africa, Steynberg (1994) selected a crop factor of 0.4 for grassland during the first half of season and increased it to 0.9-1.0 during the later half of the season. Climatic factors such as temperature, rainfall, vapour pressure deficit, duration of sunshine hours and windspeed also influence the transpiration of plants.

Table 2.13 Fuel crop and pasture uptake of N and P

Crop	Yield (dry tonnes/ha/y)	N removal (kg/ha/y)	P removal kg/ha/y
Pioneer succession Vegetation[a]	-	250	-
White spruce[a]	-	250	-
Red pine[a]	-	160	-
Alfalfa[a]	-	155-220	-
Rye grass[b]	8.6	168.41	20.21
Reed canary grass[a]	-	226-359	-
Pasture[c]	-	218	-

[a] Data taken from Overcash et al (1979)
[b] Data taken from USEPA, 1976
[c] Flood-irrigated with animal urine (Cameron et al, 1993)

2.8 Effect of land application of waste effluents on the soils and the environment

Waste effluents applied to soil may be modified by physical filtration, inorganic and organic chemical reactions and biological transformations. Because of the processes involved, the application of waste effluent may alter the physical, chemical and biological condition of the soil.

2.8.1 Physical effect of waste effluent application

The physical aspect of treatment when waste effluent is applied to land involves the processes of filtration and dilution. As waste effluents move through the soil, suspended solid are removed and the filtrate may become diluted with soil water. This process is influenced by the a) physical properties of the soil such as soil texture, structure, infiltration, permeability and water holding capacity and b) the soil composition including mineral matter, organic matter, water solution and air component. Over time waste effluent applications may impact on these soil properties.

In a short rotation forestry plantation, high suspended solids in meat processing wastewater was thought to have caused the increase in bulk density of the soil and a reduction in infiltration rates at the head of irrigation borders (Barton and Cooper, 1990). As a result of reduced infiltration rates in the soil, the root systems of the SRF trees adapted and amassed closed to the soil surface to benefit from the water and nutrients flowing on or near the surface of the wastewater entry points (Sims et al., 1993).

In another study the application of meatworks wastewater for a period of ten years resulted in the reduction of soil bulk density by 20%, an increase of organic matter content by 40% and an increased in nutrient holding capacity by 15% (Tipler et. al., 1996).

Magesan et al. (1996) reported that the application of secondary treated sewage effluent increased the macroporosity of sandy loam soil from 11% to 19% and saturated hydraulic conductivity from 39 mm hr^{-1} to 57 mm hr^{-1}. However reductions in infiltration rate have also been reported following the application of fellmongery effluent (Balks and McLay, 1996). The application of wool scour effluent also reduced the permeability of soil by 95 % (McAuliffe, 1984). The reduction of movement of water in the soil might be attributed to the accumulation of solids filtered from the effluent (Kristiansen, 1981) or could be due to the collapse of soil structure from organic dissolution (Lieffering and McLay, 1996).

Several studies suggested the improvement of soil physical conditions when composted wastes were added to the soil (Hileman, 1967; Henry and White, 1990). On the other hand, land disposal of septic tank effluents resulted in soil clogging which was reported to be accelerated by a greater concentration of organic matter and suspended solids (Mitchell et al., 1982 and Siegrist, 1987). As a consequence, wastewater applied cannot infiltrate or percolate through the soil column because the pores in the soil are clogged. This will then result in waterlogging and the nutrients cannot therefore be transmitted to the root zone of plants for assimilation.

Wood et al. (1996) also discussed the changes that occurred in the physical and chemical properties of soil when irrigated with waste effluent. He stated that the nature of changes reflects the interaction between effluent quality, soil chemical and physical properties, land management practices, and climate. In some effluent-irrigated soils, soil salinity and sodicity have increased as a result of effluent irrigation. In most case this coincided with increases in saturated hydraulic conductivity. This suggests that the flocculate effect of the increase in electrical conductivity coefficient(Ece) was greater than the dispersive effect of the increase in exchangeable sodium percentage (ESP). To remedy the situation, the regular application of gypsum should restrict ESP to levels where soils do not become dispersive, hard-setting and impermeable.

2.8.2 Chemical effect of waste effluent application

The chemical aspect involves chemical reactions between dissolved ions and compounds within the soil which affects the mobility and fate of waste constituents of effluents. Because of chemical interaction, the pH, cation exchange capacity (CEC), electrical conductivity (EC) and ability of the soil to retain nutrients like NPK and metal may be affected as a result of effluent application to land. The chemical properties of the soil when altered by waste effluent application will determine its nutrient or chemical suitability for crop production.

Several studies had been conducted on the effect of waste effluent application to soil. Barkle et al. (1994) reported that the application of dairy shed effluent increased the soil biomass, the total soil nitrogen and carbon content, indicating that carbon and nitrogen from dairy shed effluent accumulated in the soil profile.

Stewart (1988) stated the non-measurable effect of effluent application on the total soil nitrogen despite of high inputs of organic and inorganic nitrogen present in the effluent. Teal (1997) also disclosed that nitrogen added through application of sewage sludge was either stored in the sediments or taken up by the plants and lost from the plots when tops senesced or died. At least 40% of total nitrogen inputs from all sources were lost through denitrification. (Howes and Teal, 1991).

The application of composted organic amendments to soil, like the combination of composted yard wastes and composted sewage sludge, significantly increases the soil pH, organic matter content and available supplies of phosphate and magnesium in the soil (Weir and Allen, 1997).

Pascual et al. (1997) observed decreasing phytotoxicity levels in sewage sludge, sheep manure and municipal sewage effluent over time when applied to soil. He further added that these materials showed noticeable positive residual effects on the crop. This result was verified by Alker et al. (1998) when studying landfill leachate to grow SRF trees. A reduction in volume and nitrogen concentration of leachate discharges from a landfill was reported by Hasselgren (1992) when willows were planted in the landfill site. This result emphasised the beneficial effect of using soil-plant systems to reduce nutrient concentrations and volumes of discharged leachate.

A build up of P and K and higher concentrations of nitrate-nitrogen and ammonia-nitrogen to a greater depth within the soil profile from injected liquid dairy manure was more evident than surface application with the number of annual applications (Sutton, 1982). This implied that the chemical characteristics of the soil was affected by the application of dairy waste effluent.

Choudhary et al. (1996) reported increased nitrogen, phosphorus, potassium, calcium, magnesium and sodium levels in the soil as a result of pig manure application. Excessive application of pig manure increased leaching of nitrate-nitrogen, phosphorus and magnesium.

Application of pelletised mixtures of sewage sludge and other waste materials resulted in increased soil acidity, electrical conductivity, nitrate nitrogen and organic carbon. A reduction in exchangeable calcium and sodium in the soil was also observed (Hulugalle, 1996).

2.8.3 Biological effect of waste effluent application

The biological transformation processes involve the living organisms or organic materials embedded in the soil due to the addition of waste effluent can alter the biological composition of the soil. Addition of viruses, protozoa, bacteria, algae, nematodes and other animal populations. Organisms present or added to the soil help in the decomposition of organic materials requiring oxygen and release of carbon dioxide. This biological transformation determines the capacity of the soil to break down organic materials into useful nutrients. One of the factors involved in the management of biological biota in the soil is an enhanced supply of nutrients using management practices that encourage nutrient cycling from organic residues (Pankhurst and Lynch, 1994). These soil biota are often responsible in processing or transforming nutrients in the soil through waste application to be readily available for plant use.

2.9 Research directions

In every part of the world, authorities are faced with managing increasing quantities of wastewater and residual products of wastewater treatment facilities. Although utilisation of wastes and wastewaters is an old concept, the recent development and progress in public environmental awareness raises the concern of protecting the soil and water as valuable commodities for the future. Strict compliance with rules and regulations governing the protection of soil, waterways and groundwater has been administered which has led to the application of partially treated effluent on to land to sustain crop production.

However, the discharge of waste and wastewater on to the land has another potential risk of endangering the environment by creating new environmental problems if not properly managed and monitored. These problems may include the introduction of heavy metals and pathogens into the food chain or into the water resources; contamination of wastewaters with nitrates, phosphorus and salts; deterioration of soil structure and salinisation of soil. Scientific research and effective transfer of technology through well structured scientific communications are key issues to be emphasised in the land treatment of wastes and wastewaters.

The New Zealand Land Treatment Collective provides a structured forum within which various findings from research can be translated into practical results and these can be a sound basis to embark upon land treatment operational schemes.

Since the advancement of wastewater treatment technology is every aspect of environment protection, alliance among all fields of discipline is necessary to work out a solution for waste disposal that will embody the aspect of social, cultural, economic and environmental issues of a community.

Continued efforts for appropriate disposal of wastewater to land should be directed towards provision of scientific credibility to operational programs, exploration of new application opportunities and to address specific environmental issues as they emerge from operational programs of land treatment.

In recent years, research on land treatment of waste effluents had been directed in the nutrient cycling and water use of vegetative crops. However, the long term sustainability of applying waste to the land is a foreseen challenge . There is a need to develop operational land treatment schemes of waste effluent and it is vital to include:

- Effluent application
- Nutrient cycling
- Species selection
- Tree management systems
- Biomass utilisation and harvesting
- Economics
- Sustainability

In recent years, effective waste management has been implemented to recycle and treat wastes. However, there are increasing political, cultural and public pressures, d consequently resulting in more stringent environmental regulations regarding the treatment and disposal of wastewater to surface waters. Secondary treatment cannot perfectly purify the waste water to a standard level. Hence, land application with the addition of vegetation is seen as a tertiary effluent which helps in filtering the pollutant loadings on surface and ground waters.

The New Zealand Land Treatment Collective has stressed the issues on the effect of BOD or COD in terms of loading rates to soil because these can become limiting factors for irrigation of agro-industrial effluents. Another issue is the critical effect of suspended solids and particle size distribution when designing irrigation systems for agro-industrial wastewaters and for the selection of appropriate methods.

Nutrients and crop consideration were also considered by the Land Treatment (1998) to be critical constraints in the application of waste effluent to land. To ensure crop health the following key points have been emphasised:

- Characterise the waste key nutrients, on a recurring basis.
- Identify the crop to be grown, its potential yield, and nutrients requirements to achieve that yield for N, P, K, Mg, Ca, and other elements of key concern for the specific soil crop;
- Calculate appropriate waste loadings according to nitrogen, hydraulic or carbon limits as pertinent.
- Identify nutrients which are likely to be limiting, given any mismatches between waste loading and crop requirements and native soil fertility.
- Initiate a monitoring programme tailored to determine the fertility and health of the crop on a timely basis.
- Take any corrective action, including supplemental fertilisation, as necessary.

Land application of waste effluents has advantages and disadvantages for the environment, particularly on soil conditions. These effects depend on the characteristics of the waste effluents, the soil characteristics and the vegetation. Research monitoring programmes are therefore necessary to ensure that waste application systems are sustainable and that they do not damage the soil quality (Cameron, 1996).

In some areas, continued research on the advancement of waste treatment was directed to the development of technologies that will mitigate the detrimental effect of wastes and wastewaters to the environment. As a trend, a necessary alliance between engineering and ecology is evident in a number of ongoing and proposed wastewater treatment processes, centres or systems. For example Hinge and Stewart (1997) built a solar wastewater treatment in Denmark during the autumn and winter in 1988 and 1989 which, met the standards of 1.5 mg L^{-1} of total phosphorus, 8mg L^{-1} total nitrogen and 15 mg L^{-1} BOD_5. The plant consisted of three functionally independent parts, namely, solar algae system, ditch system and root-zone beds.

Reconstructing wastewater treatment systems based on ecological principles can minimise environmental problems and facilitate utilisation of the resources in wastewater (Jenssen and Etnier, 1997). Measures for optimising the reuse of nitrogen and phosphorus often result in decreased water consumption. This can be seen in a holistic system of ecological engineering. Nitrogen removal is an example in which overall system analysis should have been applied. In many European countries increased N-removal from wastewater is mandatory as per the directive in the North Sea Treaty. As a result conventional treatment plants are being rebuilt to add a denitrification step.

2.10 Conclusions and Recommendations

Waste effluents contain significant amount of nutrients. Their use for agricultural and SRF production as a source of valuable nutrients and irrigation water can increase crop production and also ameliorate the soil if properly managed and monitored.

The literature suggests that SRF crops, particularly willows and eucalyptus, have good potential for land treatment of wastewaters because of the following reasons:

- rapid growth and biomass production
- reasonable rate of nutrient stripping capacity
- high evapotranspiration capacity
- capability of filtering wastewaters
- use as a non-polluting renewable source of energy
- economic value for pulpwood and fuelwood production
- offers the opportunity to relocate nutrients from the disposal site when harvested
- enhances the scenic attribute of a disposal site because of the beautifying effect of vegetation

The nutrient stripping capacity and ability of SRF trees to use more water from waste effluents applied to land can be attributed to their fibrous mat-like root structure. Loading rates of wastewater should match the capacity of the soil and the vegetation to uptake the water and nutrients and eliminate any danger of leaching and runoff of nutrients and micro-organisms that are detrimental to the quality of surface and groundwaters and to the environment. Nitrogen is often the limiting factor when applying effluents onto the land because of the danger of contaminating the groundwater with nitrates. However, K is the limiting factor when applying dairy shed pond effluent on to the land because of the high K composition of the effluent. This will be discussed in the methodology section of chapter 3 as it determined the effluent application rate used in the field experiments.

CHAPTER 3

GROWTH, BIOMASS PRODUCTION AND NUTRIENT ACCUMULATION BY TEN SPECIES OF SHORT ROTATION FORESTS

3.1 Introduction

Willows and eucalyptus are known for their rapid growth, resprouting capacity after harvest and ease of vegetative propagation. These characteristics are suitable for the selection of biomass production when grown as short rotation forest to treat wastewater irrigation. The ability of several eucalyptus species to produce large amounts of biomass within a short time and in a range of soils including those low in nutrients and water has made these species particularly attractive for wastewater treatment purposes. Kutera and Soroko (1992) showed irrigation with wastewater effluent increases the growth and biomass of fast-growing trees and shrubs. Riddell-Black (1995) also stated that rapid growth rates and regular frequency of harvesting give good renovation. Application of wastewater onto high dry matter producing vegetation offers opportunity for the beneficial use of nutrients while renovating the wastewater (Barton, et al., 1989). The biomass produced can be used for energy purposes as fuelwood or for feedstock for the fibre industry.

Aside from preventing the possible risk of ground water contamination and eutrophication of waterways, it is desirable to recycle nutrients from wastewater wherever feasible to support sustainable crop production. Hence, the purpose of this experiment were to:

- evaluate the response of ten species of short rotation forest trees to different rates of dairy farm-pond effluent irrigation and water + nitrogen in terms of biomass production and nutrient accumulation;

- identify species of short rotation forestry trees that were suitable for dairy farm-pond effluent irrigation and
- determine the level of dairy farm-pond effluent irrigation that produced optimal biomass production and nutrient accumulation into the biomass of short rotation forestry trees.

3.2 Methodology

A field trial was established at the experimental site of the Horticultural Research, Aokautere near Palmerston North in June, 1994. Ten species of short rotation forestry (SRF) trees were planted in plots of 16 trees spaced at 0.85m on the square in a randomised block design. There were three replicates for each treatment in this experiment. The soil type was a Manawatu fine sandy loam. The soil characteristics were determined before the application of dairy farm-pond effluent began. The effluent was sourced from the Dairy Farm No. 4 of Massey University. A tank with a capacity of 10,000 litres was used to transport effluent from the source to the experimental field every irrigation schedule. The effluent was then pumped into two 5,000-litre holding tanks on the experimental site and the effluent later irrigated onto the trees. A micro sprinkler irrigation system was designed to apply the effluent at 100kPa to irrigate the plots at rates of 7.5 mm, 15 mm or 30 mm together with 7.5 mm water per fortnight + N (187.5 kgN ha^{-1} $year^{-1}$). The lowest application rate was calculated to match the nutrient requirement or assimilation capacity of trees (Overcash and Pal, 1979, Ericsson et al., 1993 and Stewart et al., 1988) and the effluent nutrient concentration level (Warburton, 1983 and Mason, 1994). The lowest application rate was doubled and quadrupled for the medium and high rates of effluent irrigation, respectively. Each application treatment was replicated three times on each of the ten tree species for each of the four irrigation treatments, giving a total of 120 plots.

Effluent applied for every irrigation schedule during the two growing seasons November-April 1994-95 and 1995-96, was sampled and analysed using standard laboratory procedures. The pH, total nitrogen, total phosphorus, potassium, calcium, magnesium, BOD, COD, and electrical conductivity of the effluent were determined following the standard procedures of wastewater analysis (APHA, AWWA, and WEF, 1992 and Nicholson, 1994). The total volume of effluent applied to SRF trees in a year was distributed within 13 fortnights during the six growing months of the year. The intensity of applying the effluent was determined to match the soil properties of the disposal site.

The biomass production for first season's growth was estimated using a non-destructive method by establishing a relationship between the diameter and height of the stem of the ten SRF trees. This was accomplished by taking branches with diameters bigger than 2 cm from trees of each species from the guard rows outside the 120 plots. The basal, mid and top diameters of each stem were measured. The branches and leaves were then oven dried overnight at 80° Celsius to obtain oven dried weight of the trees. The data were correlated using linear regression analysis. After the second growing season the trees were harvested to determine the biomass production of the ten species. Each sample tree was weighed and a representative sample for each species was taken and oven dried to determine the oven dry weights of trees. The leaves of the trees were separated from the stem for each sample to obtain the biomass properties of stem and leaves.

Stems were sampled from the bottom, middle and top. While the leaves were collected at random from the crown of each tree. Nitrogen, phosphorus, potassium, calcium and magnesium contents of the stems and leaves for each sample plant were analysed using standard laboratory methods (Bolan and Hedley, 1987 and Nicholson, 1994).

3.2.1 Nutrients in the effluent

Table 3.1 shows the average volume and nutrient composition of effluent applied for each treatment. The biomass and nitrogen, phosphorus and potassium contents of SRF trees (willows and eucalyptus) and the effluent were taken from the literature. This information was used to calculate the loading rate of effluent. Potassium was found to be the limiting factor of applying effluent to SRF crops as attributed to the potassium concentration level of effluent (Warburton, 1984) and the capacity of trees to assimilate the nutrient (Ericsson et al., 1993 and Stewart et al., 1988). Results have shown that dairy farm pond-effluent contains high concentration level of potassium, while nitrogen ranked second in concentration (Table 3.1). It was estimated that at 900 m^3 of effluent application, the amount of K applied in the effluent (Warburton, 1984) would equate the amount of K in the biomass of a eucalyptus (Stewart et al., 1988). An application of 115 kgN ha^{-1} $year^{-1}$ resulting from the lowest application rate of 900 m^3 $ha^{-1}year^{-1}$ of effluent was also determined.

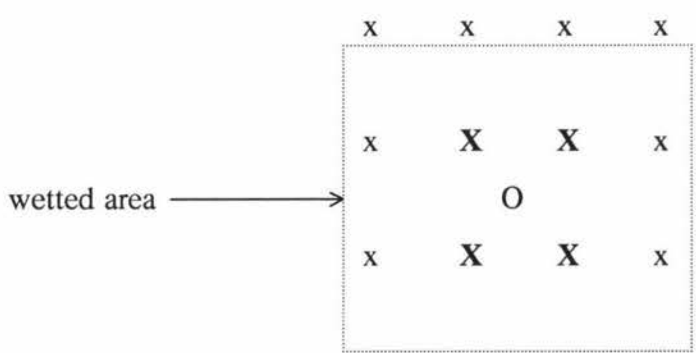
Table 3.1 Total nutrients contained in the effluent applied to SRF trees over two growing seasons.

Irrigation rate	7.5 mm	15 mm	30 mm
Volume (m^3/ha/year)	900	1800	3600
Total Nitrogen (kg/ha/year)	115	230	473
Ammonia (kg/ha/year)	88	176	351
Total Phosphorus (kg/ha/year)	23	56	91
Dissolved reactive Phosphorus (kg/ha/year)	13	26	53
Potassium (kg/ha/year)	197	394	799
Calcium (kg/ha/year)	21	42	84
Magnesium (kg/ha/year)	13	26	52
PH	7.5 - 8.1		
Electrical Conductivity (mS/m)	180 - 230		

3.2.2 The experimental site

The experiment was conducted at an experimental site at the New Zealand of Horticultural Research Institute at Aokautere, Palmerston North. The site was 27.2m X 51m with a total area of 1387.2 m^2 and the soil type was Manawatu fine sandy loam soil. The site had a 10-year mean annual rainfall of 995 mm, average daily maximum temperature of 17.2 °C and average daily minimum temperature of 8.6°C. The average annual evaporation at raised pan level was 1069 mm and the average annual sunshine total hours is 1794.

Land preparation consisting of primary, secondary and tertiary tillage were performed after the collection of pre-treatment soil data. The area was divided into three blocks and planted with ten species of SRF trees in plots of 16 trees spaced at 0.85 m by 0.82 m in a randomised block design. Four sample trees for each block of 16 trees. These were planted around a micro-sprinkler unit and within the wetted perimeter of irrigation. The planting density was at 14,000 trees per hectare. The schematic diagram for each plot is shown in figure 3.1.



x - guard rows **X** - sample trees O - sprinkler

Figure 3.1 Schematic diagram of each plot of SRF species irrigated with either effluent or water + nitrogen

3.2.3 Establishment

Ten species of SRF trees were established on the site. Nine species of salix and one of eucalyptus were planted in June 1994. Willow sticks measuring 30 cm each, were planted while 5 month old *E. nitens* seedlings were transplanted. All ten species were irrigated with the same amount of water and grown until November, 1994 before the treatment of effluent irrigation was initiated. However, *E. nitens* had zero survival rate. The roots of the seedlings had been disturbed when excavated from the plantation site and transplanted to the experimental site. The eucalyptus were also sensitive to the first frost encountered after the establishment stage of the trees. Therefore *E. nitens* plots were replanted in October, 1994 using 3 month old seedlings grown in root containers. These gave 100 per cent survival in spite of difficulties experienced. Mounds of soil were piled around the base of each eucalyptus tree to prevent loss of moisture. However, gaps were created at the base of each seedling as the trunks were blown and swayed with the wind. Each young eucalyptus tree was therefore supported initially to protect it from being blown and twisted. This technique helped the eucalyptus to survive until they grew sufficiently to withstand the wind.

The nine species of salix included in this experiment were PN 386 (*Salix kinuyanagi*), PN 695 (*Salix matsudana or Shanghai*), NZ 1002 (*Salix matsudana x alba or Aokautere*), NZ 1130 (*Salix matsudana x alba or Hiwinui*), NZ 1184 (*Salix matsudana x alba or Moutere*), NZ 1290 (*Salix matsudana x alba*), NZ 1295 (*Salix matsudana x alba*), NZ 1296 (*Salix matsudana x alba*) and NZ 1365 *(Salix matsudana x alba)*. All species planted had 100 per cent survival rate and started developing leaves in the spring of 1994. A plan and a view of the experimental site are shown in figures 3.2 and 3.3, respectively.

PN 695 1	NZ 1290 3	NZ 1184 2	PN 695 0	E.nitens 0	NZ 1290 2	PN 386 0	NZ 1365 2
NZ 1184 3	NZ 1365 3	NZ 1290 1	NZ 1295 0	NZ 1002 2	NZ 1130 3	NZ 1295 2	NZ 1130 1
PN 695 2	NZ 1002 0	NZ 1296 2	PN 386 3	E.nitens 1	NZ 1365 0	PN 386 2	NZ 1002 1
NZ 1130 0	NZ 1365 1	NZ 1296 1	NZ 1296 0	NZ 1295 1	PN 386 1	NZ 1002 3	PN 695 3
NZ 1184 1	E. nitens 3	NZ 1184 0	NZ 1130 2	NZ 1296 3	NZ 1295 3	E.nitens 2	NZ 1290 0
NZ 1365 1	NZ 1130 3	NZ 1002 1	NZ 1184 3	NZ 1130 0	NZ 1295 1	NZ 1365 3	NZ 1184 2
NZ 1290 3	PN 695 1	NZ 1002 2	NZ 1295 3	PN 695 0	NZ 1002 0	E.nitens 0	E.nitens 3
PN 386 0	NZ 1130 1	E.nitens 2	NZ 1002 3	E.nitens 1	PN 386 2	NZ 1184 1	NZ 1296 2
NZ 1290 0	NZ 1296 0	NZ 1290 0	NZ 1365 2	NZ 1184 0	NZ 1295 2	NZ 1290 1	NZ 1130 2
PN 695 3	PN 386 3	PN 386 1	PN 695 2	NZ 1296 1	NZ 1365 0	NZ 1296 3	NZ 1295 0
NZ 1296 1	NZ 1296 0	NZ 1002 1	PN 386 3	NZ 1295 2	PN 386 1	NZ 1365 1	E. nitens 1
NZ 1130 1	PN 695 2	NZ 1295 3	NZ 1290 2	NZ 1184 3	NZ 1365 0	NZ 1184 0	NZ 1365 2
NZ 1290 3	NZ 1295 1	PN 386 2	NZ 1365 3	E.nitens 0	E.nitens 3	NZ 1290 1	NZ 1184 2
NZ 1296 2	NZ 1290 0	E.nitens 2	NZ 1296 3	NZ 1184 1	PN 695 3	NZ 1295 0	NZ 1130 3
NZ 1002 3	NZ 1130 2	NZ 1002 0	PN 695 1	NZ 1130 0	NZ 1002 2	PN 386 0	PN 695 0

Figure 3.2 Experimental layout of ten species of SRF trees irrigated with dairy farm pond effluent or water + nitrogen (0 = 7.5mm water + N; 1 = 7.5mm effluent; 2 = 15mm effluent; and 3 = 30mm effluent)

Figure 3.3. Salix and eucalyptus newly established in the experimental site

3.2.4 Maintenance

Weed control was necessary throughout the plantation area to reduce competition for light and soil nutrients until all the trees reached the closed canopy stage (at 12 months for willows and 24 months for eucalyptus after transplanting). Weed control was also necessary to minimise the disruption of effluent distribution pattern from the sprinklers. Manual hoeing and chemical weed control by spraying herbicide (Roundup) were both carried out on the salix until the start of the second growing season and until the summer of the second growing season for the eucalyptus. The eucalyptus did not reached full closed canopy prior to harvesting (after 20 months from transplanting). Canopy closure in these trees normally occurs 22-24 months after transplanting at this plant density (CSIRO, 1994).

Wind damage and stem breakage, particularly at the top of the trees were common to the nine species of willows at canopy closure. The development of foliage of several willows had resulted in an imbalance of crown to roots which might be due to the supply of effluent containing high concentration of nitrogen. Several insects and birds were observed during the experimental period, but there was no incidence of insect damage or pathogenic diseases.

3.2.5 Monitoring

After the first year of irrigation following tree establishment, the three best performing species of SRF trees were selected based on the estimated biomass production (section 3.2). The soils under PN 386, NZ 1295 and Eucalyptus nitens that were to be irrigated at the highest rate of effluent (30 mm) were sampled before irrigation began. Two sets of soil samples were taken within the anticipated wetted perimeter of each plot along the designated guard rows for the four sample trees during the first year to avoid disturbing the soil along the four sample plants for each block.. The sampling depths was down to one metre depth to determine chemical changes within the soil for the first year.

The trees were harvested after the second growing season before the *Salix* species shed their leaves. Bulk density and infiltration rates were determined for the second year immediately after harvesting. The cylinder method was used for determining the bulk density of the soil (McLaren and Cameron,1996) and a double ring infiltrometer was used to determine the infiltration rates (Raes, 1989).

The exchangeable cations and cation exchange capacity for the first and second growing seasons were only determined for the soils under PN 386, NZ 1295 and Eucalyptus nitens that were irrigated at different rates. However, after the first growing season, only the soils under the trees irrigated at 30 mm of effluent were analysed for chemical properties, limited by the cost of analysis.

3.3 Results and discussions

3.3.1 Growth of SRF trees

3.3.1.1 Cumulative height of SRF trees

The height of the trees were monitored during both growing seasons. The initial heights were recorded on the 18-11-94 at the start of effluent application. Figure 3.4 shows the cumulative height of each tree species under the four irrigation treatment over both growing seasons. The increments in height were recorded on the 5 May 1995, 18 November 1995 and at harvest on the 5 April, 1996.

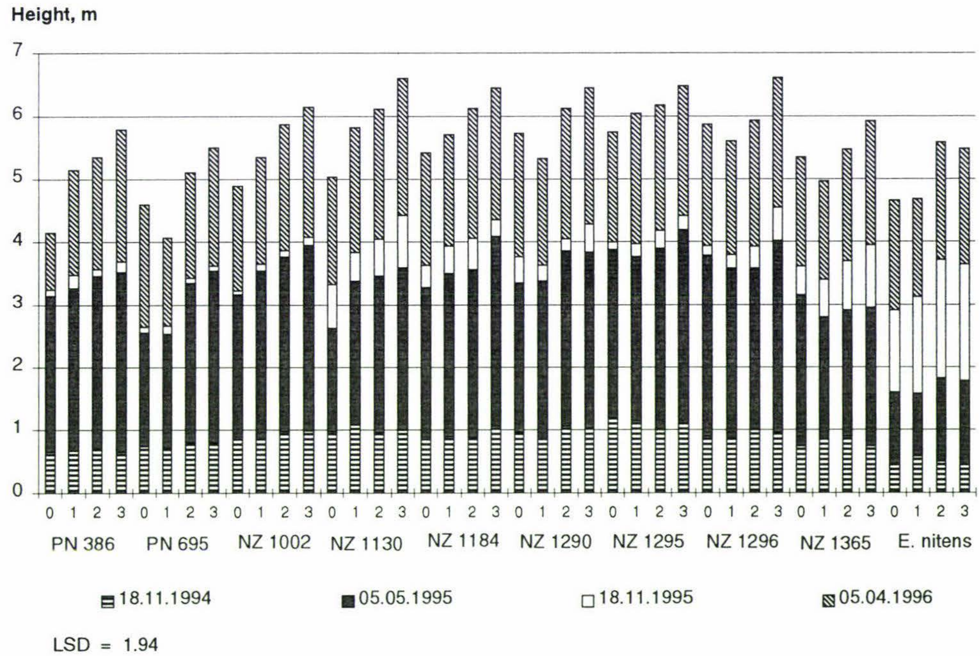


Figure 3.4. Average heights of ten tree species irrigated with 3 rates of dairy farm-pond effluent and water + nitrogen and measured at four stages over two growing seasons (0 = 7.5 mm water + 187.5 kg N $ha^{-1}year^{-1}$, 1 = 7.5 mm effluent, 2 = 15 mm effluent and 3 = 30 mm effluent)

At the start of applying effluent to SRF trees, all the ten species appeared healthy. The period between the initial application of effluent in early summer of 1994 and May 1995 resulted in a 2 to 3 m increment in height for all salix species. This was attributed to the effect of irrigation and suitable growing climatic regime during the growing season. The days were long with extended sunshine hours during this period and these conditions were suitable for the substantial increments in the height. The eucalyptus grew up slower than the salix during the first year of establishment.

The nine species of salix showed little increment in height between late autumn of year one and late spring of year two as they were dormant having shed their leaves in May. The eucalyptus continued to grow being non-deciduous. The increment in height was affected by the irrigation treatment. Trees irrigated with the highest rate of effluent were significantly taller than the trees irrigated without he lower rates of effluent and with water + nitrogen.

Overall the cumulative height varied with respect to species and with the amount of effluent applied to trees. NZ 1295, NZ 1296, NZ 1184, NZ 1290 and NZ 1130 were all significantly higher ($p > 0.01$) at harvest than the other species of SRF trees. This result is similar to the findings of Senelwa (1997) that a gradual variation and differentiation in early tree growth occurred among species. The eucalyptus had initially lower cumulative height and showed slow growth during the first year possibly due to the stabilisation period requirement of these trees to their new environment (White et al., 1993; Sennerby-Forsse et al., 1993).

The comparison among irrigation treatment means of cumulative height of each species at harvest were significantly higher ($p > 0.01$) when irrigated at 30mm of effluent per fortnight than the other irrigation treatments. Growth of plants is sensitive to soil water deficits. Cienciala et al., (1993) reported that the growth of willows is highly correlated with the amount of water entering the soil. Hillel (1990), Doorenbos et al. (1979) and Stone et al. (1996) also showed that crop yields is highly dependent on the level of water supply. Trees irrigated with 7.5 mm of effluent did not differ in cumulative height at harvest when compared to trees irrigated with 7.5 mm water and fertilised with 187.5 kgN ha^{-1} $year^{-1}$, but were significantly shorter than trees irrigated at higher rates.

3.3.1.2 Dry matter assessment

The oven dry biomass production of trees was assessed during the first year using a non-destructive method (refer to 3.1)

The following equations were derived for non-destructive measurement of oven dry biomass of one year old SRF trees.

Salix sp. $OD = 94.21 * (MD^2 * H^{0.3})^{1.033}$ (1)

Eucalyptus $OD = 45.67 * (BD^2 * H^{0.33})^{0.994}$ (2)

where:

OD = oven dry biomass, g

BD = basal diameter, cm

MD = mid diameter, cm

H = height of stem, m

The above ground dry matter biomass of the nine species of salix were highly correlated with the mid diameter and height of stems ($R^2 = 0.92$). These results were similar to the findings of Ek (1990). The aboveground biomass of *Eucalyptus nitens* was found to be correlated with its basal diameter and height ($R^2 = 0.88$) which is similar to the findings of Madgwick (1981).

The mean annual increment of oven dry biomass for the ten species irrigated with effluent in both year 1 and year 2 was estimated from the derived algorithms in year 1 and measured by destructive harvesting in year 2, respectively (figure 3.5). NZ 1295, a tree willow, was significantly higher than the other species. Eucalyptus nitens had the lowest estimated mean oven dry above ground biomass production after year one partly due to late planting of these seedlings three months after the willow sticks. The trend for eucalyptus to grow slowly initially, and particularly until soil temperature rise was similar to the findings of White et al.(1993) and Sennerby-Forsse et al. (1993).

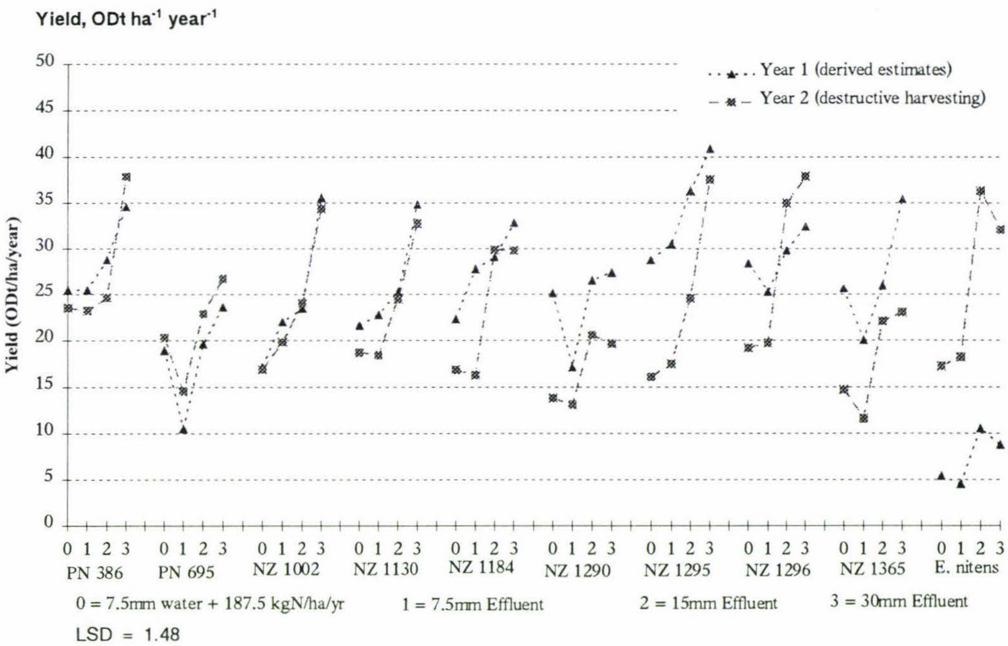


Figure 3.5 Above ground biomass yields ten tree species irrigated with effluent or water after one growing season derived from tree height and diameter and measured after the destructive harvest in year two

Mean estimated oven dry above ground biomass of all species in year one also varied significantly with respect to irrigation treatment. Plots irrigated with the highest rate of effluent per fortnight (30mm) produced significantly higher biomass than the other irrigation treatments. The tree willow, NZ 1295, when irrigated at 30mm of effluent produced the highest biomass production of over 40 ODt ha^{-1} $year^{-1}$. This result confirms other findings that salix were among the fastest and highest producers of biomass when treated optimally concerning nutrient and water supply (Siren et al., 1984; Perttu, 1991; Christerson, 1992 and Senerby-Forsse et al., 1992).

The oven dry above ground biomass of trees at year two were significantly different between species and among irrigation treatment ($p > 0.01$). NZ 1296 and PN 386 produced significantly higher ($p > 0.01$) above ground biomass than all the other species giving 27.95 and 27.36 ODt ha^{-1} $year^{-1}$, respectively. NZ 1295 and *Eucalyptus nitens* followed producing incremental biomass yields of 25.97 and 23.92 ODt ha^{-1} $year^{-1}$, respectively.

The mean oven dry above ground biomass significantly differed between species of SRF trees and the irrigation treatment. SRF trees irrigated with the highest rate of effluent were significantly higher yielding than the other irrigation treatments ($p > 0.01$) and produced a mean above ground biomass of 31.19 ODt ha^{-1} $year^{-1}$ which was almost twice the yields from the lowest irrigation rates. This result supports the findings of Cienciala et al. (1993), Sopper (1980), Perttu (1993) and Stewart et al. (1988) that irrigation is likely to accelerate and increase the growth and production of fast-growing trees and shrubs where water is limiting. Stone et al. (1996) also concluded that yield of crops increased when the rate of mineral nitrogen fertiliser and slurry application was also increased.

Trees irrigated with 7.5 mm water and fertilised with 187.5 kgN ha^{-1} $year^{-1}$ were significantly higher than the trees irrigated at the same rate of effluent application. The reason was possibly that nitrogen applied through dissolved inorganic urea fertiliser was more readily available for trees to uptake than the nutrients applied through effluent.

With regard to interactions between properties, NZ 1295, NZ 1296 and PN 386 significantly produced higher biomass than all the other treatments at rates of 37.58 37.91 and 37.87 ODt ha^{-1} $year^{-1}$, respectively, when irrigated at 30mm of effluent for two growing seasons ($p > 0.01$). In year two, there was a huge increase in the biomass production in every irrigation treatment of Eucalyptus nitens (figure 3.3) which had at this stage outgrown six salix species. However, it did not reach canopy closure before harvesting in year two which further explains the lower biomass yield from *Eucalyptus nitens*. Moreover, Myers, et al. (1994) showed that biomass accumulation to 2.5 years of age in eucalyptus was high due to the fast growth rate of these trees before canopy closure which occurred 28 months after planting.

3.3.1.3 Stem biomass

Stem biomass of the ten species irrigated with effluent or water + nitrogen was compared (figure 3.6). NZ 1296 and NZ 1295 when irrigated at 30 mm of effluent were significantly higher in producing 35.29 and 35.68 ODT ha^{-1} $year^{-1}$ of stem biomass, respectively, than all the other treatments ($p > 0.01$). This was followed by PN 386 with 33.62 ODt $ha^{-1}year^{-1}$ of stemwood.

The stem biomass production were also significantly increased as a result of effluent irrigation. Trees irrigated at the highest rate of effluent produced significantly higher stem biomass than the other trees irrigated with the other three treatments. The highest total mean stem biomass production of trees when irrigated at 30mm of effluent 29.04 ODT ha^{-1} $year^{-1}$ followed by the application of effluent at 15 mm at 25.34 ODT ha^{-1} $year^{-1}$. Analysis also revealed that trees applied with 7.5 mm water and nitrogen were significantly higher in stem biomass than trees irrigated with 7.5 mm effluent. This trend was similar to the total biomass.

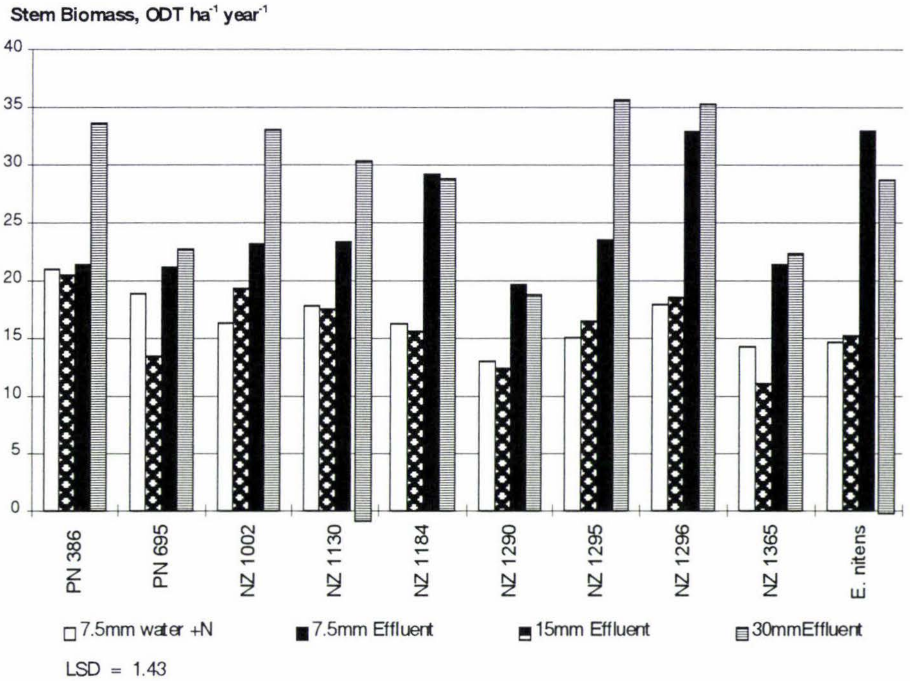


Figure. 3.6 Mean annual increment of stem biomass of ten species with irrigation treatments averaged over two growing seasons.

3.3.1.4 Leaf biomass

The leaf biomass of SRF trees are presented in figure 3.7. There was a wide variation in the amount of oven dry leaf biomass among the ten species evaluated. PN 386 produced significantly higher leaf biomass ($p > 0.01$) than the other species at 3.18 ODt ha^{-1} $year^{-1}$. This was followed by Eucalyptus nitens at 3.0 ODt ha^{-1} $year^{-1}$. The leaf biomass can be associated with the characteristics of leaves. The leaves of PN 386 are thick and silvery while other willows are much thinner. On the other hand, the leaves of the eucalyptus were broad and thicker compared to the willows. Figure 3.7 shows the oven dry leaf biomass. The shrub willows contained more leaf biomass than the tree willows. PN 695, a shrub willow, showed dominance in terms of leaf biomass over the seven tree willows but was significantly lower than PN 386 and *Eucalyptus nitens*.

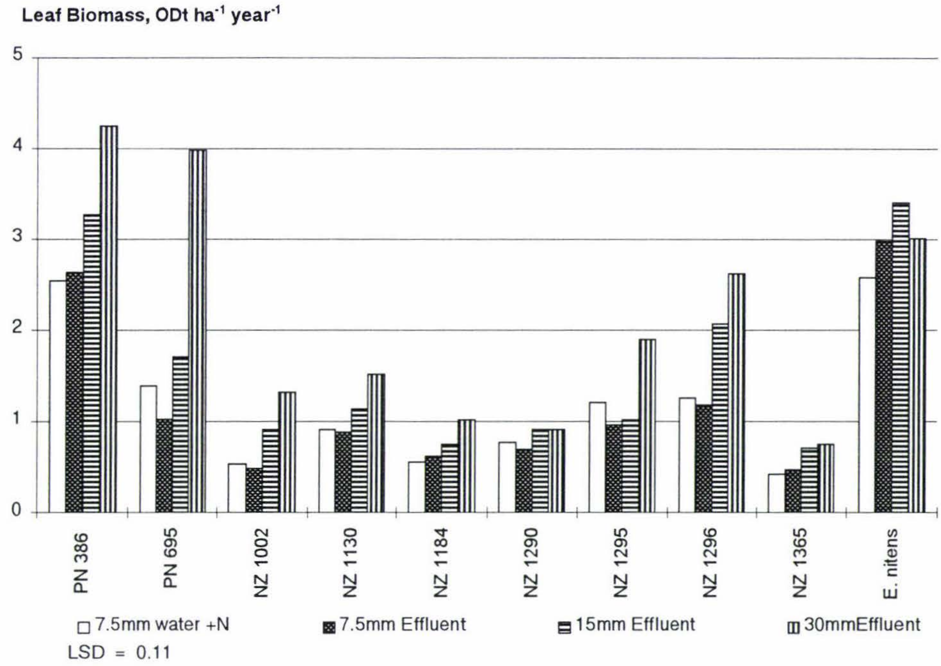


Figure 3.7. Mean annual increment of leaf biomass of ten species with irrigation treatments averaged over two growing seasons

Irrigation with effluent significantly increased the oven dry leaf biomass of SRF trees ($p > 0.01$). Trees irrigated at the highest rate of effluent resulted to significantly higher mean oven dry leaf biomass of 2.13 ODT ha^{-1} $year^{-1}$. This was followed by the application of 15 mm of effluent with leaf biomass production of 1.59 ODT ha^{-1} $year^{-1}$. Application of the lowest rate of effluent at 7.5 mm did not differ in the production of leaf biomass to trees irrigated with 7.5 mm water + nitrogen. The shrub willows, PN 386, *Eucalyptus nitens* and PN 695 responded well particularly to the application of effluent at 30 mm.

3.3.2 Nutrient uptake of SRF trees

The establishment of SRF trees is comparable to the nutrient demand of arable crops because of its rapid growth and frequency of harvest (McLaren and Cameron, 1996). Riddle-Black (1995) stated that SRF tree crops have relatively high nutrient requirements since N, P, and K are present in the stem tissues of willows and poplars in the approximate ratio of 20:10:14. At harvest these are removed from the plantation site.

There are 16 essential elements that are essential for plant life. And in modern intensive SRF biomass production, the natural supply of nutrients from soil is not adequate to sustain the nutrient requirement of trees for high yields sustainably over the long term. A situation of low supply of nutrients and inaccessibility of nutrients, this will result in poor health, appearance and low biomass production. For this reason, supply of nutrients through application of waste effluent is one method to supplement the soil nutrients that can be readily taken up by the trees. However, the nutrient requirements of plants vary depending on other factors, such as plant genera, length of vegetative stage, moisture and climatic regime of the area (Ericsson, 1993).

3.3.2.1 Nitrogen uptake

Nitrogen is an essential nutrient required by SRF trees that can influence the emergence of leaves and development of canopy. It is the most important yield-increasing plant nutrient and its unavailability will limit growth (Hansen et al., 1988 and Rytter, 1990). Restricted supplies of nitrogen will also result in increased biomass partitioning below ground level to enable the roots to explore the soil in search of nutrients.

The amount of nitrogen taken up above ground level by the ten species trees above the ground level is presented in Figure 3.8. Nitrogen accumulation increased with the volume of effluent applied. This can be attributed to the increasing amount of nitrogen supplied through increased amount of effluent irrigation (refer to table 3.1).

Results also showed that most of the nitrogen was accumulated in the stems of tree willows, whilst in the shrub willow, PN 386, the leaves contained more nitrogen. Nitrogen in the leaves of *E. nitens* equated to that of the stem.

The partitioning of nitrogen in the biomass of SRF species is influenced by the dry weight biomass of each part of the tree. PN 386 and *E. nitens* had higher leaf biomass compared with the tree willows (figure 3.7) which explains the high amount of nitrogen locked in the leaves of these trees.

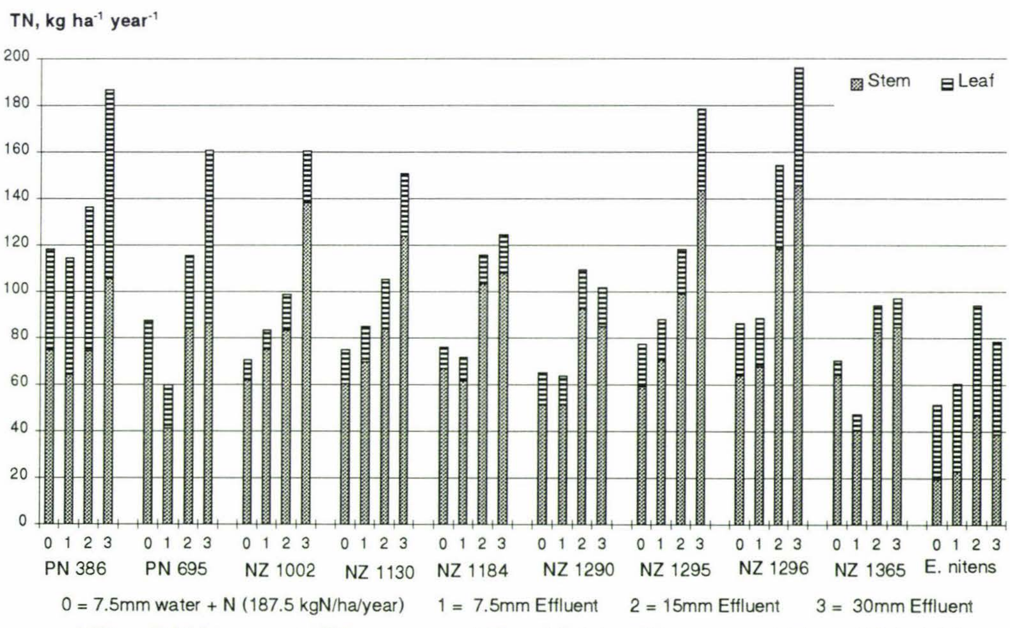


Figure 3.8 Above ground TN of ten SRF trees irrigated with dairy farm-pond effluent and water (7.5 mm) + N (187.5 kg ha^{-1} $year^{-1}$) over two years

Accumulation of nitrogen in the above-ground biomass of SRF trees varied significantly between species and between irrigation application treatments. SRF trees irrigated at the highest rate of effluent (30mm per fortnight) accumulated significantly more nitrogen ($p > 0.01$) in their biomass compared with other treatments for all ten species. NZ 1296 showed the greatest significant ($p > 0.01$) accumulation of nitrogen at a mean level of 196.02 kg N ha^{-1} $year^{-1}$, followed by PN 386 when irrigated with the highest rate of effluent (30 mm). *E. nitens* recovered the lowest amount of nitrogen among the ten SRF species. Application at 15 mm of effluent was higher than both 7.5 mm treatments for all species. Nitrogen in the effluent may have exceeded the trees' requirements and this could result in luxury uptake of nitrogen. This confirmed the results of Rytter (1994) that daily irrigation and fertilisation with 2117 kg N ha^{-1} $year^{-1}$ for seven years resulted in enhanced nutrient status of the trees. Thereby resulting in high nutrient concentration in the litter. Rytter and Ericsson (1993) also found that irrigation and fertiliser application to willows increased the foliar N content. Stone et al. (1996) reported that increasing the rate of mineral nitrogen fertiliser and pig slurry application increased the nitrogen uptake of crops. This result supported the findings of Perttu (1993) that various salix species are suitable crops to renovate nutrients from wastewater through nutrient uptake. Ledin (1996) disclosed in his report that willow was efficient in taking up nutrients because of its well developed root system and long growing period. Pempkowiak (1994) found that concentrations of nitrogen, phosphorus and chemical oxygen demand in effluents decreased by a factor of two or three after application to pots planted with willows. This indicated nutrient uptake by the willow cuttings.

The positive response of biomass production to effluent application suggests renovation of the nitrogen by the trees. Results obtained by Brockway et al. (199x) that nitrogen applied at rates of 400 to 500 kg/ha have been associated with tree growth increases of up to 40% without producing soil leachate concentrations of nitrate that exceed the 10 mg/l limit U.S. EPA. The nitrogen uptakes of NZ 1296, PN 386 and NZ 1295 were 196.02, and 186.41 kg N ha^{-1} year^{-1} (figure 3.8) for every 473 kg N/ha/year (30mm effluent/fortnight) applied (table 3.1).

Nitrogen levels in the biomass when applied with in the treatment of 7.5 mm water and inorganic nitrogen did not differ with those applied from those with the lowest effluent irrigation treatment (7.5 mm effluent).

The amount of nitrogen in the stem varies significantly between species and between irrigation treatments (figure 3.8). Higher nitrogen was found in the stems of tree willows than in the stems of *E. nitens*. NZ 1296 contained significantly higher amounts of nitrogen ($p > 0.01$) in its stem when irrigated with 30 mm of effluent.

Trees irrigated with the highest rate (30mm of effluent) were significantly higher in nitrogen level ($p > 0.01$) in their stems than at lower irrigation treatments. This result might be due to luxury uptake of nutrients because the amount of nitrogen supplied through effluent application exceeded the nitrogen requirement of trees (refer to table 3.1). However, trees irrigated with 7.5 mm of effluent did not differ with 7.5 mm of water + N irrigation treatment

Figure 3.8 shows the trend of the amount of nitrogen in the leaf biomass of the SRF trees. There is a significant variation in the amount of nitrogen accumulated in the leaf biomass between SRF species and irrigation treatments. Significant amount of nitrogen was accumulated in the leaf biomass of PN 386 (80.9 kg ha^{-1} year^{-1}) when irrigated at 30 mm of effluent. The accumulation of nitrogen in the leaves can be associated with the leaf biomass produced by the trees.

The supply of nitrogen through effluent irrigation exceeded the requirement of trees that might had led to luxury uptake of nitrogen in the leaves. However, trees irrigated at 7.5 mm of effluent did not differ in nitrogen uptake with those irrigated with 7.5 mm of water + N treatment.

3.3.2.2 Phosphorus uptake

Phosphorus, like nitrogen, is an essential nutrient for plant and animal growth. It is important that phosphorus supply meet the demands of plants or trees to achieve optimum growth and biomass production. For example in willows and poplars the ratio of N P K in the stems are 20:10:14 (Riddle-Black, 1995). This indicate that phosphorus should be supplied to match the requirement of trees. In this scenario, the dairy farm - pond effluent is a valuable resource of phosphorus to supplement the requirement of SRF trees because it contains 24 g m^{-3} of total phosphorus (Bolan et al., 1996).

The above ground TP (total phosphorous) in the biomass of the SRF trees are shown in figure 3.9. The total phosphorus levels accumulated by the trees widely varied between species and between irrigation treatments. NZ 1296 was significantly higher ($p > 0.01$) in accumulating TP in its biomass at 37.62 kg^{-1} ha^{-1} year when irrigated with the highest rate of effluent (30 mm) than all the other treatments. The irrigation treatments affected the ability of the trees to accumulate total phosphorus in their biomass. Dale and Chesnin (19XX) showed very high concentrations of P in plants applied with sludge.

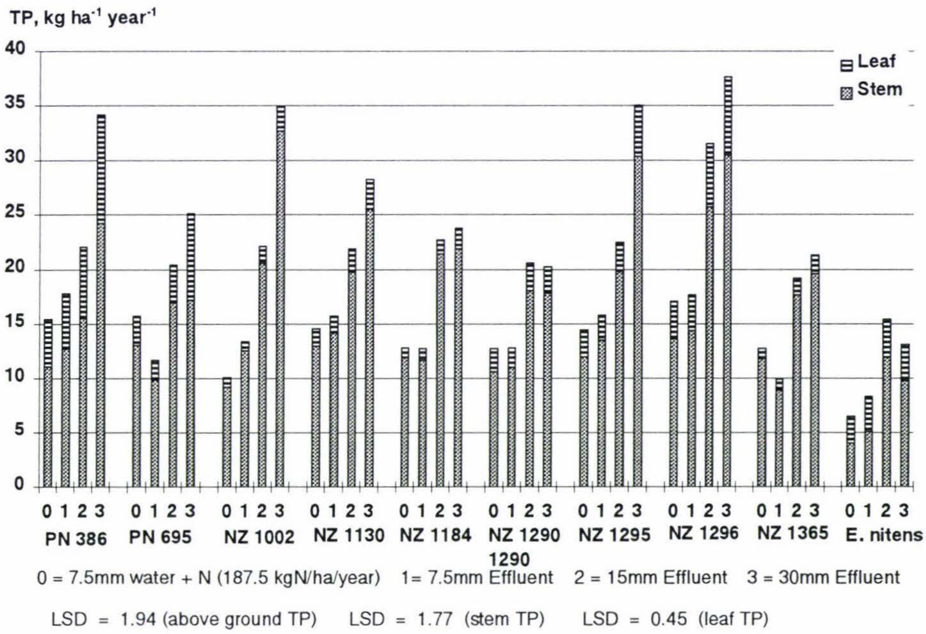


Figure 3.9 Above ground total phosphorus of SRF trees irrigated with dairy farm-pond effluent and water + N (187.5 kgN/ha/year) over two years

The total phosphorus uptake of NZ 1296, NZ 1295 and PN 386 were 37.62, 36.65 and 34.16 kg ha^{-1} year^{-1}, respectively, when applied with 91 kg ha^{-1} year^{-1} (30mm effluent) of TP. *E. nitens* accumulated 15.45 kg TP ha^{-1} year^{-1}, when applied with 56 kg TP ha^{-1} year^{-1} (15 mm effluent). This result for the eucalyptus confirms the findings of Myers et al. (1997) regarding the tree accumulation of 15 kg P ha^{-1} year^{-1} in a plantation of eucalyptus and pines in Australia. However, nutrient accumulation of trees is influenced by different factors such as the type of crop, plant population density, climatic regime of the plantation and supply of moisture and nutrients (Potash and Phosphate Institute of Canada, 1988).

Phosphorus accumulation in the stem of trees is significantly different between species and between irrigation treatments. NZ 1002, when irrigated at 30 mm of effluent accumulated significantly higher TP (32.72 kg TP ha^{-1} year^{-1}) in the stem than all the other treatments ($p > 0.01$). This was followed NZ 1296 at 30.49 kg TP ha^{-1} $year^{-1}$. PN 386 accumulated 24.22 kg TP ha^{-1} $year^{-1}$ and *E. nitens* accumulated the least amount of 9.82 kg TP ha-1 $year^{-1}$.

This result suggests that the uptake of total phosphorus by trees is a function of the amount of phosphorus supplied to the trees. The amount of stem biomass also indicates that phosphorus is locked up in the stem of the trees. Trees irrigated with water and applied with fertiliser did not differ with those applied with 7.5 mm of effluent in accumulating total phosphorus in its biomass.

Results revealed that phosphorus in the leaves was significantly different between species and between irrigation treatments ($p > 0.01$). PN 386, when irrigated with 30 mm of effluent accumulated significantly higher TP in the leaves (9.95 kg ha^{-1} $year^{-1}$) than all the other treatments. *E. nitens* accumulated 3.27 kg TP ha^{-1} $year^{-1}$ in the leaves when irrigated with 30 mm of effluent. This confirms the findings of Knight and Nicholas (1997) regarding the TP in the leaves of eucalyptus when supplied with the total phosphorus requirement of the tree.

3.3.2.3 Potassium uptake

Potassium in plants plays a vital role in photosynthesis, the process by which the sun's energy in combination with water and carbon dioxide is converted into sugars and organic matter. It has been said that the nitrogen is the most important yield-increasing plant nutrient, but potassium is the most significant nutrient in stabilising yields and growth stimulants in plants (Potash and Phosphate Institute of Canada, 1988). Because potassium is highly mobile, this allows the roots of the trees to uptake the nutrients into the plant system. The mobility of this nutrient also allows the plants to uptake large quantities of potassium for plant growth and metabolism.

Figure 3.10 shows the amount of potassium absorbed in the biomass of the ten SRF trees. Accumulation of potassium in the biomass of SRF trees varied significantly between species and between irrigation treatments ($p > 0.01$). *E. nitens,* when irrigated at 15 mm of effluent significantly accumulated higher potassium in its biomass at rate of 141.42 kg ha^{-1} year^{-1} than all the other treatments. NZ 1296, when irrigated at 30 mm of effluent ranked second in accumulating potassium in its biomass at 130.87 kg ha^{-1} year^{-1} and was found to be significantly superior over the other willows except NZ 1295. Riddell-Black (1995) reported tree crops, such as like willows have relatively high potassium requirement.

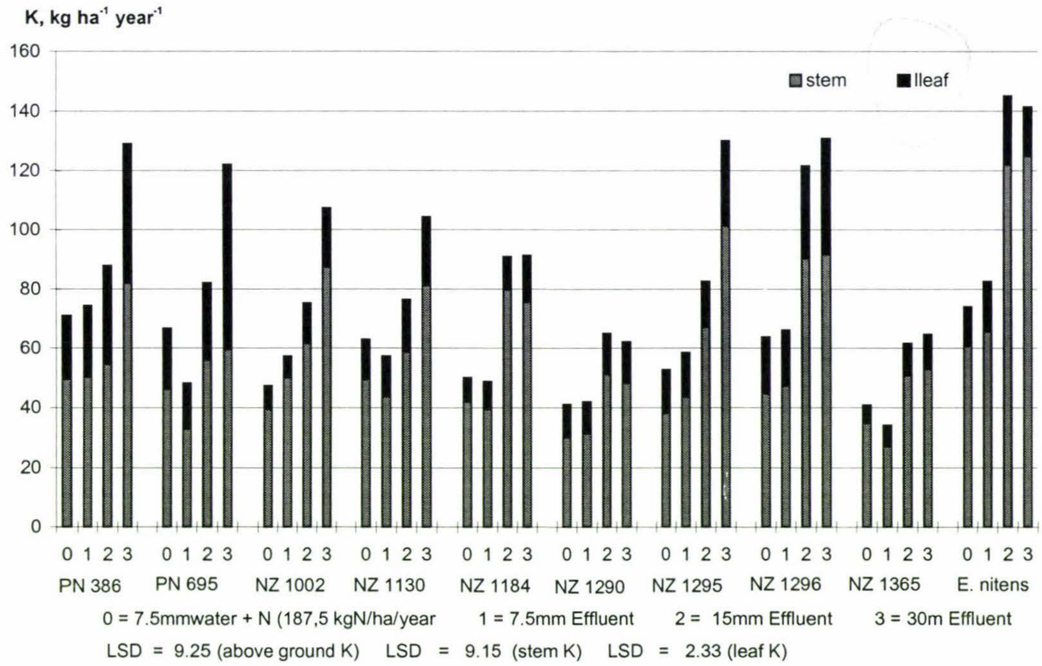


Figure 3.10. Above ground K of SRF trees irrigated with dairy farm-pond effluent and water (7.5 mm) + N(187.5 kg ha^{-1} year^{-1}) for two years

The abundant supply of potassium through the application of effluent, particularly at 30mm level of irrigation, allowed the luxury uptake of the nutrient by the *E. nitens*. The availability of water more than the requirement of the trees through effluent application also influenced the mobility of potassium to be readily taken up by the trees. The same trend was found by the Potash and Phosphate Institute of Canada (1988) when crop responded to addition of potassium when water is supply is excessive. Chappin (1991) stated that the rate of nutrient uptake of plants depends on both the rate of nutrient supply and the amount of moisture in the soil. Similarly, the sufficient supply of potassium sped up the flow of water and the products of photosynthesis (assimilates) within the plant enhancing the storage of compounds in the different parts of the plants (Potash and Phosphate Institute of Canada, 1988).

The accumulation of potassium in the biomass of SRF trees at the highest rate of effluent application might have been enhanced by the sufficient supply of other plant nutrients supplied through effluent application like nitrogen and phosphorus. This result was also disclosed by the Potash and Phosphate Institute of Canada (1988) based on several experiments that demonstrated the greater need for and response from potassium fertiliser when application rates of nitrogen phosphorus, sulphur and micronutrients are increase on soils.

Results showed that potassium in the stems of trees varied between species and between irrigation treatments. *E. nitens* accumulated significantly higher amount of potassium ($p > 0.01$) in its stem than all the other treatments at 124.87 kg $ha^{-1}year-^{1}$ when irrigated with 30 mm of effluent.and NZ 1295 at 101.20 kg ha^{-1} $year^{-1}$.

Potassium in the leaves of trees were significantly different between species and between irrigation treatments ($p > 0.01$). The leaves of PN 695, when irrigated with 30 mm of effluent were significantly higher in potassium level (62.44 kg ha^{-1} $year^{-1}$) than all the other treatments.

The sufficient supply of nitrogen and phosphorus through the highest rate of effluent application might have enhanced the assimilation of potassium in the leaves of SRF species. This confirms the findings of O'Connell and Grove (1993) that showed increased potassium level in the litterfall of trees with the increasing application of nitrogen and phosphorus.

3.3.2.4 Calcium uptake

Calcium is a major determinant of growth in plants (McColl, 1970) along with other macronutrients. The amount of calcium in the biomass of SRF trees irrigated with dairy farm-pond effluent and water + nitrogen is presented in figure 3.11. The amount of calcium in the above ground biomass of SRF trees varies significantly between species and irrigation treatments. *E. nitens* was significantly higher in calcium in its biomass ($p > 0.01$) than all the other treatments when irrigated with 30 mm of effluent. In several studies, eucalyptus were found to have large requirement for, and uptake of nutrients, and in particular, calcium (Turner and Lambert 1983; 1996; Lambert and Turner 1991; and Madeira 1989).

Trees that were not supplied with calcium, like the trees irrigated with 7.5 mm of water + nitrogen showed the lowest response of calcium accumulation in its biomass. This suggests that the application of calcium through effluent irrigation at a large supply resulted to higher amount of calcium accumulated in the biomass of trees that fuelled the rapid growth and high biomass production of trees. The absorption of calcium at large quantities by the trees was also enhanced by the sufficient supply of phosphorus through effluent application at 30mm per fortnight. The same result was obtained by O'Connell and Grove (1993), when calcium concentration in trees increased from 1.75% to 1.91% as a consequence of increasing the rates of phosphorus application to trees.

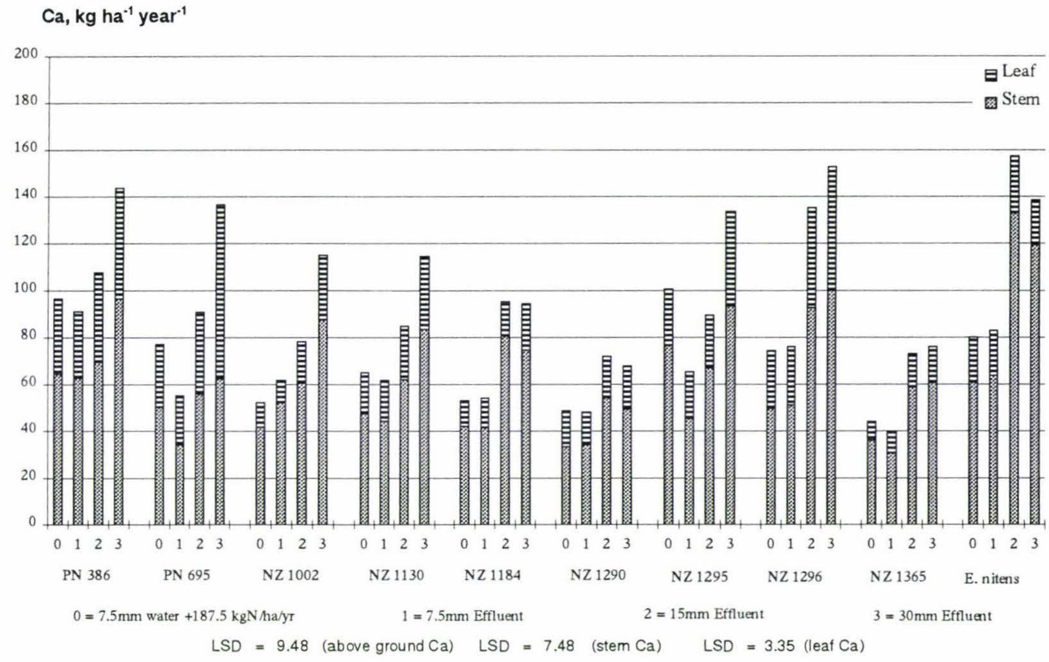


Figure 3.11. Above ground Ca in the biomass of SRF trees irrigated with dairy farm-pond effluent and water (7.5 mm) + N (187.5 kg ha^{-1} year^{-1}) over two years.

E. nitens, when irrigated with 30 mm of effluent significantly accumulated higher amount of calcium ($p > 0.01$) in its stem biomass than all the other treatments. The calcium requirement and uptake of eucalyptus were found to be large (Turner and Lambert, 1996) compared to other species of SRF trees. NZ 1296 and PN 386 ranked second and did not differ in the amount of calcium in their stem biomass.

Calcium in the leaves of trees were significantly different between species and irrigation treatments ($p > 0.01$). PN 695, when irrigated at 30 mm of effluent accumulated significantly higher amount of calcium in its leaves than all the other treatments. This result might be due to the amount of calcium in the effluent used for irrigation.

3.3.2.5 Magnesium uptake

Magnesium is an essential plant nutrient used in relatively large amounts (Brady, 1984). This nutrient has a function in the chlorophyll molecule and several other physiological functions in plants (Metson, 1968).

The Mg level in the biomass of SRF trees is presented in figure 3.12. Accumulation of Mg in the above ground biomass of SRF trees varied significantly between species and between irrigation treatments. NZ 1296, when irrigated with 30 mm of effluent accumulated significantly higher ($p < 0.01$) amount of Mg in its biomass (103.55 kg ha^{-1} $year^{-1}$) than all the other treatments. The amount of magnesium taken up by the trees increases as the amount of effluent applied was increased. This result might be due to magnesium level in the effluent applied to SRF trees.

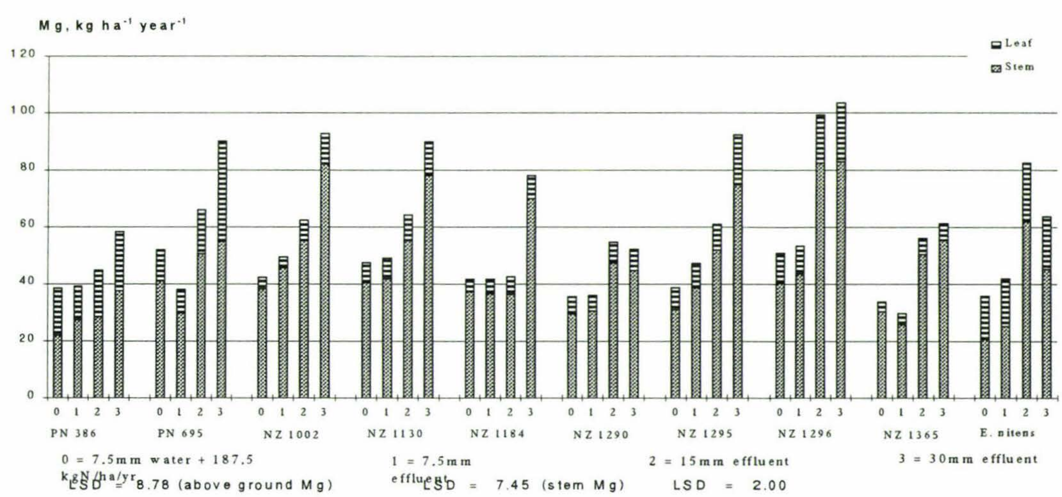


Figure 3.12. Mg in the above ground biomass of SRF trees irrigated with dairy farm-pond effluent and water (7.5 mm) + N (187.5 kg ha^{-1} $year^{-1}$) for two years.

Figure 3.12 also shows the magnesium level in the stem of ten species of SRF trees. Results revealed that the magnesium uptake of trees varied significantly between species and between irrigation treatments ($p > 0.01$). NZ 1296, when irrigated with 30 mm of effluent accumulated significantly higher amount of magnesium in its stem (82.86 kg ha^{-1} $year^{-1}$) than all the other treatments.

Magnesium level in the leaves of the trees was significantly different between species and irrigation treatments ($p > 0.01$). PN 695, when irrigated with 30 mm of effluent accumulated significantly higher amount of magnesium in the foliage (34.9 kg ha^{-1} year $^{-1}$) than all the other treatments. This result might be due to the adequate supply of magnesium through 30 mm of effluent application.

3.4 Conclusions and recommendations

The following conclusions can be drawn from the results of this section of the study:

- The response of the ten species of SRF trees to dairy farm-pond effluent application in terms of growth, biomass production and nutrient uptake can be used to select suitable species for land treatment.

- Irrigation of dairy farm-pond effluent at 30mm per fortnight, giving a total of 360 mm over a growing season, promoted the growth and increased the yield of SRF trees more than trees irrigated with 15 mm or 7.5 mm of effluent or with 7.5 mm of water + 187.5 kgN ha^{-1} $year^{-1}$.

- NZ 1296, PN 386, and NZ 1295, when irrigated with 30 mm of effluent were the most suitable of the species evaluated which gave the highest biomass yield of 37.91, 37.87 and 37.58 kg ha^{-1} $year^{-1}$, respectively. *E. nitens*, when irrigated with 15 mm of effluent produced a biomass yield of 36.33 kg ha^{-1} $year^{-1}$. *E. nitens* is the most suitable species for stem biomass production when irrigated with 15 mm of effluent, while NZ 1295 or NZ 1296 ranked as suitable species for biomass production when irrigated with 30 mm of effluent. All the nine salix species responded positively to the highest rate of effluent application. *E. nitens* responded positively to 15 mm but not to 30 mm of effluent irrigation.

- The highest uptake of nitrogen, phosphorus, potassium, calcium and magnesium occurred from the highest (30 mm) effluent application in the nine salix species, while *E. nitens* occurred from 15 mm of effluent application. Though there was no significant difference between K, Ca and Mg uptake between 15 mm and 30 mm rates for some species.

- NZ 1296, when irrigated at 30 mm of effluent accumulated significantly more nitrogen, phosphorus and magnesium in its above ground biomass at rates of 196.02, 37.62 and 103.55 kg ha^{-1} $year^{-1}$, respectively .

- *E. nitens* accumulated the highest amount of potassium and calcium in its above ground biomass when irrigated at 15 mm of effluent application at the rates of 145.42 and 148.08 kg ha^{-1} $year^{-1}$, respectively.

- NZ 1296, NZ 1295, PN 386 and *E. nitens* were identified as the best performers of the ten species of SRF trees evaluated and were used for obtaining more detailed analysis as (except NZ 1296) outlined in chapters 4, 5, 6 and 7. NZ 1296 being a tree willow like the NZ 1295was not included in the detailed analysis because the latter showed higher biomass yield than the former during the first year.

CHAPTER 4

EFFECT OF THE APPLICATION OF DAIRY FARM-POND EFFLUENT ON THE SOIL UNDER SRF TREES

4.1 Introduction

The application of waste to land is a promising approach to meet the desired standards of wastewater disposal as a tertiary treatment option. The main purpose is to provide a sustainable process for the treatment and disposal of wastes through natural processes occurring in the plant-soil-water matrix. The soil matrix is often conceptualised as a porous media. This concept has important implications for the movement of pollutants and the use of field soils to filter waste water. It follows that when wastewater is applied to the soil some constituents may pass through the soil to the groundwater; some are utilised by growing plants; some are metabolised by micro-organisms; and others are retained in the soil.

Soil is a very important resource for waste disposal. It is therefore imperative that land application of wastes should accommodate the natural conditions of the disposal site and the composition of the wastes. From a sustainable point of view the application rate of wastewater should be less than the infiltration capacity of the soil (Polprasert, 1996). The risk of ponding is eliminated when a proper design of hydraulic loading rate is applied.

The composition of wastewater is also an important consideration when land application is the preferred treatment. Balks (1995) mentioned that effluents with high suspended solids can cause blockage of soil pores and a decline in infiltration rates during effluent application. For example the land disposal of septic tank effluents resulted in soil clogging, accelerated by greater concentrations of organic matter and suspended solids (Mitchell et al., 1982 and Siegrist, 1987). When soil pores are clogged, wastewater cannot infiltrate or percolate into the soil column. This condition may result in waterlogging and nutrients cannot be transported to the root zone.

An important consideration is the fate of nutrients in the waste effluent and the effect of other chemical properties when applied to the soil. Ideally the application of waste should be effectively managed to utilise the nutrients for crop production. But the soil is so complex that not all the nutrients from the effluents are as readily available for uptake by plants as those in the manufactured fertilisers. According to the National Milk Harvesting Training Centre (1993), approximately 50% of the nitrogen and phosphorus in the dairy farm waste is available to plants, compared with approximately 90% for potassium. The presence of these nutrients beyond the buffering limit of the soil will eventually degrade the soil and there is a potential risk of groundwater contamination. To avoid detrimental effect of applying dairy farm waste effluent to the environment, land application of waste should be aimed at efficient production and effective resource management to avoid the occurrence of point and diffuse sources of pollution.

The purpose of this chapter is to determine the effects of applying different rates of secondary treated dairy farm-pond effluent to Manawatu fine sandy loam soil under three SRF trees. An optimal application rate of effluent to SRF trees will be recommended to match the characteristics of the soil without posing any threat of degradation and groundwater pollution. Specifically, this chapter aims to look at the effect of applying different rates of effluent on :

- the soil bulk density and infiltration rate;
- the total nitrogen, nitrate and phosphorus levels of the soil;
- the exchangeable cations (potassium, calcium, magnesium and sodium);
- the cation exchange capacity; and
- the soil pH.

4.2 The experimental site

The experiment was conducted at an experimental site at the New Zealand of Horticultural Research Institute at Aokautere, Palmerston North (refer to section 3.xx).

4.3 Methodology

Pre-treatment data on the bulk density, infiltration and chemical composition of the soil were determined before any land preparation was carried out. Soil samples were collected randomly from the experimental area. The area was divided into three blocks and three pre-treatment soil samples from each block were collected randomly for soil chemical characterisation. A soil sampling depth of one metre was selected on the basis of the assumed root depth of the SRF trees (Sims et al., 1994).

Chapter 3 described the details of the land preparation, irrigation design and application. The amount of effluent, nutrients and characteristics of effluent that was applied to the experimental site are presented in table 3.1.

After the first year of irrigation following tree establishment, the three best performing species of SRF trees were selected based on the estimated biomass production (section 3.2.1.2). The soils under PN 386, NZ 1295 and Eucalyptus nitens that were to be irrigated at the highest rate of effluent (30 mm) were sampled before irrigation began.

Two sets of soil samples were taken within the anticipated wetted perimeter of each plot along the designated guard rows for the four sample trees during the first year to avoid disturbing the soil along the four sample plants for each block.. The sampling depths was down to one metre depth to determine chemical changes within the soil for the first year.

The trees were harvested after the second growing season before the salix species shed their leaves. Bulk density and infiltration rates were determined for the second year immediately after harvesting. The cylinder method was used for determining the bulk density of the soil (McLaren and Cameron,1996) and a double ring infiltrometer was used to determine the infiltration rates (Raes, 1989).

The exchangeable cations and cation exchange capacity for the first and second growing seasons were only determined for the soils under PN 386, NZ 1295 and Eucalyptus nitens that were irrigated at different rates. However, after the first growing season, only the soils under the trees irrigated at 30 mm of effluent were analysed for chemical properties, limited by the cost of analysis.

4.4 Results and discussions

4.4.1 Total nitrogen in the soil

Nitrogen is considered as one of the most important components in wastewater from a resource as well as a water pollution point of view. It is also an essential nutrient for the living organisms and is often added in quantities of several hundred kg ha^{-1} to agricultural lands to obtain high yields of crops. Moreover, the crop withdrawal of this nutrient from the soil is large which requires appropriate amount of application to meet the nitrogen requirements of the crops. The application of this nutrient beyond the appropriate uptake capacity of the crop grown may lead to excess nitrogen in the soil which has the potential to be leached to the groundwater at unacceptable value. According to the Ministry of Health (1995), the maximum acceptable value for NO_3^{-1} - nitrogen level in the drinking water is < 11.3 mg L^{-1} to avoid methemoglobinemia if ingested by infants.

Figure 4.1 shows the total nitrogen content of the soil planted with PN 386, NZ 1295 and *E. nitens* when irrigated with dairy farm pond effluent or water + nitrogen during the first and second growing seasons. A decreasing trend of total nitrogen content from pre-treatment to the second growing season was observed in all the treatments and depths except at 0-5 cm layer. The rate of irrigation significantly affected the total soil nitrogen level under the species of SRF trees in all the depths observed. A decreasing trend of total nitrogen content of the soil was also observed as depth increased from 0 cm to 100 cm of the soil profile. This was attributed to the filtering effect of different soil layers and organic matter in the soil.

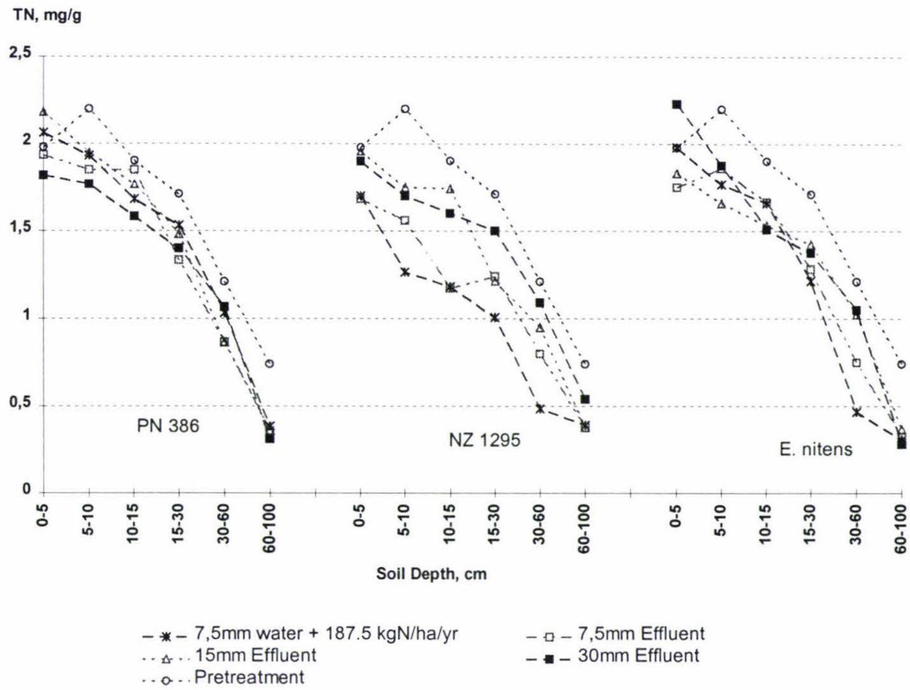


Figure 4.1 Total nitrogen of soil under three SRF trees irrigated with different rates of dairy-farm pond effluent and water + nitrogen after two growing seasons (LSD_{0-5} = 0.19; LSD_{5-10} = 0.21; LSD_{10-15} = 0.16; LSD_{15-30} = 0.14; LSD_{30-60} = 0.23; LSD_{60-100} = 0.51)

The decrease in the nitrogen content of the soil, despite application of nitrogen through irrigation, can be attributed to the uptake of SRF trees, leaching and volatilisation. This result parallels to the finding of Stewart et al. (1988) regarding the non-measurable effect of effluent application on the total soil nitrogen despite high inputs of organic and inorganic nitrogen present in the effluent.

Because of the high concentration of ammonia in the dairy farm-pond effluent (95 g m^{-3}), ammonia might had volatilised when discharged from the nozzles of the sprinkler irrigation system in the form of aerosols. The nitrogen that reached the ground were converted into nitrates. Some of the nitrates were taken up by the plants, some were leached or oxidised into ammonium and lost to the atmosphere and some were retained in the soil matrix. As Bolan (1996) stated, the nitrogen added to the soil through the effluent was subjected to mineralisation, immobilisation, nitrification, denitrification, ammonia volatilisation and nitrate leaching.

Teal (1997) reported similar results that added nitrogen at a low rate of 140 g N m^{-2} through application of nutrient-enriched sewage sludge on salted marsh was either stored in the sediments or taken up by the plants. Moreover, 40% of the total nitrogen inputs from all sources can be lost through denitrification (Howes and Teal, 1991). Cameron et al. (1993) also mentioned that nitrogen loss through denitrification and the amount of remaining nitrogen in the soil when effluent is irrigated on to pasture were found to be around 28 and 20% of applied nitrogen, respectively. Myers et al. (1995) also mentioned that nearly all ammonium- nitrogen in the effluent that was applied to trees was lost to the atmosphere within 48 hours of irrigation.

The total nitrogen content of soil at the different depths varied significantly with irrigation and the species of SRF trees. At the top 5 cm level of the soil, the total nitrogen in the soil irrigated at 30 mm, 15 mm and 7.5mm water + nitrogen was significantly higher than in the soil applied with 7.5mm of effluent. The accumulation of total nitrogen in the soil at this depth can be attributed to the amount of total nitrogen applied through the application effluent. The nitrogen applied at these two irrigation rates exceeded the nitrogen optimum uptake capacity of the trees. The differences of the SRF trees in structure and rate of nutrient uptake also affected the amount of total nitrogen retained in the soil.

At 0-5 cm depth under the *E. nitens* when irrigated at 30 mm of effluent that had the highest significant increased from 1.89 mg g^{-1} (pre-treatment) to 2.48 mg g^{-1} (year 2) of total nitrogen ($p > 0.05$). Under the other tree species, the decline in total nitrogen at various depths ranged from 9.8 to 61.7%. On the other hand, the application of inorganic fertiliser might have contributed to the concentration of total nitrogen in the soil that was comparable to 15 and 30 mm level of effluent application. The transformation of nitrogen in inorganic nitrogen fertiliser might had been faster than that of the nitrogen in the effluent which might caused faster adsorption of nitrogen into the top 5 cm layer of the soil.

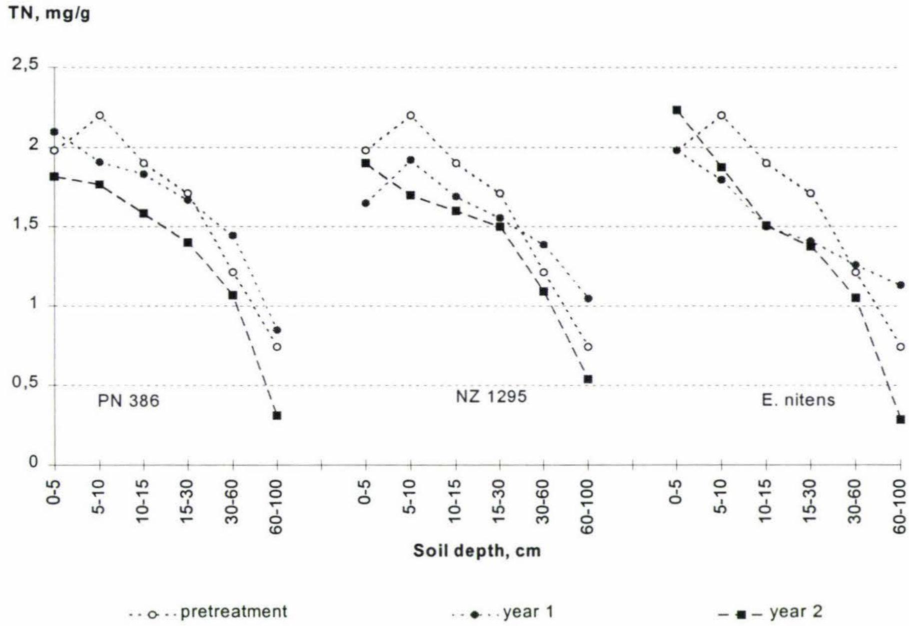


Figure 4.2 Total nitrogen of soil under three SRF trees irrigated with different rates of dairy-farm pond effluent and water + nitrogen after 1 year growth and 2 year growth

The extent of nitrogen retention or losses in the soil is highly dependent on several factors which include the concentration and form of nitrogen in the irrigation media, the amount of irrigation applied, climate, soil type, plantation design, species selection, stage of stand development and silvicultural management (Myers et al., 1997).

Despite of the addition of total nitrogen that was more than the requirement of the trees (table 3.1) there was no build up of total nitrogen in the soil, but a decline in the total nitrogen level in the soil occurred over time . This result can be attributed to the loss of nitrogen through volatilisation, mineralisation, leaching and uptake of the trees (refer to figure 3.6). The decline of total nitrogen in the soil, except at 0-5 cm layer, suggests that some nitrogen reserve in the soil was taken up by the trees.

Myers et al. (1997) stated that the supply of nitrogen from soil was measured as a significant decreased in soil nitrogen during the first two years of effluent irrigation. This incident suggests that effluent-irrigated forest plantations during the early stage of plantation and development , the soil acted as a source of nitrogen.

4.4.2 Soil nitrate

The secondary treated dairy farm-pond effluent that was used in this study contained high amounts of ammonia (88 kg ha^{-1} $year^{-1}$ at 7.5 mm of effluent) (see table 3.1, chapter 3) which was the product of organic breakdown through mineralisation in the dairy ponds. As soon as the effluent was applied to the soil, the ammonium in the effluent was oxidised to form nitrates which was the main available form of nitrogen in the soil after effluent irrigation (McLaren and Cameron, 1996):

$$2NH_4 + 3O_2 \longrightarrow 2NO_2^- + 2H_2O + 4H^+ + \text{energy} \quad (1)$$

$$2NO_2^- + O_2 \longrightarrow 2NO_3^- + \text{energy} \quad (2)$$

Nitrates are negatively charged ions and therefore unstable and highly soluble in water. Hence, this nutrient is highly susceptible to leaching as water drains through the soil. Nitrates pose a threat to the quality of drinking water once it percolates to the groundwater.

In surface water, nitrates enhance the proliferation of algae which occur in the presence of phosphorus and result in the deterioration of potable water. Excessive nitrates in the soil also encourage luxury uptake by crops which may result in the production of nitrous oxide, lethal to animals and human beings (Black et al., 1984). It is then important that loading rates of nutrients should match the soil-water-plant matrix to eliminate the risk of pollution and unacceptable pollutants in the environment.

The nitrate level in the soil under the three selected species is shown in figure 4.2. At different depths, the nitrate concentration in the soil was significantly influenced by the level of effluent irrigation and by the species ($p > 0.05$). Nitrate concentration levels in the soil under the PN 386 increased throughout the soil profile with increasing level of effluent irrigation. The nitrate level of the soil under the *E. nitens* increased with increasing level of effluent irrigation below 15 cm depth. While, under NZ 1295 it was below 30 cm depth. Increased soil nitrate levels was possibly due to mineralisation of nitrogen (Bolan, 1996) when effluent was applied to the soil under the three species of SRF trees.

The peak soil nitrate accumulation under the three SRF trees was reached at the 60 cm depth under 30 mm irrigation. The nitrate levels in the soils at this depth were increased to 21.5, 14.6 and 29.6 times, more than the pre-treatment level for PN 386, NZ 1295 and *E. nitens*, respectively.

This increased was possibly influenced by the mineralisation of nitrogen when effluent is applied to the soil. The movement of nitrate below 30 cm of soil depth under *E. nitens* can be attributed to its root structure and the amount of irrigation at 30 mm of effluent application. During the first year of transplanting, *E. nitens* was slow in growth and possibly slow in nutrient uptake because the fork-like roots were still at the establishment stage. The root mass of the effluent irrigated trees was situated mainly at the top 400 mm (Sims et al., 1994).

Unlike the eucalyptus, willows have root dense mat-like structure at the upper layer of the soil. These fibrous roots of the willows might have aided the soil particles in trapping the effluent and the nutrients applied. This condition can influenced the mineralisation of more nitrogen in the soil as effluent was applied and transported to the different layers of the soil.

The nitrate levels of soils that were irrigated with 30 mm of effluent at the upper 15-30 cm depth under NZ 1295 and *E. nitens*, respectively, were lower in concentration than the soils irrigated at 15 mm. This possibly suggests that there was a large nitrate uptake by the NZ 1295 (see figure 3.6) and leaching in the soil under Eucalyptus nitens. The uptake of nitrates by the NZ 1295 can also be associated with the profuse branching out of roots at the 30 cm depth of the soil. The root mass of effluent irrigated tree with fully developed canopy can be found in the upper 40 cm layer (Sims et al., 1994). The leaching of nitrates at the top 15 cm depth of soil under *E. nitens* (less than 2 years old) can be associated with the fork-like root structure of the tree. The nitrogen in the effluent that passed through the upper 15 cm depth of the soil possibly had percolated into the deeper layer of the soil and some might had transformed into nitrates. This situation might have influenced the increased nitrate level below the 15 cm depth.

The water in the effluent may possibly encouraged the continued uptake of nitrates by the plant roots from the soil during periods of low rainfall. It is also evident from the results (figure 4.2) that nitrification in the soil was possibly stimulated by the increasing soil water content that was applied through the highest rate of effluent irrigation. Feigin et al. (1991) showed increasing rate of nitrification in soil as moisture is increased maintaining 4 to 40°C temperature and 6-8 soil pH.

The results suggests that irrigation with secondary treated dairy-farm pond effluent affects the levels of nitrates in the soil, and the level varies with the amount of effluent applied, the species of SRF trees and length of application period.

The nitrogen in the effluent that was applied to the soil became a part of the soil nitrogen cycle. Feigin et al. (1991) explained that ammonium contained in the effluent, as well as that derived from organic nitrogen, is usually oxidised to nitrate by nitrification. Both nitrate and ammonia from the soil are taken up by the trees and immobilised in the plant tissues. Losses of nitrogen in the form of nitrates were suspected to have been leached to the ground water. Volatilisation of ammonia was also a major avenue for losses of the nutrient during the experiment because of the pH of the effluent (7.5-8.1) used for irrigating the plots. When the effluent was irrigated to plots, volatilisation possibly occurred because of the presence of free ammonia (NH_3) that was applied on the surface of the soil. The ammoniacal nitrogen (115 g m^{-3}) applied to the soil might had quickly hydrolysed to ammonium carbonate under moist condition of the soil. The ammonium carbonate that might had been produced dissociated to ammonium, and then converted to gas that volatilised. Feigin et al. (1991) further added that some losses of nitrates by leaching below the rooting depth can be in the form of dinitrogen or nitrogen oxide through denitrification are often large (25-30% of nitrates in the soil).

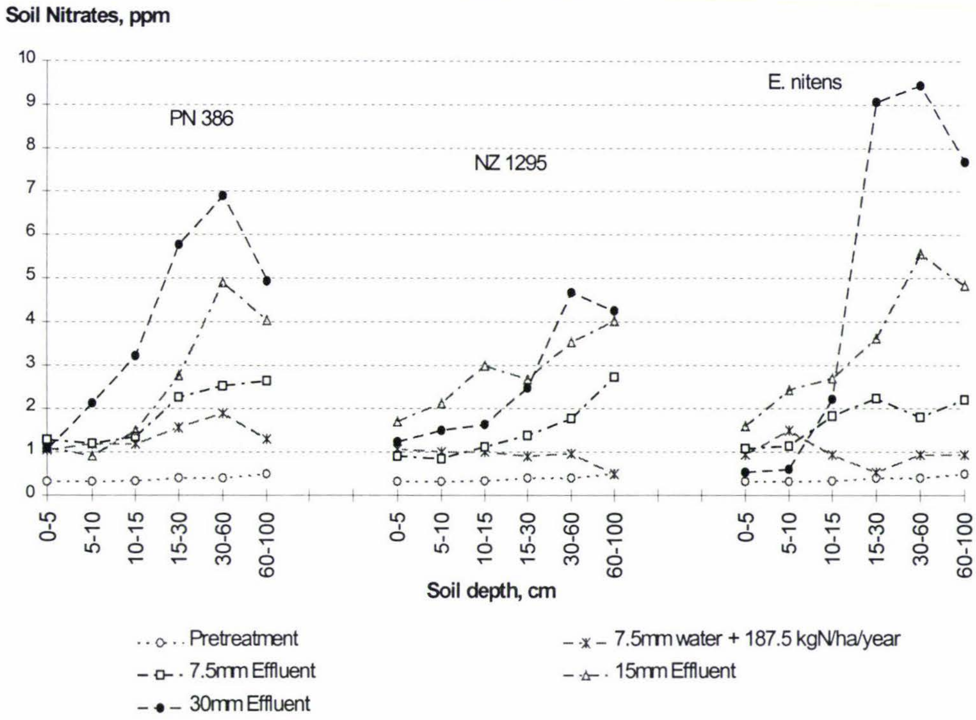


Figure 4.3 Nitrates in the soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen after two growing seasons ($LSD_{0\text{-}5}$ = 0.19; $LSD_{5\text{-}10}$ = 0.21; $LSD_{10\text{-}15}$ = 0.16; $LSD_{15\text{-}30}$ = 0.14; $LSD_{30\text{-}60}$ = 0.23; $LSD_{60\text{-}100}$ = 0.51)

The accumulation of nitrates over time in the soils under three SRF trees that were irrigated with 30 mm of effluent is shown in figure 4.3. The soil nitrates for year one were low compared to year two. The build up of nitrates in year 2 varied as a result of the differences of SRF trees to uptake the nutrients. As a result, the nitrate level of the soil under the *E. nitens* was significantly higher ($p > 0.05$) than the willows when irrigated with 30 mm of effluent. The soil nitrates under the three species increased by 12.52, 8.21 and 15.39 times the pre-treatment nitrate level of the soil as a result of applying 30 mm of effluent. Nitrates are negatively charged, and therefore these nutrients are repelled by cation exchange sites and are susceptible to leaching. Excessive amount of nitrates in the soil also encourage the leaching of calcium and magnesium into the ground water (sections 4.3.4 and 4.3.5). The negatively charged nitrate ions can fuse with the positively charged ions like calcium and magnesium. When water drains through the soil, then the fused nitrate and calcium or magnesium can leach to the groundwater. This situation can therefore aggravate the leaching of nitrates.

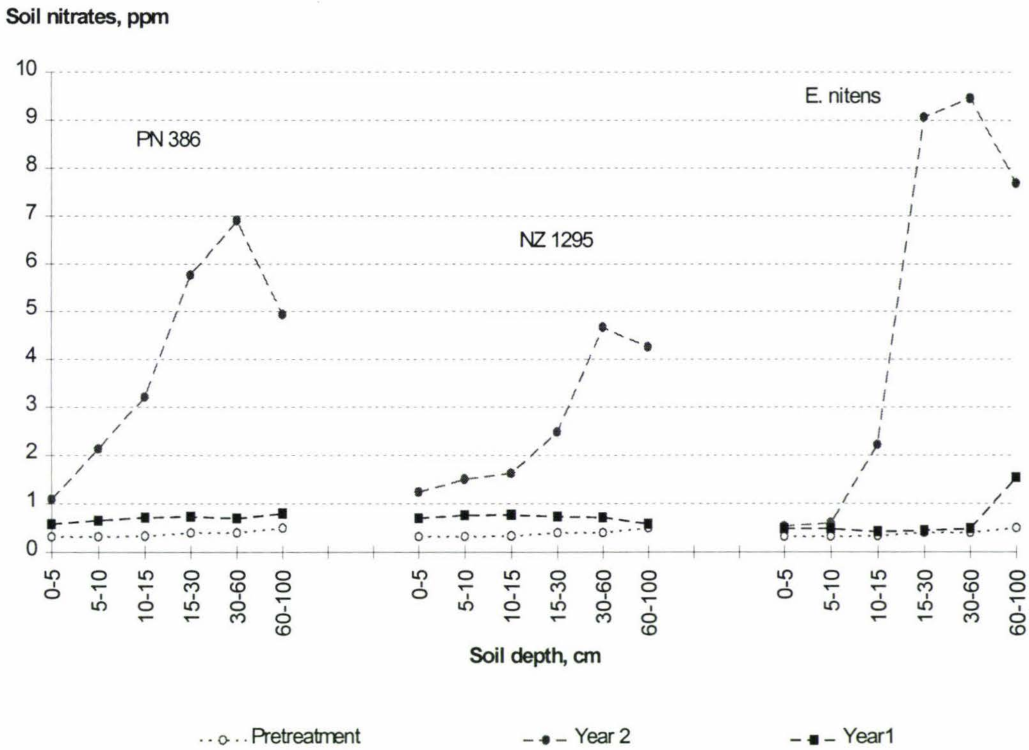


Figure 4.4 Nitrates in the soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen after 1 year growth and 2 year growth

4.4.3 Total phosphorus in the soil

Phosphorus is a major nutrient required by plants and often found in low concentrations in soil and water. The addition of phosphorus through the application of dairy farm-pond effluent can contribute to the phosphorus cycle in the soil. Excess phosphorus is not considered to be toxic to plants but may induce deficiencies of calcium, zinc, iron or manganese (Black et al., 1984). However, substantial addition of phosphorus to a body of water usually results in increased algae production and increased decomposition of organic matter, which causes depletion of oxygen. When liquid effluent is applied to soil in quantities that exceed the requirement for efficient plant production, there may be a risk of phosphorus leaching to ground and surface water which may lead to eutrophication of the valuable water resources.

The total phosphorus level in the soil after two growing seasons are shown in figure 4.5. At the upper 10 cm layer of the soil, there was an increase of the total phosphorus concentration level which can be attributed to the addition of phosphorus through the of effluent. However, at a soil depth between 10 cm to 100 cm, a decline in the total phosphorus level was evident under the three species that were applied with different rates of irrigation. This trend could be attributed to the plant uptake and to preferential flow of effluent that leached the phosphorus to the groundwater. Doyle et al. (1977) confirmed the effectiveness of forest buffer strips using crops in reducing phosphorus concentrations in run-off following natural rainfall events. The reduction of phosphorus can possibly be attributed to the uptake of phosphorus by the forest trees.

Soil irrigated at 7.5 mm of water + nitrogen had the lowest concentration of total phosphorus throughout the 60 cm depth of soil under the willows. This result confirms that phosphorus in the soil had been taken up by the trees. There was no replacement for the phosphorus taken up by the trees and this resulted in the reduction of total phosphorus level in the soil (figure 4.5).

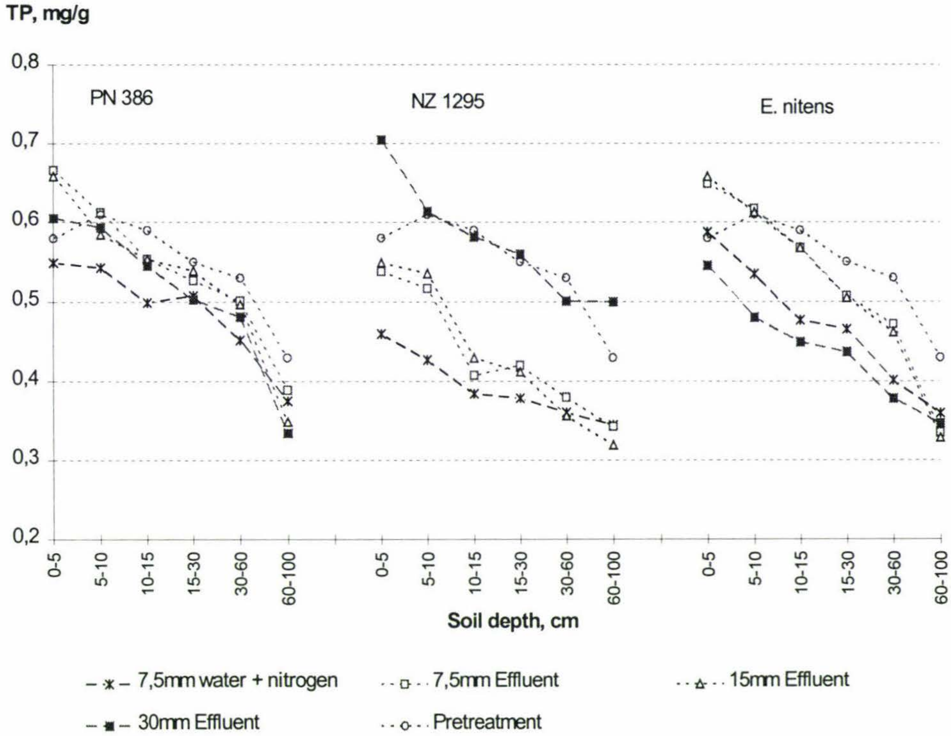


Figure 4.5 Total phosphorus in the soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen after two growing seasons (LSD_{0-5} = 0.05; LSD_{5-10} = 0.03; LSD_{10-15} = 0.04; LSD_{15-30} = 0.03; LSD_{30-60} = 0.03; LSD_{60-100} = 0.04)

The soil under *E. nitens* that was irrigated at 30 mm of effluent after two growing seasons had the lowest total phosphorus concentration level. The reduction can be attributed to the application of total phosphorus through effluent irrigation that might exceed the soil total phosphorus retention capacity. This findings is similar to Choudhary et al. (1996) reporting that excessive application of pig manure increased leaching of nitrate nitrogen, phosphorus and magnesium and can also be associated with the findings of Nagpal (1986) regarding the flow of effluent along preferred pathways and through large pores. This had a reducing effect on the phosphorus adsorption at equilibrium in two coarse textured soils. Such pathways or pores permit the breakthrough of phosphorus to groundwater before the adsorption site is fully saturated and the precipitation takes place. Beven and Germann (1980) disclosed that most of the channels or macropores in soils are formed by earthworms and the main roots of annual crops that have greater importance in terms of the volumes of water and solutes moved.

At different depths, the concentration of total phosphorus in the soil varied with irrigation and species of SRF trees. The total phosphorus level in the upper 5 cm depth of the soil varies significantly with respect to the irrigation and species of SRF trees. Analysis revealed that the application of 30 mm of effluent significantly increased the total phosphorus level of soil under NZ 1295 compared with the irrigation of water + nitrogen. The application of effluent increased the total phosphorus level of the soil resulting from adsorption and precipitation of phosphorus as an insoluble fraction, such as calcium phosphates. Below 10 cm depth, the total phosphorus of the soil declined in all treatments. The trees accumulated total phosphorus from the applied effluent and from the pool of the soil reserve.

The total phosphorus concentration level of the soil at 0-5 cm layer under NZ 1295 that was irrigated at 30 mm of effluent per fortnight over two growing seasons was significantly higher ($p > 0.05$) than in the soils of other treatments (Figure 4.6). The greater accumulation of total phosphorus in the top layer of NZ 1295 might be due to phosphorus inputs from the effluent. At 30 mm of effluent irrigation per fortnight, 91 kg ha^{-1} $year^{-1}$ of TP (Table 3.1) was applied. This nutrient might have been fixed on the top 5 cm depth of the soil which can be associated with the presence of cations, like calcium, magnesium and sodium. The temperature during the growing season and the soil pH

(6.15 - 6.49) for soils under 30 mm of effluent at the top 5 cm depth might have helped in the minimum fixation of phosphorus in the form calcium or magnesium phosphates. At this range of pH, available phosphorus is at maximum for plant uptake. This led to a slight increase of the nutrient at the upper 0-10 cm of the soil and a substantial decline of total phosphorus at the lower depths. McLaren and Cameron (1996) confirmed the influence of soil pH ranging from 6.0 to 7.0 having an influence on the minimum fixation of total phosphorus in the soil and the maximum availability of phosphorus to plants. Broschat (1995) also reported that the complex chemical reaction in the top 0-30 cm layer of the soil may partly contribute to the total phosphorus in this soil layer.

An increasing pattern of total phosphorus level in the soil under the three SRF tree species irrigated with 30 mm of effluent is shown in figure 4.5. The average level of total phosphorus throughout the depth in the soil under NZ 1295 after year 2 increased by 2.85 %, while PN 386 and *E. nitens* decreased by 3.78 and 10.29 %, respectively. This increase can be associated with phosphorus fixation in the upper soil layers, while the decline in level was a result of plant uptake and preferential flow of the effluent through macropores developed by roots and the activity of worms (calcium being applied in the soil). The decline can also be the effect of leaching of soluble organic phosphorus compounds following the application of effluent or rainfall. The type of soil (Manawatu very fine sandy loam) might have contributed to the losses of phosphorus since the sandy fraction of the soil had low phosphate adsorption capacity (McLaren and Cameron, 1996).

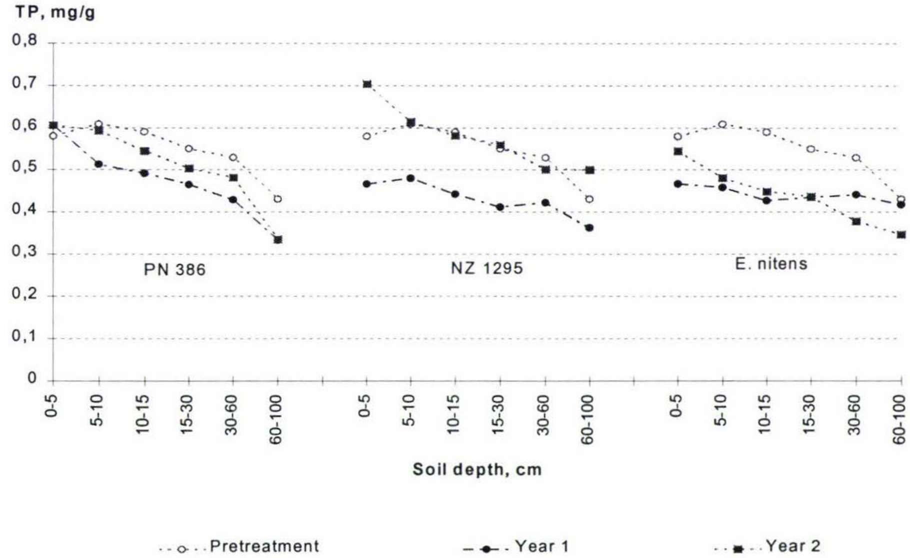


Figure 4.6 Total phosphorus in the soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen after 1 year growth and 2 year growth

4.4.4 Exchangeable potassium in the soil

Potassium is an essential nutrient that is taken up by crops in quantities similar to or even greater than the uptake of nitrogen. The potassium level in the soil is often below the requirement of crops grown requiring addition of potassium fertiliser, effluent or manure application.

Dairy farm-pond effluent is rich in potassium. It is usually higher than the nitrogen concentration in the effluent (table 3.1). While there is little evidence that potassium in drinking water is detrimental to human health, the maximum admissible concentration of potassium in drinking water is set at 12 mg per litre by the Drinking Water of European Economic Community (Johnston and Goulding, 1992). Hence, potassium was considered to be the limiting design factor for hydraulic loading in this study (section 3.2).

The exchangeable potassium level in the soil varied with irrigation rates and species of SRF trees at all the depths. The level of exchangeable potassium in the soil increased as irrigation level increased (Figure 4.6). Analysis revealed that soils irrigated at the highest rate of effluent application were significantly higher in exchangeable potassium than in the lower rates of irrigation. The amount of exchangeable cations in soils was found to be significantly higher in soils under NZ 1295 than under PN 386 and Eucalyptus nitens. Among the treatments, the soil under NZ 1295 irrigated at 30 mm of effluent were significantly higher in exchangeable potassium level ($p > 0.05$) than the soils under other treatments.

The amount of potassium progressed at a substantial level because of the increasing amount supplied through increasing levels of effluent irrigation. At 0-5 and 15-30 cm depths, the level of exchangeable potassium in the soil under NZ 1295 irrigated at 30 mm of effluent was significantly higher than under the other treatments. This result has an implication on the amount of potassium assimilated by the trees. The lower level of exchangeable potassium in the soil in the soil under *E. nitens* compared with the soils under the willows and confirmed that a substantial amount of potassium had been assimilated by the tree (see Figure 3.8). Under the conditions of excess supply of exchangeable potassium in the soil, the eucalyptus nitens demonstrated a luxury consumption of the nutrient, amassing the potassium that was supplied through effluent irrigation and by the soil pool of exchangeable potassium. The early stage of the *E. nitens* (before canopy closure) also influenced the luxury uptake of potassium by the tree. The condition of potassium being supplied in a solution (through effluent application), a form that makes the nutrient available for the tree, further influenced the rapid uptake of potassium by the *E. nitens*. Hence, resulting in a lower level of exchangeable potassium in the soil under this tree.

The remaining potassium in the soil in excess of plant uptake that was added through effluent application has been fixed and this contributed to the increased level of exchangeable potassium. Exchangeable potassium is positively charged, so there is a tendency for this nutrient to bond with the negatively charged particles of the soil.

However, potassium in a solution, like potassium in the effluent, is highly susceptible to leaching. Some of the exchangeable potassium might have leached to the groundwater as the effluent percolated into the soil column or as the water drains through the soil during the occurrence of heavy rainfall. The cation exchange capacity of the soil under *E. nitens* at 30 cm depth of the soil (where roots of irrigated trees are profusely found, Sims et al., 1994) had been increased by 7.69 %. This indicated a substantial uptake of potassium at this depth, implying an insignificant leaching of the potassium.

The higher level of exchangeable potassium in the soil under NZ 1295 throughout the soil to one metre depth indicated lower uptake of the nutrient by this specie and leaching of potassium might result. This situation is also shown by the decreasing cation exchange capacity level of the soil over time, from pre-treatment to year 2.

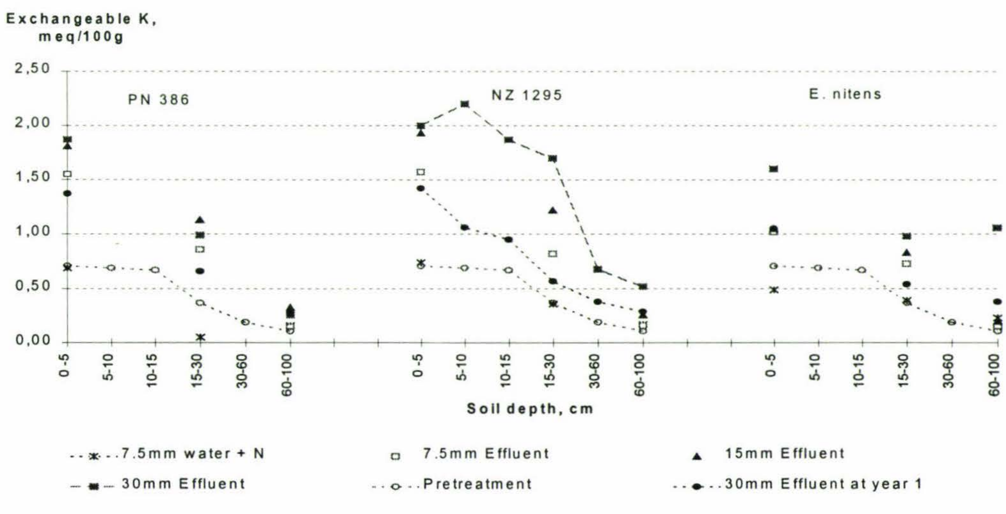


Figure 4.7 Exchangeable potassium in soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen after two growing seasons

The amount of potassium applied through effluent application at 30 mm per fortnight exceeded the nutrient requirement of all three species (Overcash and Pal, 1979, Ericsson et al., 1993 and Stewart et al., 1988). This led to the increase of exchangeable potassium level throughout the soil profile under PN 386, NZ 1295 and *E. nitens* as compared with the other irrigation levels.

Exchangeable potassium concentration level throughout the soil profile under NZ 1295 when irrigated at 30 mm of effluent per fortnight was higher than all the other treatments. At the 0-5 cm depth, the change in the exchangeable potassium of soils under PN 386, NZ 1295 and *E. nitens* were 2.63, 2.82 and 2.25 times the pre-treatment levels, respectively. At the 15-30 cm depth, the soil under NZ 1295 had increased to 4.59 times the pre-treatment level, while PN 386 and *E. nitens* increased by 2.68 and 2.65 times the pre-treatment level, respectively. At 60-100 cm depth, the exchangeable potassium level of soil under the *E. nitens* increased by 9.64, while PN 386 and NZ 1295 increased by 2.36 and 4.73 times the pre-treatment level, receptively.

Increased potassium level in the soil under the willows can also be attributed to the fibrous mat-like roots of these trees that are found on the upper 30 cm level of the soil column. Sims et al. (1993) disclosed the profuse development of roots at the upper 30 cm depth for irrigated SRF trees. These roots possibly able to hold the effluent for a longer time compared to *E. nitens* and this condition might have favoured the exchange of potassium cations in the upper 30 cm depth of the soil column. The exchangeable potassium level in the soil is expected to increase until it reaches an equilibrium. The amount in excess of plant uptake and fixation might be leached to the groundwater.

4.4.5 Exchangeable calcium in the soil

Calcium, the fifth most abundant element in the earth's crust (approximately 3.64%) (McLaren and Cameron, 1996) is a macronutrient that is essential for plant and animal growth. Figure 4.8 shows the exchangeable calcium in the different depths of soil under the three SRF crops that were irrigated at different rates of effluent over two growing seasons. At different depths, the level of exchangeable calcium in the soil varied with the rate of irrigation and species of SRF trees.

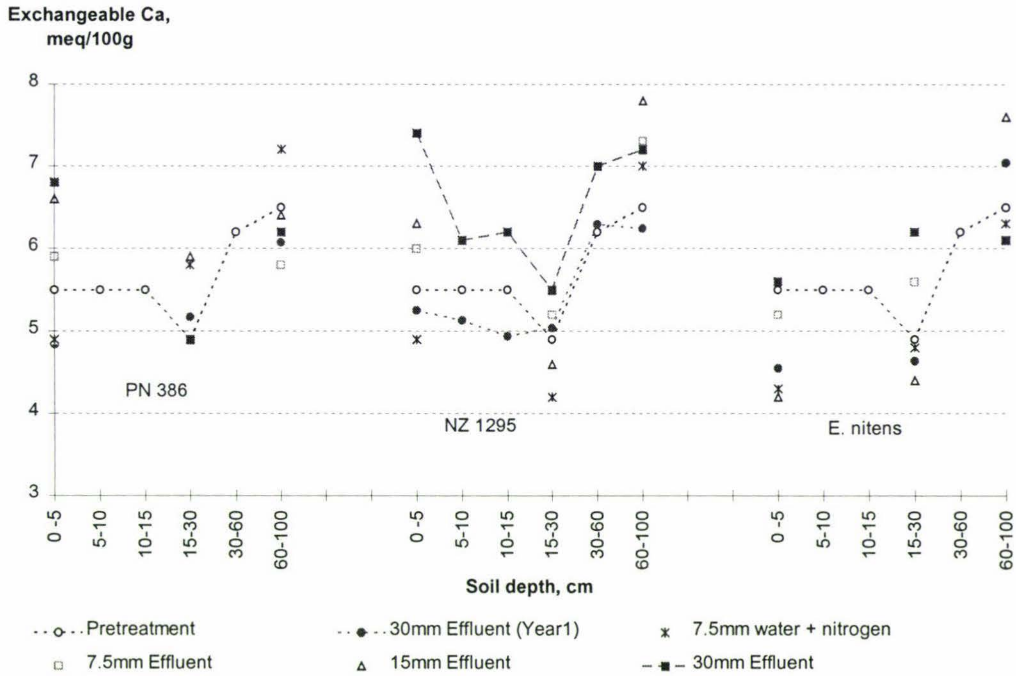


Figure 4.8 Exchangeable calcium in soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen over two growing seasons

At the 0-5 cm depth, the soils under the NZ 1295 that were irrigated with 30 mm of effluent showed higher significant levels of exchangeable calcium at 7.40 meq/100g , than the soils under PN 386 and *E. nitens* at 6.80 and 5.60 meq/100g. There is an increasing trend of exchangeable calcium in the soil as the level of effluent irrigation was increased from 7.5mm to 30 mm. The effluent added to the soil was rich in calcium (23 g m^{-3}) which can be detected through the pH value (7.5-8.1) of the effluent added (see table 3.1). The addition of calcium through effluent application increased the exchangeable calcium level in the soil (figure 4.7). McLaren and Cameron (1996) found increasing amount of calcium and basic cations in the soil as the soil pH was increased.

At 15-30 cm depth, the level of exchangeable calcium in the soils increased with increasing level of effluent irrigation, except for PN 386. The exchangeable calcium in the soil under the *E. nitens* at 30 mm of effluent irrigation was higher at 6.20 meq/100g than the soils under NZ 1295 and PN 386 at 5.50 and 4.90 meq/100g, respectively. The increase in exchangeable calcium in the soils was possibly influenced by the addition of calcium through effluent application and calcium uptake by the trees. Some exchangeable calcium that was in excess of the optimum uptake of the tree might have bonded with nitrates and been translocated to a lower depth or leached to the groundwater.

At 60-100 cm depth, the level of exchangeable calcium varied with the rate of irrigation and species of SRF trees. The 7.20 meq/100g of exchangeable calcium level of soil under NZ 1295 at 30 mm of effluent irrigation was higher than the other treatments. The lower levels of exchangeable calcium in the soil under PN 386 and *E. nitens* irrigated at 30 mm of effluent can be attributed to the leaching of nutrients. The amount of nitrates at this depth accumulated in the soil under the trees when irrigated at 30 mm of effluent can be associated with the decreased of exchangeable calcium level in the soil. At this rate of effluent irrigation, the soil under the Eucalyptus nitens had the highest amount of nitrates which might have caused the leaching of exchangeable calcium.

The soil under NZ 1295 retained more exchangeable cations throughout the soil profile than the soil under Eucalyptus nitens and PN 386 when irrigated at 30 mm of effluent. The supply of calcium from the effluent (84 kg ha^{-1} $year^{-1}$) and from the soil pool possibly exceeded the calcium uptake capacity of SRF trees. The excess exchangeable calcium might have been translocated to the lower layer of the soil. The movement and accumulation of calcium through the soil profile can also be attributed to the macropores in the soil that were formed by the roots of trees, annual weeds and activities of earthworms (Beven and Germann,1980). These facilitated the movement of effluent and transport of nutrients through the soil profile. Parallel to this, McLaren and Cameron (1996) also added that calcium in the soil encourages earthworm activity.

The decrease in exchangeable calcium in the lower irrigation treatments under the three species of SRF trees was due to plant uptake when supply of the nutrient does not meet the optimum uptake capacity of the tree.

During the first year, the magnitude of exchangeable calcium level in the soil was lower than the pre-treatment level. This is because during the early stage of the seedling growth, the young stands of trees required sufficient calcium for the full development of their canopy. Goncalves et al. (1997) disclosed that after establishment, the plants enter a stage of rapid growth and nutrient uptake from the soil, especially if there is sufficient water. He further added that the rate of nutrient absorption of trees from the soil is parallel to the rate of biomass accumulation with age. Consequently, results revealed that application of 30 mm of effluent per fortnight over two years during the growing season had increased the exchangeable calcium in the soil under all three SRF trees. The upper 30 cm depth of soil among the three species of SRF trees held higher level of exchangeable calcium (Figure 4.8). Below the 30 cm depth, the soil under all the three species of trees differed in the adsorption of exchangeable calcium. The soil under NZ 1295 held more amount of exchangeable calcium than the soils under PN 386 and *E. nitens* which illustrated the differences of species in stripping the nutrients from the soil. At 30 mm of effluent irrigation, the exchangeable calcium level at 0-5 cm depth of soil under PN 386, NZ 1295 and *E. nitens* increased by 23.64, 24.55 and 1.82 %, respectively.

At 15-30 cm, the exchangeable calcium of the soil under PN 386 equalled the pre-treatment level, while the Eucalyptus nitens and NZ 1295 increased by 26.53 and 12.24 %. At the lower depth, 60-100 cm, the exchangeable calcium of the soil decreased by 6.15 and 4.62 % for Eucalyptus nitens and PN 386, respectively, while NZ 1295 increased by 10.77%.

Figure 4.8 shows that at the upper 60 cm depth of the soil, the exchangeable calcium level in the soil increases from year 1 to year 2. Values of exchangeable calcium level in the soil in year 1 were lower than the pre-treatment level because the trees required more calcium at the early stage of development. As the trees matured, the demand for the nutrient decreased. This contributed to the increase of exchangeable calcium in the soil over time.

A study on the differences of two species of eucalyptus in accumulating nutrients from the soil despite of comparable biomass accumulation was measured by Pereira as cited by Goncalves et al. (1997). The increase in exchangeable calcium in the soil (Figure 4.9) as a result of effluent application over time has the potential to be leached with nitrates (Figure 4.3 and 4.4). Calcium has the potential to be forced to combine with nitrates ions when nitrification process releases hydrogen ion. This condition suggests that when nitrates are leached, calcium will also be leached to the groundwater. The rate of removal of calcium is therefore accelerated when nitrification occurs (McLaren and Cameron, 1997).

4.4.6 Exchangeable magnesium in the soil

Most magnesium in the soil is found in mineral form and is only released slowly for plant use. Like other soil nutrients , magnesium is important to support the activity of crops for biomass accumulation. It is an essential nutrient found in the chlorophyll molecule that is needed in the process of photosynthesis (Metson, 1968 and McLaren and Cameron, 1996). The application of fertiliser or other amendments to soil is essential to replenish magnesium. However, the cost of fertiliser can be offset by the use of dairy-farm-pond effluent containing magnesium at 14 g m^{-3} to supplement magnesium (see table 3.1).

Figure 4.9 shows an increasing level of exchangeable magnesium in the soil with an increasing rate of effluent applied. The amount of exchangeable magnesium in the soil tended to increase as a result of applying effluent to the soil over two growing seasons. The build up of this nutrient in the soil might be accounted for the low magnesium demand of trees for biomass production compared to calcium, potassium, nitrogen and phosphorus (McLaren and Cameron, 1996).

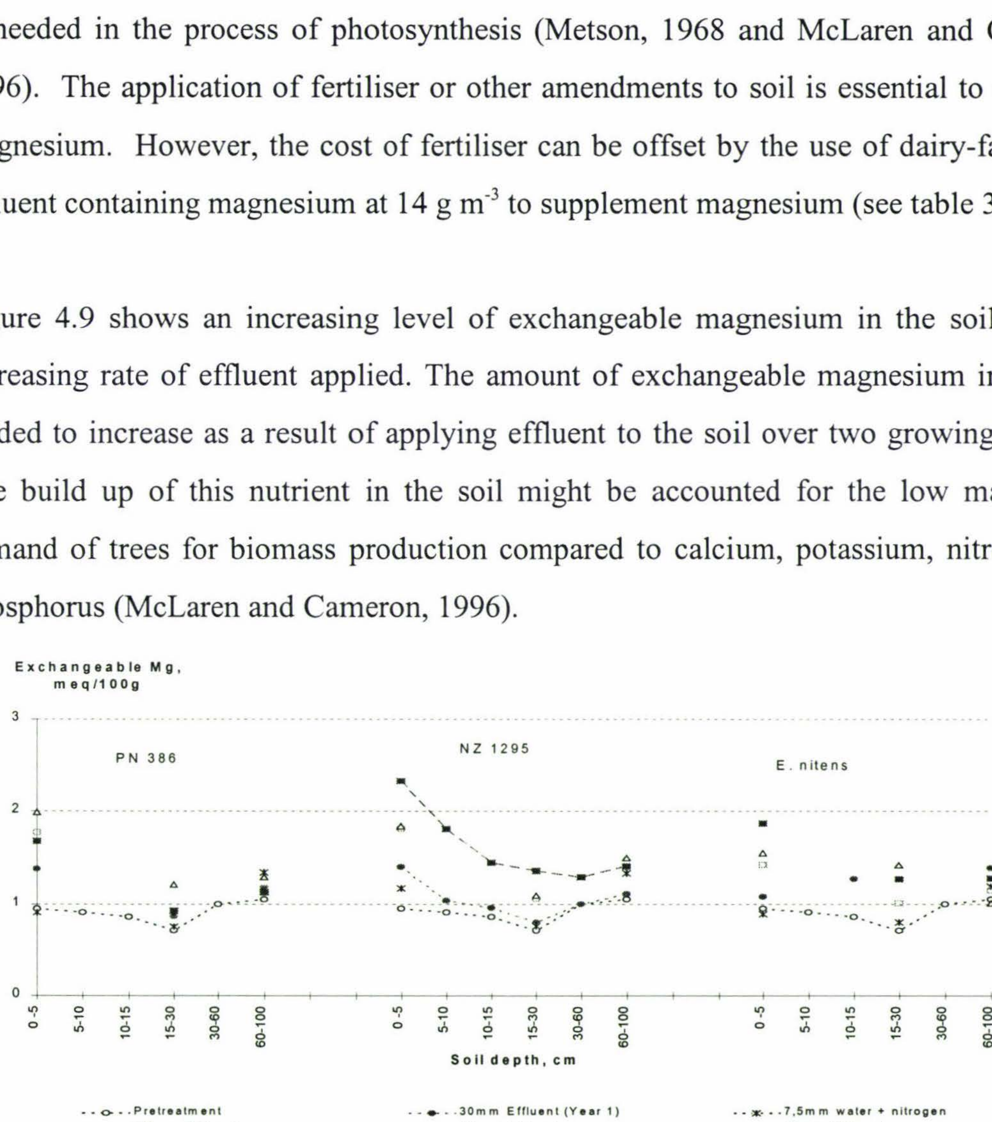


Figure 4.9 Exchangeable magnesium in soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen over two growing seasons

In all the depths of measurement, the magnitude of exchangeable magnesium in the soil varies with the amount of irrigation and species of SRF trees. The magnitude of exchangeable magnesium in the soil increased with increasing level of effluent irrigation. Based on the second year results, at 0-5 cm depth under NZ 1295, soils applied with the highest rate of effluent were higher in exchangeable magnesium than all the other treatments with a value of 2.33 meq $100g^{-1}$. Soils under PN 386 and Eucalyptus nitens increased to 1.68 and 1.87 meq $100g^{-1}$, respectively. At 15-30 cm depth, the soil under NZ 1295 was higher in exchangeable magnesium level at 1.36 meq $100g^{-1}$ than PN 386 and *E. nitens* with values of 0.93 and 1.27 meq $100g^{-1}$, respectively. At the lower depth, measured at 60-100 cm, the level of exchangeable magnesium of soil under NZ 1295 at 15 mm of effluent irrigation was 1.41 meq $100g^{-1}$ which was slightly higher than the other treatments. At this depth, some exchangeable magnesium in the soil had been suppressed by potassium and ammonium of the effluent and was leached through the groundwater.

Table 3.5 showed that NZ 1295 had the least leaf biomass. This explains the lower magnesium demand of this tree, leaving higher amount of exchangeable magnesium in the soil pool. Weir and Allen (1997) recorded a significant increase in magnesium and phosphorus along with soil pH, and organic matter when composted organic amendments were applied. The significant amount of potassium that was applied through effluent irrigation had possibly antagonised the mobility of magnesium for plant uptake. McLaren and Cameron (1996) stated that heavy rates of potassium induced the luxury uptake of this nutrient by crops and suppressed the availability of magnesium during the rapid vegetative stage during late winter and spring. Trees irrigated with 7.5mm water + nitrogen utilised exchangeable magnesium from the soil pool but at insignificant amount compared to trees supplied with Mg. The magnesium level in the soil increased under all the three species possibly due to 30 mm effluent application. The pre-treatment level of exchangeable magnesium in the soil may not have been used by the trees.

The supply of magnesium through the application of effluent might have exceeded the requirement of the trees. This explains the significant balance of exchangeable magnesium in the soil pool when applied with of effluent. The same trend was noticed by Pascual et al. (1997) and Alker et al. (1998) regarding the residual effect of waste application to soil.

Exchangeable magnesium, like exchangeable calcium has the potential to be leached to the groundwater when supply exceeds the requirement of crops and the retention capacity of soil to store this nutrient. Nitrification, like in calcium, encourages the leaching of magnesium along with nitrates (McLaren and Cameron, 1996). In a another study, excessive application of swine manure increased the leaching of nitrate-nitrogen, phosphorus and magnesium(Choudhary et al., 1996).

4.4.7 Exchangeable sodium in the soil

Most soils contain sufficient sodium for plant growth and responses since the demand of crops for this nutrient is small compared to the quantity of potassium required. There are some crops that have high sodium uptake potential. The exchangeable sodium has the ability to substitute for potassium in some functions in the plant. But the excessive amount of potassium in the soil will antagonise the availability of sodium to plants. This situation induced sodium deficiency in crops, then in animals. When sodium in the soil exceeds the requirement of crops, there is a potential risk of making the soil saline. If the sodium buffering zone of the soil is overloaded, the soil structure may collapse and organic matter may flocculate. High concentrations of sodium in soil solution can also reduce osmotic water potential and thus decrease the amount of water that is readily available for plant uptake.

Figure 4.10 shows the exchangeable sodium in soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen. Accumulation of exchangeable sodium below the 10 cm depth of soil tended to increase as the level of effluent irrigation increased from 7.5mm to 30 mm. The addition of sodium through effluent irrigation had increased the exchangeable sodium in the soil at an increased level particularly those soils irrigated at the highest rate of effluent. The build up of exchangeable sodium in the soil can be attributed to the low sodium intake of trees and excessive supply of exchangeable potassium that limited the intake of sodium by crops. Mclaren and Cameron, (1996) stated that exchangeable potassium can affect the availability of sodium to crops. Hence, the addition of sodium to soil will build up the exchangeable sodium level of the soil in the presence of potassium in excess of the optimum uptake of the tree. Soils under the three species were different in the level of exchangeable sodium. The uptake of sodium varied from species to species. This explains the build up of exchangeable sodium in the soil under NZ 1295. The adverse effect of excessive supply of exchangeable sodium will suppress the availability of potassium and calcium.

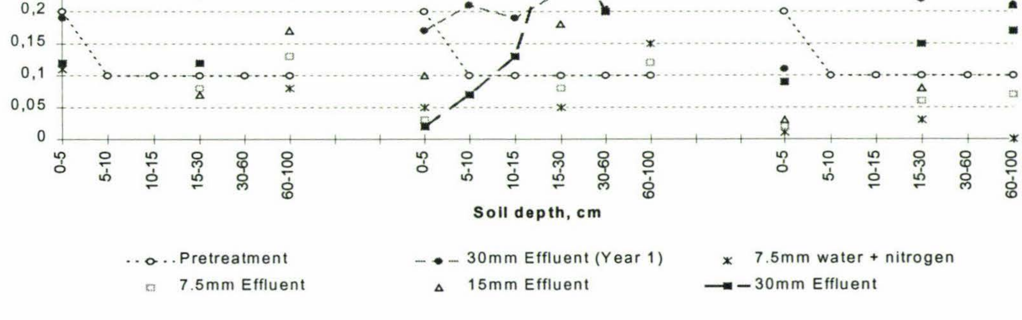


Figure 4.10 Exchangeable sodium in soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen following two growing seasons

Figure 4.10 shows the build up of exchangeable sodium in the soil under the three species that were applied with 30 mm of effluent over two growing seasons. Over time, the level of exchangeable sodium in the soils were different. The differences of pattern of transport of exchangeable sodium through the soil profile can be attributed to the differences in species of SRF trees. The root structure of these trees were possibly different creating different patterns and sizes of pores that transported the exchangeable sodium through the soil profile. Evidence of sodium leaching was apparent in the soil under Eucalyptus nitens due to the decreased level of exchangeable sodium throughout the soil profile. The level of exchangeable sodium in the soil under NZ 1295 increased at 60-100 cm depth. The nutrient had leached from the upper layers of the soil to the lower depth. Possibly the slow transport of the nutrient in year two can be attributed to the fibrous root structure of NZ 1295 that intercepted the sodium supplied through effluent application. However, the species accumulated small amount of sodium when compared to its intake of potassium. Despite the build up of sodium throughout the soil profile, the site did not show any degradation signs after two years of effluent irrigation as shown by the healthy condition of SRF trees at harvest. The SAR (sodium adsorption ratio) of the upper 0-5, 15-30 and 60-100 cm depth of the soil under NZ 1295 that was irrigated at the highest rate of effluent was 0.575, 0.18 and 0.22, respectively. The sodium adsorption ratios (SAR) of the soil were determined using the equation below:

$$SAR = Na^{+} / [(Ca^{++} + Mg^{++})/2]^{1/2}$$

These values were lower than the limit (SAR < 6.0) that indicates sodicity problems in the soil. According to Polprasert (1996), soils with SAR < 6.0 do not present any sodicity problem. Surapaneni et al. (1996) also reported an SAR = 0.5 after application of dairy shed effluent in a loam soil. In a longer term of effluent irrigation, sodium may build up in the soil profile which could lead to a degradation of soil structure and reduction in water percolation rates (Polprasert, 1996) if not properly managed. However, under field conditions, like in this experimental, the addition of sodium was possibly balanced by rainfall at the experiment site (mean annual rainfall = 995 mm). Rainfall in excess of the water holding capacity of the soil might have leached salts in the site.

4.4.8 The cation exchange capacity (CEC) of the soil

The cation exchange capacity of the soil is a quantitative measure of the its ability to hold exchangeable cations. It indicates the quantity of negative charge present per unit of mass of soil. Typical soils have considerable capacity to absorb many of the cations in wastewater. According to Polprasert (1996) the cation exchange capacity of soils can range between 10 to 30.

The cation exchange capacity of the soil before effluent and after treatment in year 1 and year 2 are presented in figure 4.11. The CEC of the soil after the two years of applying effluent ranged from 4 to 14 meq/100g. The cation exchange capacity of the soil declined from pre-treatment over time. The decreased in cation exchange capacity of the soil through out the soil profile was significantly influenced by the level of irrigation and species of SRF trees. Each level of irrigation contained varying amount of potassium, calcium, magnesium and sodium. Some of the cations that were not assimilated by the crops were upheld by the soil particles and this caused the declining cation exchange capacity of the soil. Over time, the soil will reach its equilibrium state of cation exchange capacity. This might lead to leaching of cations into the ground water and build up of salts in the soil giving water degradation.

Soil moisture through irrigation helps the trees to uptake the cations. The soils under NZ 1295 and *E. nitens* applied with the lowest amount of effluent showed lower cation exchange capacity level because the cations applied adhered to the particles of the soil and possibly insufficient moisture prevented the uptake of cations by the trees. The movement of cations was also possibly limited by the lower rate of effluent irrigation.

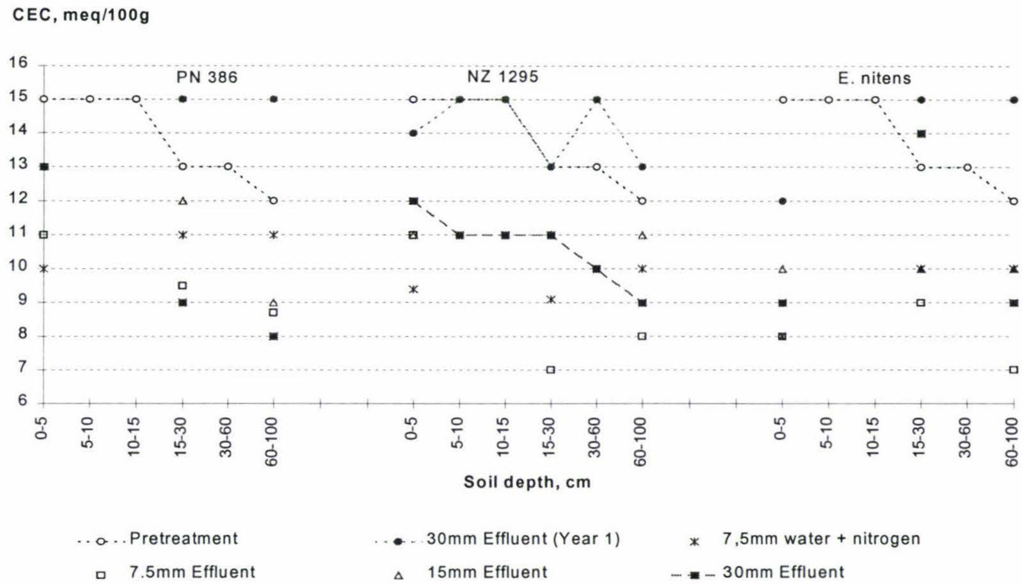


Figure 4.11 Cation exchange capacity in soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen following two growing seasons.

The soils under the three SRF crops that were irrigated with 30 mm of effluent were significantly different in their ability to hold exchangeable cations. The differences of soils to hold exchangeable cations in their mass can be attributed to the differences in species and the capacity of the trees to assimilate nutrients from the soil. The soils under PN 386 showed the lowest cation exchange capacity level. The cation exchange capacity of the soil differs throughout the soil profile possibly because of the differences in the amount of soil particles that allows the exchange of cations.

At 30 mm of effluent application, the soil under the *E. nitens* at 0-5 cm depth of soil declined in CEC level at 40 % compared with the soils under PN 386 and NZ 1295 with a decline of 13.33 and 20 %, respectively. At 15-30 cm depth, the soils under the *E. nitens* increased in CEC level by 7.69 %, while those under the PN 386 and NZ 1295 decreased by 30.77 and 15.38 %, respectively. At 60-100 cm, the decline in CEC for soils under PN 386 was 33.33% and 25 % for both NZ 1295 and *E. nitens*.

The upper 30 cm depth of soils under the tree SRF trees had possibly held more cations than the depth below 30 cm because most of roots of irrigated trees were within the upper level of the depth (Sims et al., 1994). The uptake of nutrients by the trees at this depth had possibly caused the soil to hold more exchangeable cations.

4.4.9 Soil pH

Soil acidity influences the availability of nutrients to plants and micro-organisms. Basic macronutrient cations like exchangeable calcium, magnesium, sodium and potassium are usually found in higher amounts in alkaline soils and lower amounts in acid soils.

Figure 4.12 shows the pH of soil under the three SRF species that were irrigated at different rates of effluent and the pH of effluent applied to the soils ranged from 7.5 to 8.1. At all depths observed, the pH of the soil varied significantly with both the level of irrigation applied and species of SRF trees. The soil under NZ 1295 when irrigated at 30 mm of effluent had a significant increase of pH ($p > 0.05$) compared with those soils applied with lower rates of effluent and water + nitrogen. The pH of soils under *E. nitens* increased at the upper 15 cm depth of the soil as the irrigation level of effluent is increased. Below this depth, the pH of the soil declined below the pre-treatment level.

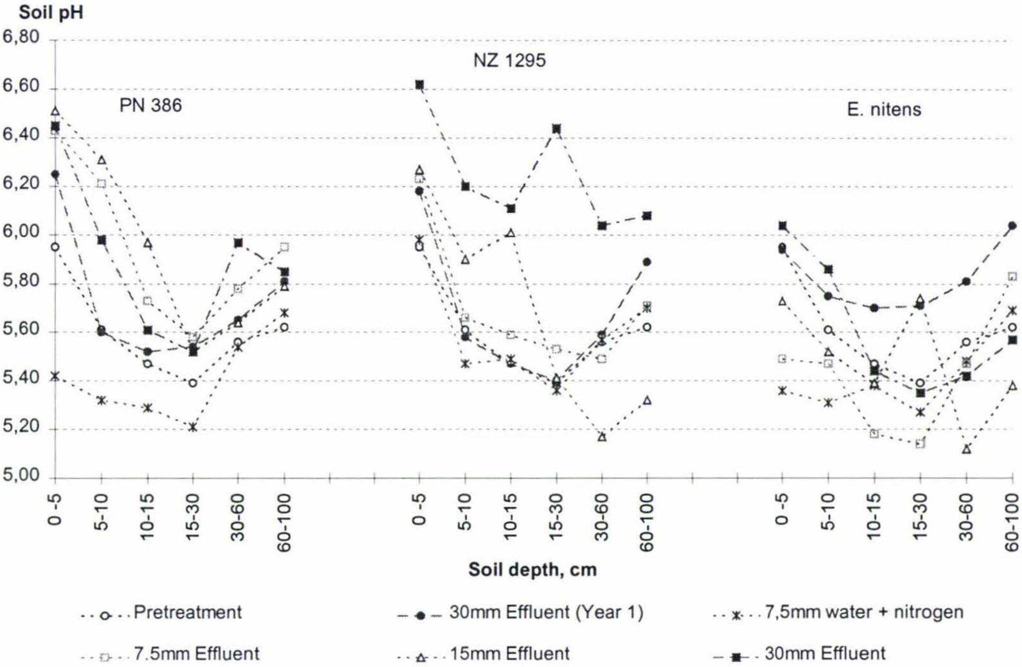


Figure 4.12 pH of soil under three SRF trees irrigated with different rates of dairy farm pond effluent and water + nitrogen following two growing seasons ($LSD_{0-5} = 0.41$; $LSD_{5-10} = 0.40$; $LSD_{10-15} = 0.39$; $LSD_{15-30} = 0.47$; $LSD_{30-60} = 0.35$; $LSD_{60-100} = 0.32$)

The soils under PN 386 showed another pattern of pH level. At the upper 30 cm depth, the soil pH were lower when irrigated at 30 mm of effluent than those irrigated at the lower rates. However, the soil pH in between the depths of 30 to 60 cm increased as the effluent level was increased. The addition of effluents more than the crop requirement of water and nutrients also implied addition of exchangeable cations to the soil. The increase in the pH level of the soil under the three SRF species also reflected the level of exchangeable cations present at the different layers. Soils under NZ 1295 irrigated with 30 mm of effluent over two growing seasons, in particular contained higher level of exchangeable potassium, calcium , magnesium and sodium than the soils under PN 386 and Eucalyptus nitens (see Figures 4.7, 4.8, 4.9 and 4.10). The rate of potassium and magnesium assimilation of soils under NZ 1295 which were significantly lower than the PN 386 and *E. nitens* (Figures 4.7 and 4.10) also indicated the magnitude of remaining cations from effluent application that adhered to the soil particles. This contributed to the higher pH level of the soil under NZ 1295. For *E. nitens*, the pH of the soil was significantly lower at the upper 60 cm depth because the rate of potassium and calcium assimilation of this crop was significantly higher than the willows (Figures 3.8 and 3.9). This condition left the soils under *E. nitens* to be comparatively lower in exchangeable potassium, calcium and sodium when applied at the highest rate of effluent irrigation. This situation also showed that the uptake of cations is a function of the moisture in the soil through effluent application. It follows that the pH of the soil under the Eucalyptus nitens crop at 30-60 cm depth was significantly lower than the soils under the two species of SRF trees, particularly at an irrigation rate of 30 mm of effluent.

At 30 mm of effluent application, the soils under the Eucalyptus nitens at 0-5 cm depth had the lowest increase in pH by 1.51 % compared to soils under PN 386 and NZ 1295 by 8.4 and 11.26 %, respectively. At the 15-30 cm depth, the pH of soil under the Eucalyptus nitens decreased by 0.74 %, while the soils under PN 386 and NZ 1295 increased by 2.41 and 19.48 %, respectively. At 60-100 cm, the pH of soils under the *E. nitens* decreased by 0.89 %, while the soils under PN 386 and NZ 1295 increased by 4.09 and 8.19 %. The decreased in the soil pH under the *E. nitens* at a depth below the 30 cm level confirmed the uptake of cations by the trees, reducing the exchangeable cations of the soil. It may also mean leaching of cations. The nitrates in the soil bonded with exchangeable calcium or exchangeable magnesium of the soil and leached to the groundwater.

The soil under the three SRF trees that were irrigated with 7.5mm of water + nitrogen (187.5 kg ha^{-1} $year^{-1}$) declined over time at the upper 60 cm layer of the soil when compared to the pre-treatment soil pH. This confirms an increasing effect on the soil pH when inorganic nitrogen fertiliser is applied to the soil. The inorganic fertiliser was quickly hydrolysed to ammonium carbonate by the enzyme urease. The ammonium carbonate produced dissociated to ammonia which then converted to ammonia gas that volatilises. As a result, OH^- ions from ammonium carbonate were released which caused an increase of pH in the soil that was fertilised with urea. The overall chemical reaction is described by the following equation (McLaren and Cameron, 1996):

$$\underset{\text{urea}}{(NH_2)_2CO} + 2H_2O \rightarrow \underset{\text{ammonium carbonate}}{(NH_4)_2CO_3} \rightleftharpoons NH_4^+ + NH_3 + CO_2\uparrow + OH^-$$

Bolan (1996) discussed that application of nitrogen fertilisers such as urea and ammonium sulphate to soils produces acid by 1) undergoing nitrification process, in which acid is released and 2) leaching of nitrates, along with positively charged cations adhering to the negatively charged nitrates, resulting in acidification of the soil.

4.4.10 Soil bulk density

The soil bulk density is the ratio of the mass of dry soil to the total bulk volume of soil (Raes, 1989). Because bulk density includes the mass of air and water spaces in the soil, it can give an indication on the permeability of soil and its ability to allow root growth and development. The soil bulk density can be calculated by the following formula:

$$\rho_b = \frac{\text{mass of dry soil}}{\text{total volume of soil}} = \frac{m_s}{V_t}$$

$$\rho_b = m_s / (V_s + V_w + V_a)$$

where: V_s = volume of soil

V_w = volume of water

V_a = volume of air

The bulk density of the soils under the three SRF crops that were irrigated with dairy farm-pond effluent and water over two growing seasons is shown in figure 4.17. Bulk densities at the upper 30 cm depth varied with irrigation rates and species of SRF trees.

Both the soil bulk densities under PN 386 and NZ 1295 were significantly different from the soil under *E. nitens* in bulk density when irrigated at 30 and 15 mm of effluent. The decrease in bulk density at this depth can possibly be attributed to the macropores created by the roots of the trees. The amount of moisture and nutrients from the application of 15 and 30 mm of effluent had fuelled the development of roots at this depth of soil. An improvement for the bulk density of 4.0 % was observed for both willows, while the *E. nitens* improved by 3.2 % at the upper 5 cm depth of the soil. The improvement of this property of soil can affect the entry of wastewater in to the soil for plant uptake, also favours root development of trees for aeration and absorption of water and nutrients for growth and yield development. High bulk density implies soil compaction that prohibit root growth, resulting to poor plant growth and production. Similar results were reported by Tipler et al. (1996) regarding an 11.89 % improvement in the bulk density of soil when meatworks wastewater was used for irrigation in a farm. They further added that this improvement in the bulk density of soil reflects improved structure of the soil and worm population in the farm.

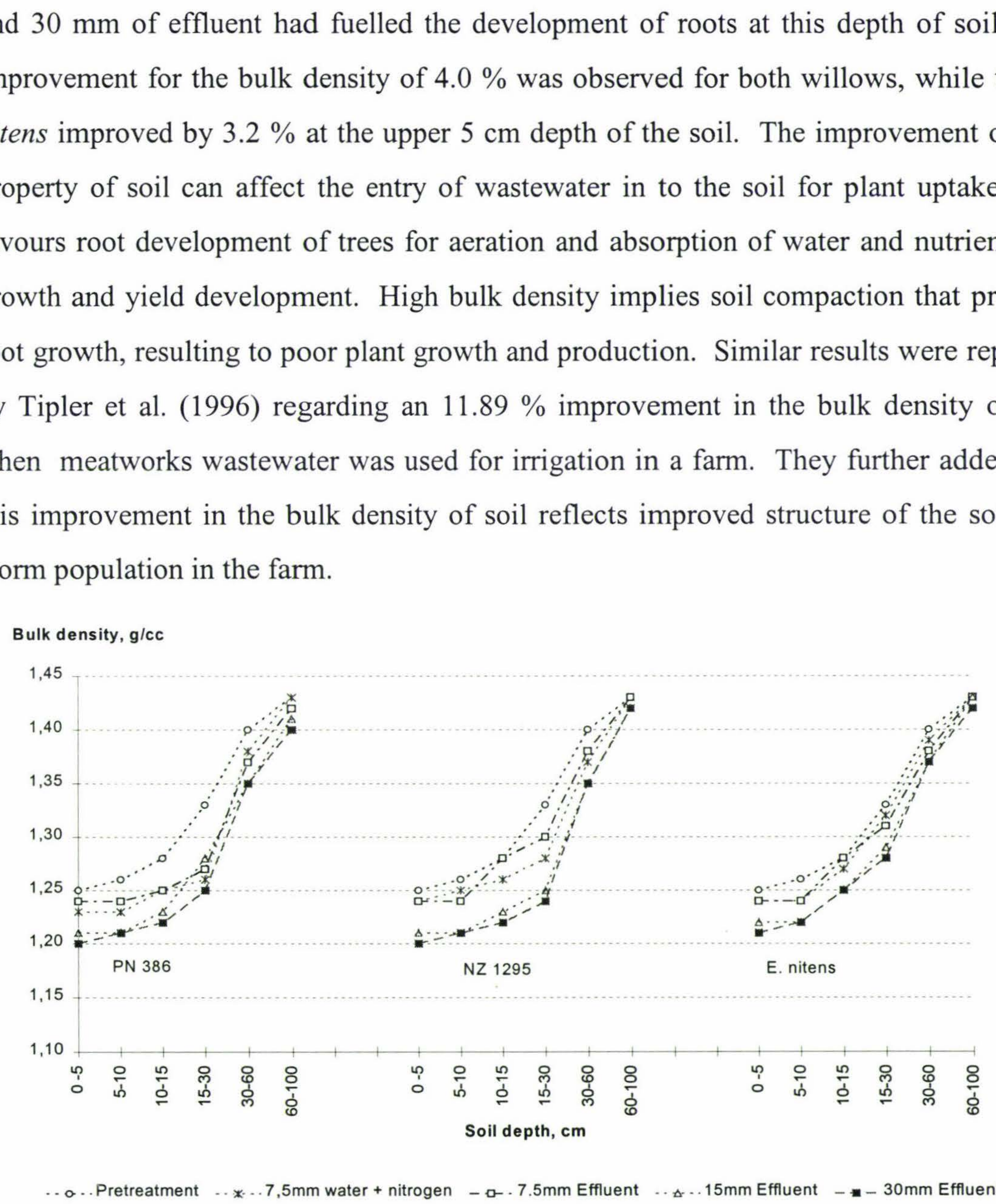


Figure 4.13 Bulk density of soil under three SRF trees irrigated with different rates dairy farm-pond effluent and water + nitrogen after two growing seasons

4.4.11 Soil infiltration rates

The rate at which water enters the soil surface is the infiltration rate that develops after some time has elapsed from the start of irrigation (Raes, 1989). The infiltration rate of the soil is important in the design of any land treatment scheme because it gives a basic rule on the appropriate amount of wastewater that can be applied to the disposal site at a given time to avoid flooding and runoff. The infiltration rate of soil is described by the following equation:

$$I = S / (2t^{1/2} + k_i)$$

where : I = quantity of water infiltrating a unit cross sectional area

S = sorptivity of the soil (capacity of the soil to absorb water)

k_i = ability of the soil to transmit water (conductivity)

In principle, Polprasert (1996) discussed that the application rate of waste effluent should not exceed the infiltration rate of the soil to eliminate the risk of ponding and runoff of nutrients and other pollutants that potentially threaten the quality of surface and groundwaters. The infiltration rate of soil is affected by the texture, structure and pore characteristics of the soil.

Figure 4.18 shows the infiltration rates of soils under the three SRF species that were irrigated with different rates of effluent. The infiltration rates varied with the irrigation rates and species. At the application of 30 mm of effluent, the infiltration rates of soils under PN 386 increased by 7.14 %, while *E. nitens* and NZ 1295 improved by 4.76 %.

This increase in infiltration rate implied an improvement in the soil structure of the soil. The decline in the bulk density of soil especially at the upper depths confirmed an improvement in the infiltrability of soil. The profuse branching out of roots of trees particularly at the top 30 cm depth and worm activities as a result of calcium addition through effluent application probably contributed to the formation of macropores that then serve as water channels, thus increasing the infiltration rates of the soil.

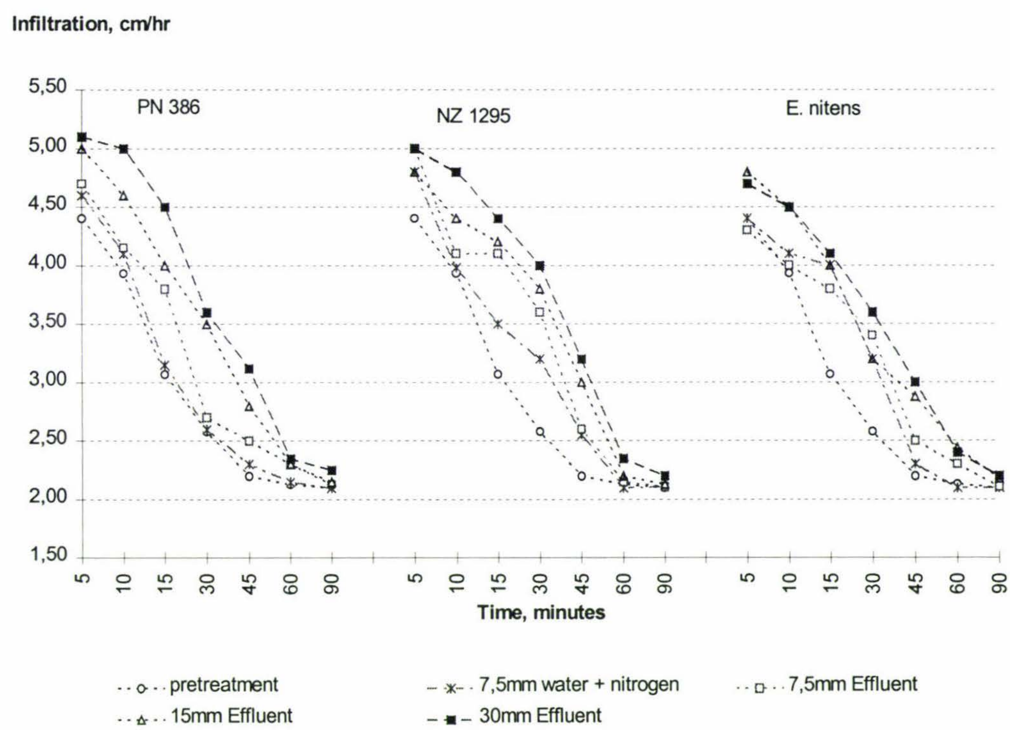


Figure 4.14 Infiltration rates of soil under three SRF trees irrigated with different rates of dairy farm-pond effluent and water + nitrogen after two growing seasons

4.5 Conclusions

The following conclusions can be drawn from this chapter.

- The total soil nitrogen level was significantly influenced by the rates of effluent irrigation and species of SRF trees ($p > 0.05$). The highest increase in total nitrogen occurred at the 0-5 cm depth of soil under *E. nitens* being 12.73 % greater than before irrigation began at 30 mm of effluent. At depths lower than 5 cm the nitrogen level decreased.

A reduction of soil total nitrogen occurred between pre-treatment to after harvest at year 2 and this indicated the following:

- uptake of total nitrogen by the SRF trees;
- lost total nitrogen during the process of nutrient transformation and volatilisation, and
- leaching of total nitrogen following rainfall or irrigation when soil water exceeded field capacity.

- At different depths, the nitrate levels in the soil were influenced by the rate of effluent irrigation and the species of SRF trees. Nitrate levels under PN 386 increased throughout the soil profile with increasing levels of effluent irrigation. The soil nitrate level under *E. nitens* started to increase with increasing effluent level only below the 10-15 cm depth. The nitrate level in the soil under NZ 1295 started to increase at 30 cm depth with increasing effluent irrigation, but only at the highest application rate.

The peak level of nitrate accumulation in the soil under the three species was reached at the 30 cm depth of the soil at 30 mm of effluent irrigation. The nitrate levels were significantly increased to 9.45, 5.8 and 4.6 parts per million, for *E. nitens*, PN 386 and NZ 1295, respectively.

After two growing seasons, the application of effluent increased the soil nitrate levels. The application of 30 mm of effluent significantly ($p > 0.05$) increased the soil nitrate level at 15-60 cm depths after year two to 9.45, 5.8 and 4.6 parts per million after two years for *E. nitens*, PN 386 and NZ 1295, respectively, for an original level of around 0.5 ppm.

The total phosphorus level in the soil under PN 386 and NZ 1295 increased in the top 5 cm by 2.55 and 12.45 %, respectively, when irrigated at the highest rate of effluent (30 mm). The soil under *E. nitens* increased by 11.85 % at this depth but at the 15 mm of effluent irrigation. The increase was due to phosphorus fixation. Below the 10 cm depth, the total phosphorus for all the treatments decreased probably due to tree uptake.

The application of 15 mm effluent to *E. nitens* was optimal before canopy closure occurred in this study. Application of 30 mm resulted in a lower amount of total phosphorus retained in the soil probably due to preferential flow of the effluent.

- The level of exchangeable potassium in the soil under the SRF trees increased with increasing rate of effluent irrigation. Exchangeable potassium levels were highest at 30 mm of effluent application for all three SRF species.

At 0-5 cm depth, irrigation with 30 mm of effluent to SRF trees increased the level of exchangeable potassium to 2.82, 2.63 and 2.22 times the pre-treatment level under NZ 1295, PN 386 and *E. nitens*, respectively. At 15-30 cm depth, the increases were 4.59, 2.68 and 2.65 times the pre-treatment level. At 60-100 cm, the *E. Nitens* was 9.6 times the pre-treatment level with NZ 1295 and PN 386 at 4.7 and 2.4 times, respectively. Irrigation with effluent to SRF trees increased the exchangeable potassium level of soils over the two growing seasons of application.

- At different depths, the exchangeable calcium level of the soil varied with the rate of effluent irrigation and species. At 0-5 cm depth, the exchangeable calcium level of the soil increased with increasing effluent irrigation, with NZ 1295 having the highest level of exchangeable potassium of 2.0 meq $100g^{-1}$ when irrigated at 30 mm of effluent compared to PN 386 and Eucalyptus nitens at 1.87 and 1.60 meq $100g^{-1}$, respectively. At 15-30 cm and under 30 mm of effluent irrigation, the soil under *E. nitens* was significantly higher in exchangeable calcium at 6.20 meq $100g^{-1}$ than the soils under NZ 1295 and PN 386 at 5.50 and 4.90 meq $100g^{-1}$, respectively. At 60-100 cm depth, the exchangeable calcium of soils under NZ 1295 at 30 mm of effluent irrigation were significantly higher was than those under PN 386 and *E. nitens* at 7.20, 6.20 and 6.10 meq $100g^{-1}$, respectively.

After two growing seasons, the irrigation of SRF trees with 30 mm of effluent influenced the exchangeable calcium of the soils as follows:

- under PN 386, increased by 23.64 % at 0-5 cm depth, equalled the pre-treatment level at 15-30 cm depth; and decreased by 4.62 % at 60-100 cm depth;
- under NZ 1295, increased by 24.55 % at 0-5 cm depth, increased by 12.24 % at 15-30 cm depth; and increase by 10.77 % at 60-100 cm depth; and

- under *E nitens*, increased by 1.82 % at 0-5 cm, by 26.53 % at 15-30 cm and by 6.15 % at 60-100 cm.

- The exchangeable magnesium level in the soils under the three SRF species increased with increasing effluent irrigation. After two years of irrigating, the exchangeable magnesium levels in the soils were as follows:

    - PN 386 increased 1.77 times the pre-treatment level at the 0-5 cm depth, increased by 1.31 times at 15-30 cm depth and increased by 1.08 times at 60-100 cm depth;
    - NZ 1295 increased by 2.45 times the pre-treatment level at 0-5 cm depth, by 1.92 times at 15-30 cm depth and increased by 1.34 times at 60-100 cm depth and;
    - *E. nitens* increased by 1.97 times at 0-5 cm depth, increase by 1.79 times the pre-treatment level at 15-30 cm depth and by 1.22 times at the 60-100 cm depth.

- Exchangeable sodium at different depths of soil varied with the rate of effluent and species. The exchangeable sodium after two years through effluent irrigation increased below the 30 cm depth of soil when irrigated at 30 mm of effluent. However, the level of exchangeable sodium in the soil under the three SRF species were all below the risk sodicity limit (Sodium Adsorption Ratio (SAR) < 6.0) throughout all depths.

The soils under NZ 1295 had the highest level of exchangeable sodium below the 30 cm depth of soil when irrigated at 30 mm of effluent. The SAR values for 0-5, 15-30 and 60-100 cm depth were 0.575, 0.18 and 0.22, respectively.

- The cation exchange capacity of the soils varied with the rate of effluent irrigation and species. The application of effluent to SRF trees over two growing seasons resulted in the following:
  - a significant reduction of cation exchange capacity of soils at 0-5 cm depth to 8 meq $100g^{-1}$, for *E. nitens* and 11 meq $100g^{-1}$, for both PN 386 and NZ 1295, respectively, when irrigated with 7.5 mm of effluent as compared to higher rates of effluent irrigation;
  - a significant reduction of cation exchange capacity of soils at 15-30 cm depth under PN 386, *E. nitens* and NZ 1295 to 9.50, 9.0 and 7.0 meq $100g^{1}$, respectively, when irrigated at 7.5 mm of effluent compared to higher rates of effluent application; and;
  - a significant reduction of cation exchange capacity of soils under NZ 1295, PN 386 and *E. nitens* to 9, 8 and 4 meq $100g^{-1}$, respectively, when irrigated at 30 mm of effluent irrigation.

At 30 mm of effluent application, the top 5 cm of soil under Eucalyptus nitens significantly declined in cation exchange capacity level by 40% compared with the soils under PN 386 and NZ 1295 giving reduction rates of 13.33 and 20 %, respectively. At 15-30 cm depth, the soil under *E. nitens* increased by 7.69 %, while PN 386 and NZ 1295 declined by 30.77 and 15.38 %, respectively. At 60-100 cm depth, the soil under PN 386 declined by 33.33 % and 25% for both NZ 1295 and *E. nitens*. The cation exchange capacity of soils after two years of applying 30 mm of effluent reduced the average cation exchange capacity of the soil by 19.10, 25.81 and 43 % for *E. nitens*, PN 386 and NZ 1295, respectively.

- At all the depths, the pH of the soil varied with the rate of effluent irrigation and species. The soil pH under NZ 1295 irrigated at 30 mm of effluent was significantly higher in all the depths observed than under the other treatments. The pH of soil under the NZ 1295 increased with increasing rate of effluent irrigation giving a soil pH ranging from 5.71 to 6.49. PN 386 and *E. nitens* responded differently to the different rates of effluent irrigation.

- The application of 7.5 mm of water + 187.5 kg N ha^{-1} $year^{-1}$ significantly decreased the pH of soils under all three species at the upper 60 cm depth, as compared to the application of effluent.

- The bulk density at the top 30 cm depth varied with irrigation and species. The bulk density of soils under both PN 386 and NZ 1295 improved by 40%, while under *the E. nitens* improved by 3.2% at the top 5 cm depth of the soil. At 15-30 cm depth, NZ 1295 improved by 6.77 % followed by PN 386 at 6.0% and *E. nitens* at 3.8 %. At 60-100 cm depth, PN 386 improved by 2.10% while both the *E. nitens* and NZ 1295 improved by 0.70 %.

- The infiltration rate of the soil varied with irrigation rate and species. The infiltration rate of soil under PN 386 increased by 7.14 % while, for both *E. nitens* and NZ 1295 it increased by 4.76 % when irrigated with 30 mm of effluent after two growing seasons.

CHAPTER 5
UPTAKE OF NUTRIENTS

5.1 Introduction

Application of waste effluents on agricultural land has become increasingly popular because the disposal to surface water is environmentally unacceptable to New Zealand society. Moreover, the disposal of treated waste effluent by land treatment activities is generally regarded as being culturally acceptable to Maori (Glasson, 1998). A vegetated land treatment scheme that is properly designed and managed in accordance with the prevailing soil and plant properties can be environmentally safe method of treatment of waste effluents without impairing the quality of the soil and water resources.

The vegetation component of a land treatment system can filter and absorbs certain nutrients contained in the wastewater to achieve a desired standard of renovation. SRF trees as a renovating mechanism for example have the ability to remove a range of nutrients as they move through the soil. The rate that trees uptake the nutrients that are temporarily stored in the soil is an essential feature of the treatment system which determines the design. The age and physical features of plants such as tree size, crown architecture, root formation and biomass production are basic features that suggest the ability and suitability of a tree species to absorb nutrients. The filtering or absorption capability of the soil is another factor.

The rate and method of application of wastewater should match the properties of the soil to avoid the potential risk of water logging, runoff or rapid downward movement that can pollute the groundwater resources. Since land is a valuable resource, it is important to optimise its role in the renovation of waste effluents in a land treatment scheme without impairing the growth of vegetation and quality of the environment. Therefore information is needed to determine the capabilities of SRF trees together with the soil type in renovating dairy farm-pond effluent. The main purpose of this part of the study was to quantify the portion of nutrients in the dairy farm-pond effluent which when applied at various application rates, can be taken up by the SRF trees or absorbed by the soil matrix over two growing seasons.

5.2 Methodology

From the field experiment as described in section 3.2 , ten species of SRF trees irrigated with three rates of dairy farm-pond effluent together with a water + nitrogen treatment, the three species of SRF trees that showed the most significant growth response during the first growing season were selected for this section of the research. These species selected were PN 386, NZ 1295 and *E. nitens*. The leaves were separated from the stems and were weighed to get the biomass yields for each plot. The leaves and stems were separately analysed for nutrients that accumulated in the biomass (refer to section 3.2,) to quantify the amount of nutrients removed in each treatments.

Soil parameters such as bulk density, total nitrogen, total phosphorus, exchangeable potassium, calcium and magnesium were measured before and after effluent treatments were applied (refer to sections 4.2, 4.3). These parameters were used to quantify the amount of nutrients present at each depth range.

To give a nutrient balance of the SRF treatment system based on the effluent input, the total amount of each nutrient applied through irrigation (refer to section 3.1.1) was quantified and balanced with the amount of nutrients accumulated in the above ground biomass of the SRF trees. The differentials between pre- and post-treatment levels of soil nutrient at each depth range were also included to determine the total balance of the soil-SRF system.

The percentage of each nutrient (N_d) applied in the effluent and then retained in each of the six depth ranges was determines as follows:

$$N_d = [S_x / (S_a + S_p)] * 100 \qquad \text{(equation 5.1)}$$

where: S_x = amount of nutrient at depth range x after treatment, kg ha^{-1} $year^{-1}$

S_a = amount of nutrient applied through effluent, kg ha^{-1} $year^{-1}$

S_p = pre-treatment total amount of nutrient at the depth range measured, kg ha^{-1} $year^{-1}$

The percentage uptake of nutrients by each SRF species (T_s) as taken from the total supply of each nutrient, from the soil and effluent was determined as follows.

$$T_s = [T_n / (Sa + S_p)] * 100 \qquad \text{(equation 5.2)}$$

where: T_n = amount of nutrient accumulated in the above ground biomass of each SRF tree

S_a = amount of nutrient applied through effluent

S_p = pre-treatment total amount of nutrient in all depths measured

The total percentage renovation of the SRF-soil system (R_T) for each tree species was determined as the sum of the percentage renovation of all measured depth and the percentage of nutrient taken up by the SRF species (equation 5.3).

$$R_T = \Sigma \{ N_{1,} N_{2,} N_{3...} N_d \} + T_s \qquad \text{(equation 5.3)}$$

where : T_s = percentage uptake of nutrients by the three SRF species

$N_{d\,=}$ percentage of each nutrient retained in each of the n depths measured under each treatment.

To show how much of the nutrients applied through effluent each of the three SRF specie can renovate, equation 5.4 was used. The renovation percentage for each SRF species (R_{SRF}) was calculated as the amount of nutrients accumulated into the above ground biomass as taken from the nutrients applied through the effluent.

$$R_{SRF} = (T_n / S_a) * 100 \qquad \text{(equation 5.4)}$$

where: T_n = amount of nutrient accumulated in the above ground biomass of each SRF tree, kg ha^{-1} year^{-1}

S_a = amount of nutrient applied through effluent, kg ha^{-1} year^{-1}

In a soil-SRF treatment system the total input of nutrients from the soil and from the effluent should be balanced with the sum of the nutrients found in the SRF species, adsorbed or precipitated in the soil, leached to the ground water or volatilised.

$$TI_n - TO_n = 0 \qquad \text{(equation 5.5)}$$

where: TI_n = Total input of nutrients

TO_n = Total output of nutrients

The total input of nutrients is the sum of the nutrients already in the soil and those added through the effluent (equation 5.6).

$$TI_n = S_p + S_a \qquad \text{(equation 5.6)}$$

where: S_p = pre-treatment total amount of nutrient at each depth range measured, kg ha^{-1} year^{-1}

S_a = amount of nutrient applied through effluent, kg ha^{-1} year^{-1}

The total output of nutrients is the sum of the nutrients accumulated in the SRF species, adsorbed or precipitated in the soil, leached to groundwater and volatilised (equation 5.7).

$TO_n = T_n + O_n + R_n + V_n + L_n$ (equation 5.7).

T_n = amount of nutrient accumulated in the above ground biomass of each SRF tree, kg ha^{-1} $year^{-1}$

R_n = amount of nutrient in the roots of SRF tree kg, ha^{-1} $year^{-1}$

O_n = total amount of nutrients adsorbed in the soil kg, ha^{-1} $year^{-1}$

V_n = amount of nutrients that volatilised, kg ha^{-1} $year^{-1}$

L_n = amount of nutrients that leached, kg ha^{-1} $year^{-1}$

Substituting equations 5.6 and 5.7 in equation 5.5;

$S_p + S_a - T_n - R_n - O_n - L_n = 0$ (equation 5.8)

5.3 Results and Discussions

5.3.1 Renovation of total nitrogen

5.3.1.1 Soils

The total nitrogen renovation capacity of the soil is shown in Table 5.1. The percentage renovated was influenced by the irrigation rate and species. Equations 5.1, 5.2 and 5.3 (refer to section 5.1) were used to determine the total nitrogen renovation capacity of the soil-SRF treatment system. The percentage of nitrogen upheld in the soil increased with an increasing amount of nitrogen added through the higher rate of effluent irrigation. The total nitrogen renovated by the soil-*E. nitens* treatment system when irrigated at 30 mm was higher than in all the other treatment giving 96.45%. PN 386 and NZ 1295 renovated 88.07 and 91.03 % of total nitrogen supplied by the soil and 30 mm of effluent applied. Only 2% of the total nitrogen was renovated by both of the salix species.

The high percentage of total nitrogen in the soil under the *E. nitens* was probably due to the relatively low renovation capacity of the smaller trees during the first 21 months after establishment. The soil was possibly able to adsorb the bulk of nitrogen supplied through irrigation due to its structure (Manawatu fine sandy loam soil) and fertility level that accommodated the nitrification of the nitrogen supplied through the application of effluent (refer to Figure 4.4). Using equation 5.4, the *E. nitens* renovated 0.88 % of the total nitrogen supplied by the soil and effluent at 30 mm of effluent irrigation (Table 5.1). Both salix species renovated higher total nitrogen into their above ground biomass than the *E. nitens*.

Table 5.1 Renovation of total nitrogen in a soil-SRF species treatment system after two years of effluent irrigation

Species	Soil Depth	Pre-treatment TN of Soil, kg ha^{-1}				Post treatment TN of soil, kg ha^{-1}				% Renovation			
	Cm	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent
PN 386	0-5	1250.0	1250.0	1250.0	1250.0	1300.6	1235.5	1356.6	1119.3	7.5	7.2	7.8	6.3
	5-10	1398.6	1398.6	1398.6	1398.6	1225.1	1183.3	1209.2	1134.8	7.1	6.9	7.0	6.4
	10-15	1228.8	1228.8	1228.8	1228.8	1088.7	1199.2	1129.0	1062.8	6.3	7.0	6.5	5.96
	15-30	3451.5	3451.4	3451.4	3451.2	3047.3	2747.6	3115.3	3166.9	17.6	16.0	18.0	17.8
	30-60	5166.0	5166.0	5166.0	5166.0	4689.3	4094.6	4520.3	5734.3	27.2	23.9	26.0	32.1
	60-100	4404.4	4404.4	4404.4	4404.4	2591.5	2773.1	3147.7	3125.3	15.0	16.2	18.1	17.5
	Effluent	375.0	230.0	460.0	946.0								
	Plant Out					236.4	228.7	272.6	373.4	1.4	1.3	1.6	2.1
Total		**17274.2**	**17129.2**	**17359.2**	**17845.2**	**14178.9**	**13461.9**	**14750.7**	**15716.8**	**82.1**	**78.6**	**85.0**	**88.1**
Unaccounted N						**3095.3**	**3667.3**	**2608.4**	**2128.4**				
NZ 1295	0-5	1250.0	1250.0	1250.0	1250.0	1084.4	1074.2	1238.7	1175.4	6.3	6.3	7.2	6.6
	5-10	1398.6	1398.6	1398.6	1398.6	822.4	990.4	1124.5	1076.2	4.8	5.8	6.5	6.0
	10-15	1228.8	1228.8	1228.8	1228.8	776.6	790.0	1162.7	1024.2	4.5	4.6	6.7	5.7
	15-30	3451.4	3451.4	3451.2	3451.2	2030.7	2556.1	2523.6	3011.4	11.8	14.9	14.5	16.9
	30-60	5166.0	5166.00	5166.0	5166.0	2190.6	3680.6	4574.4	5351.1	12.7	21.5	26.4	30.0
	60-100	4404.4	4404.4	4404.4	4404.4	2410.7	2944.8	3284.0	4249.4	14.0	17.2	18.9	23.8
	Effluent	375.0	230.0	460.0	946.0								
	Plant Out					154.8	176.5	236.6	357.3	0.9	1.0	1.4	2.0
Total		**17274.2**	**17129.2**	**17359.2**	**17845.2**	**9470.2**	**12212.6**	**14144.4**	**16244.8**	**54.8**	**71.3**	**81.5**	**91.0**
Unaccounted N						**7804.0**	**4916.6**	**3214.7**	**1600.3**				
E.nitens	0-5	1250.0	1250.0	1250.0	1250.0	1260.0	1115.5	1166.4	1368.5	7.3	6.5	6.7	7.7
	5-10	1398.6	1398.6	1398.6	1398.6	1144.2	1188.8	1084.0	1161.5	6.6	6.9	6.2	6.5
	10-15	1228.8	1228.8	1228.8	1228.8	1084.0	1123.5	1045.2	1011.0	6.3	6.6	6.2	5.7
	15-30	3451.4	3451.4	3451.4	3451.4	2466.9	2736.6	3104.5	3502.9	14.3	16.0	17.8	19.6
	30-60	5166.0	5166.0	5166.0	5166.0	2153.5	3475.0	5361.0	6244.7	12.5	20.3	30.8	35.0
	60-100	4404.4	4404.4	4404.4	4404.4	2048.7	2487.0	3469.0	3766.6	11.9	14.5	20.0	21.1
	Effluent	375.0	230.0	460.0	946.0								
	Plant Out					102.8	121.1	188.6	156.9	0.6	0.7	1.1	0.9
Total		**17274.2**	**17129.2**	**17359.2**	**17845.2**	**10259.8**	**12248.0**	**15418.6**	**17212.1**	**59.4**	**71.5**	**88.8**	**96.5**
Unaccounted N						**7014.3**	**4881.2**	**1940.6**	**633.1**				

Equations 5.5, 5.6, 5.7 and 5.8 were used to quantify unaccounted amount of total nitrogen which can possibly be attributed to the volatilisation, leaching and root uptake of the nutrient. The amount of unaccounted nitrogen decreased with increasing rate of effluent applied. The soil-*E. nitens* treatment system when irrigated at 30 mm of effluent recorded the lowest unaccounted total amount of 633.1 kg N ha^{-1} (3.65%) (Table 5.1). McLaren and Cameron (1996) suggested that whenever nitrates are present in amounts greater than the plant can assimilate, then leaching will occur if water drains through the soil .

5.3.1.2 SRF species

Figure 5.1 shows the percentage of total nitrogen applied which was taken up by each of the of three SRF species per growing season. The renovation capacity of the SRF trees was taken as the percentage of the amount of each nutrient accumulated in the above ground biomass of the trees from the total amount of nutrients supplied through the effluent (equation 5.4). The nitrogen was immobilised by the biomass of the trees. Harvesting the trees away from the disposal site, particularly the willows before the trees shed their leaves will contribute to the effluent renovation efficiency of the tree and soil system.

The amount of effluent irrigation influenced the renovation capacity of the SRF trees. Differences in the species of SRF trees also resulted in significant variation ($p > 0.05$) in the renovation capacity of the trees. The lowest application rate of nitrogen at 7.5 mm of effluent resulted in significantly higher renovation capacity by the trees. PN 386 showed superiority in renovating the effluent being up to 99.5% per growing season when applied at 7.5 mm. The amount of nitrogen applied through effluent application was 115 kg N ha^{-1} $year^{-1}$ which closely matched the accumulated nitrogen in the above ground biomass of the tree at the rate of 114.3 kg N ha^{-1} $year^{-1}$.

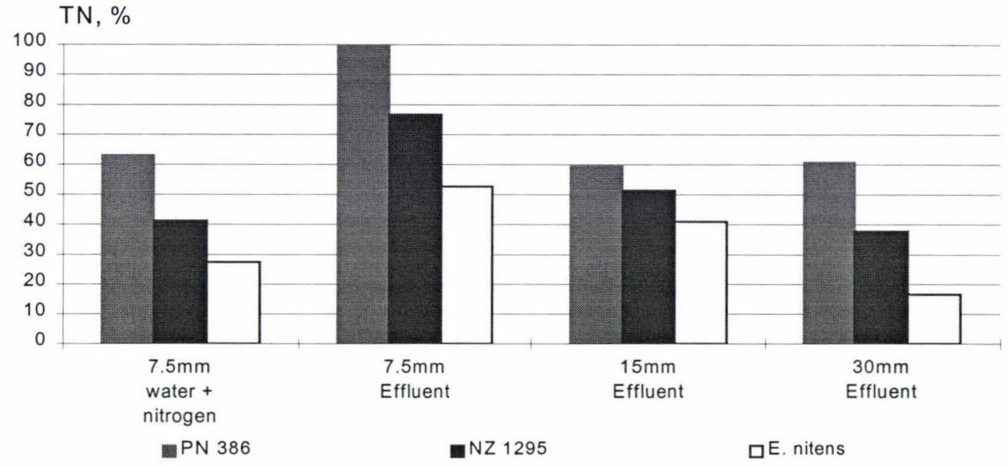


Figure 5.1 Percentage uptake by three SRF species of total nitrogen applied per year from the effluent over for two growing seasons

Increasing the amount of nitrogen through increased irrigation with effluent that far exceeded the possible uptake by the tree decreased the renovation capacity of the trees to 59.3 and 60.6 % for PN 386 at 15 and 30 mm of effluent application, respectively. NZ 1295 renovated 76.8 % of nitrogen from the effluent during the first year and declined to 51.4 and 37.8 % when irrigated at 15 and 30 mm of effluent, respectively. *E. nitens* renovated the least amount being 52.6 % per year and decreased to 41.0 and 16.6 % when the irrigation was pushed to 15 and 30 mm of effluent, respectively. The high renovation capacity of PN 386 can be attributed to its high above ground biomass accumulation, the dense foliage architecture (4.3 ODt ha^{-1} $year^{-1}$, Figure 3.5) and possibly the root-mat like structure of the roots. Although the renovation capacity of the PN 386 was high at 7.5 mm of effluent application, the optimum above ground biomass production of the tree (37.9 ODt ha^{-1} $year^{-1}$, Figure 3.3) was achieved at a nitrogen renovation capacity of only 60.6 % when applied at 30 mm of effluent.

5.3.2 Renovation of phosphorus

5.3.2.1 Soils

The percentage of total phosphorus applied that was retained in the various depths of soil under the three SRF species after two years of irrigation with dairy farm-pond effluent and water + nitrogen is shown in Table 5.2. Equations 5.1, 5.2 and 5.3 (refer to section 5.1) were used to determine the total phosphorus renovation capacity of the soil-SRF treatment system. The percentage of total phosphorus retained in the soil was significantly different ($p > 0.05$) under each species and irrigation treatment. The addition of total phosphorus above the content at 7.5 mm of effluent promoted a decrease in the renovation capacity of the soil under PN 386. This species showed the highest total phosphorus renovation capacity of 92.7 % which decreased to 87.6 and 83.1 % when irrigated at 15 and 30 mm of effluent (Table 5.2). Around 92.7% (6446.9 kg ha^{-1})of the input total phosphorus (6953.3 kg ha^{-1}) was renovated by the PN 386-soil system when irrigated with 7.5 effluent after two years. Soil-*E. nitens* treatment system renovated 86.7% when applied with 7.5 mm effluent and decreased to 84.2 and 74.6% at 15 and 30 mm of effluent application. Soil-NZ 1295 renovated 88.6% at 30 mm of effluent application and 76.2 and 71.2% when applied with 7.5 and 15 mm of effluent. It is probable that phosphorus was taken up by the roots of the SRF species and some was also adsorbed by the soil. The phosphorus retention capacity of sandy loam soil can range between medium (31-55%) and high (56-85%) (Bolan, 1996).

The TP taken up by the PN 386 and NZ 1295 (Table 5.2) was higher than all the other treatments being 0.5% (35.6 kg ha^{-1} after two years) of the TP supplied by the soil and 30 effluent mm (7089.3 kg ha^{-1}). Some of the nutrients might have been fixed in the soil profile below the one metre depth and were also probably immobilised in the roots.

Table 5.2 Renovation of total phosphorus in a soil-SRF species treatment system after two years of effluent irrigation

Species	Soil Depth	Pre-treatment TP of Soil, kg ha^{-1}				Post treatment TP of soil, kg ha^{-1}				% Renovation			
	Cm	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent
PN 386	0-5	362.5	362.5	362.5	362.5	337.6	412.8	398.3	363.3	4.9	5.9	5.7	5.1
	5-10	384.3	384.3	384.3	384.3	334.0	380.2	353.8	359.0	4.8	5.5	5.0	5.1
	10-15	377.6	377.6	377.6	377.6	312.0	346.1	340.6	332.7	4.5	5.0	4.9	4.7
	15-30	1097.3	1097.3	1097.3	1097.3	960.1	1003.6	1035.5	943.4	13.9	14.4	14.8	13.3
	30-60	2226.0	2226.0	2226.0	2226.0	1871.7	2058.7	2012.6	1949.2	27.1	29.6	28.7	27.5
	60-100	2459.6	2459.6	2459.6	2459.6	2144.0	2210.0	1966.4	1873.3	31.0	31.8	28.0	26.4
	Effluent		46.0	112.0	182.0								
	Plant Out					30.9	35.6	44.1	68.2	0.5	0.5	0.6	1.0
Total		**6907.3**	**6953.3**	**7019.3**	**7089.3**	**5990.3**	**6447.0**	**6151.3**	**5889.1**	**86.8**	**92.7**	**87.6**	**83.1**
Unaccounted TP						**917.0**	**506.3**	**868.0**	**1200.2**				
NZ 1295	0-5	362.5	362.5	362.5	362.5	284.9	333.6	332.3	422.7	4.1	4.8	4.7	6.0
	5-10	384.3	384.3	384.3	384.3	267.0	320.2	323.9	371.6	3.9	4.6	4.6	5.2
	10-15	377.6	377.6	377.6	377,6	242.3	260.8	264.4	354.7	3.5	3.8	3.8	5.0
	15-30	1097.3	1097.3	1097.3	1097.3	727.3	820.1	772.6	1041.8	10.5	11.8	11.0	14.7
	30-60	2226.0	2226.0	2226.0	2226.0	1481.70	1572.6	1444.4	2028.9	21.5	22.6	20.6	28.6
	60-100	2459.6	2459.6	2459.6	2459.6	1971.4	1960.5	1814.7	1988.0	28.5	28.2	25.9	28.0
	Effluent		46.0	112.0	182.0								
	Plant Out					28.8	31.6	45.0	71.3	0.5	0.5	0.6	1.0
Total		**6907.3**	**6953.3**	**7019.3**	**7089.3**	**5003.5**	**5298.9**	**4997.2**	**6279.1**	**72.5**	**76.2**	**71.2**	**88.6**
Unaccounted TP						**1903.8**	**1654.3**	**2022.0**	**810.2**				
E.nitens	0-5	362.5	362.5	362.5	362.5	364.5	402.4	401.5	330.0	5.3	5.8	5.7	4.7
	5-10	384.3	384.3	384.3	384.3	331.4	382.7	374.1	293.1	4.8	5.5	5.3	4.1
	10-15	377.6	377.6	377.6	377.6	302.8	363.2	354.7	280.8	4.4	5.2	5.1	4.0
	15-30	1097.3	1097.3	1097.3	1097.3	921.1	996.3	977.5	838.7	13.3	14.3	13.9	11.8
	30-60	2226.0	2226.0	2226.0	2226.0	1674.2	1952.3	1898.3	1553.9	24.2	28.1	27.0	21.9
	60-100	2459.6	2459.6	2459.6	2459.6	2057.9	1913.9	1879.2	1968.8	29.8	27.5	26.8	27.8
	Effluent		46.0	112.0	182.0								
	Plant Out					13.0	16.7	27.9	26.9	0.2	0.2	0.4	0.4
Total		**6907.3**	**6953.3**	**7019.3**	**7089.3**	**5665.0**	**6027.4**	**5913.2**	**5291.5**	**82.1**	**86.7**	**84.2**	**74.6**
Unaccounted TP						**1242.3**	**925.9**	**1106.0**	**1797.8**				

Equations 5.5, 5.6, 5.7 and 5.8 were used to quantify unaccounted amount of total phosphorus which can possibly be attributed to the root uptake of the nutrient and adsorption below the one metre root depth. The soil-PN 386 treatment system when irrigated at 7.5 mm of effluent recorded the lowest unaccounted total amount of 506.3 kg TP ha^{-1} (7.3%) (Table 5.2).

5.3.2.2 SRF species

The renovation capacity of the three SRF species is presented in figure 5.2. In a scenario of maintaining crop productivity, nutrients renovated by the trees or crops after harvesting can be replaced by the application of effluent. The renovation capacity of the SRF species was taken as the percentage of the amount of each nutrient accumulated in the above ground biomass of the trees from the total amount of nutrients supplied through the effluent (equation 5.4). At 7.5 mm of effluent application (23 kg of total phosphorus ha^{-1} $year^{-1}$), the highest renovation capacities of the species were reached at 79.2, 70.3 and 37.1 % per year, for PN 386, NZ 1295 and *E. nitens*, respectively. The PN 386 showed superiority in the renovation of total phosphorus from the effluent over the other two SRF species at 7.5 mm of effluent application. At the higher rates of effluent irrigation, both PN 386 and NZ 1295 were similar in their efficiency at removing total phosphorus from the effluent. The *E. nitens* showed a lower efficiency in renovating the total phosphorus supplied by the effluent. It was evident that during the first two years of the *E. nitens* , the renovation capacity of this tree was limited to an application rate of 15 mm of effluent. At higher application rates (30 mm) the PN 386 and NZ 1295 renovated total phosphorus at 37.4 to 39.7 %, respectively, for each growing season.

Harvesting and removing the SRF trees away from the disposal site will eventually maintain the total phosphorus renovation capacity of an SRF-soil system to remove contaminants like phosphorus from the disposal site. This process in a land treatment scheme will lengthen the life span of a disposal site as determined by the phosphorus adsorption capacity of the soil. PN 386 can remove 18.2 kg (79.2 %) from the supply of 23 kg ha^{-1} $year^{-1}$ of total phosphorus at 7.5 mm of effluent irrigation if harvesting is done every year before the trees shed their leaves. Timing of harvesting is a critical consideration to avoid the return of phosphorus through litterfall in the autumn.

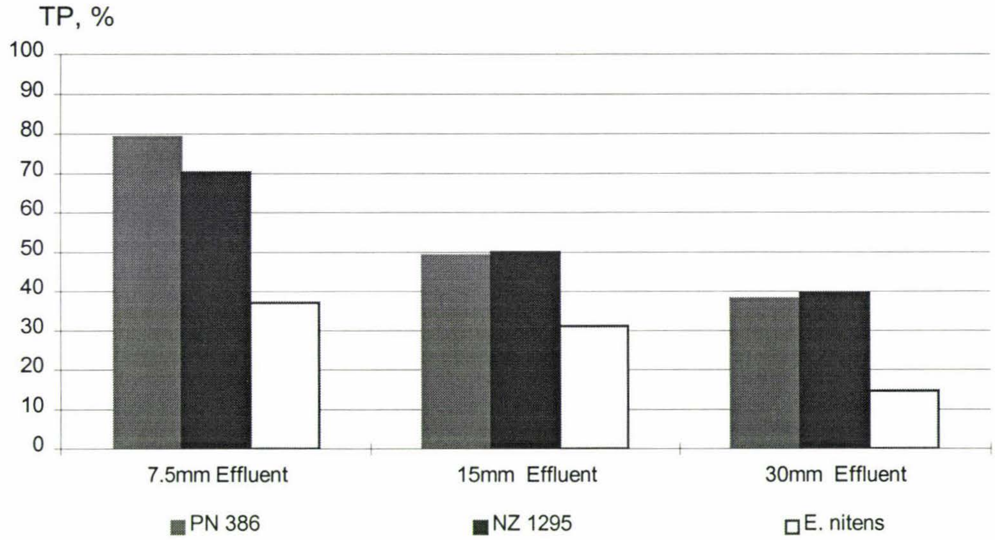


Figure 5.2 Percentage uptake by three SRF species of total phosphorus applied per year from the effluent over for two growing seasons

5.3.3 Renovation of potassium

5.3.3.1 Soils

The exchangeable potassium in the soil under the three SRF species is shown in Table 5.3. Only three depths of soils were monitored under most treatments due to cost constraints. All six depths were included only under NZ 1295 at 30 mm of irrigation. Equations 5.1, 5.2 and 5.3 (refer to section 5.1) were used to determine the potassium renovation capacity of the soil-SRF treatment system.

The total of 3457.3 kg K ha^{-1}, was available to NZ 1295 as supplied by the soil (1859.3 kg ha^{-1}) and 30 mm (1598 kg ha^{-1}) of effluent irrigation applied over two growing seasons. The soil-NZ 1295 renovated 99.5 % of the potassium over two growing seasons. Using equation 5.4, the SRF NZ 1295 alone renovated 7.5 % of the total potassium available from the soil and effluent over two growing seasons.

There was a build up of soil exchangeable potassium at the 60-100 cm depth range under the *E. nitens* and possibly some nutrient moved below the root zone of the tree which might leached to the ground water. The increase in the percentage of potassium renovated denotes the interception of the nutrient in the soil mass which can then be possibly accessed by the plant system for additional renovation of unwanted nutrients.

Equations 5.5, 5.6, 5.7 and 5.8 were used to quantify the unaccounted amount of total potassium which can possibly be attributed to root uptake and leaching of the nutrient. The soil-NZ 1295 treatment system when irrigated at 30 mm of effluent recorded an unaccounted total amount of 17.1 kg ha^{-1} of potassium (0.5%) (Table 5.3).

Table 5.3 Renovation of potassium in a soil-SRF species treatment system after two years of effluent irrigation

Species	Soil Depth	Pre-treatment K of Soil, kg ha^{-1}				Post treatment K of soil, kg ha^{-1}				% Renovation			
	Cm	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent
PN 386	0-5	173.5	173.5	173.5	173.5	165.9	375.7	428.1	438.7	8.9	16.7	16.2	12.7
	5-10	170.0	170.0	170.0	170.0								
	10-15	168.0	168.0	168.0	168.0								
	15-30	296.4	296.4	296.4	296.4	37.0	640.5	848.3	725.8	2.0	28.4	32.0	21.0
	30-60	492.6	492.6	492.6	492.6								
	60-100	559.1	559.1	559.1	559.1	357.8	333.1	727.7	569.3	19.3	14.8	27.5	16.5
	Effluent		394.0	788.0	1598.0								
	Plant Out					142.0	149.0	176.0	256.0	7.6	6.6	6.6	7.4
Total		**1859.0**	**2253.3**	**2647.3**	**3457.3**								
NZ 1295	0-5	173.5	173.5	173.5	173.5	179.4	380.6	432.9	441.0	9.7	16.9	16.4	12.8
	5-10	170.0	170.0	170.0	170.0				444.7				12.9
	10-15	168.0	167.7	168.0	168.0				443.6				12.8
	15-30	296.4	296.4	296.4	296.4	270.3	625.2	645.1	640.0	14.5	27.8	24.4	18.5
	30-60	492.6	492.6	492.6	492.6				633.4				18.3
	60-100	559.1	559.1	559.1	559.1	380.2	357.8	577.4	577.4	20.5	15.9	21.8	16.7
	Effluent		394.0	788.0	1598.0								
	Plant Out					105.0	117.0	165.0	260.0	5.7	5.2	6.2	7.5
Total		**1859.0**	**2253.3**	**2647.3**	**3457.4**				**3440.2**				**99.5**
Unaccounted									**17.1**				
E.nitens	0-5	173.50	173.5	173.5	173.5	118.8	247.3	250.4	378.5	6.4	11.0	9.5	11.0
	5-10	169.96	170.0	170.0	170.0								
	10-15	167.65	168.0	168.0	168.0								
	15-30	296.40	296.4	296.4	296.4	301.9	560.8	627.9	735.7	16.2	24.9	23.7	21.3
	30-60	492.63	493.0	492.6	492.6								
	60-100	559.10	559.1	559.1	559.1	514.4	335.5	447.3	1110.4	27.7	14.9	16.9	32.1
	Effluent		394.0	788.0	1598.0								
	Plant Out					148.0	165.0	291.0	283.0	8.0	7.3	11.0	8.2
Total		**1859.00**	**2253.3**	**2647.3**	**3457.3**								

5.3.3.2 SRF species

The potassium renovation efficiency of three SRF species is shown in figure 5.3. The efficiency of SRF species to renovate potassium from the effluent decreased with increasing rate of irrigation. *E. nitens* renovated higher amount of potassium at all levels of irrigation over the willows. The renovation capacity of the SRF species was taken as the percentage of the amount of each nutrient accumulated in the above ground biomass of the trees from the total amount of nutrients supplied through the effluent (equation 5.4). At 7.5 mm of effluent application, the *E. nitens* achieved its highest renovation efficiency of 41.7 % per growing season. The irrigation level can be optimised at 15 mm of effluent application for the *E. nitens* because it renovated 36.9 per cent of the applied potassium through effluent irrigation for each growing season since at this level of irrigation the optimum above ground biomass was achieved (refer to Figure 3.3). The PN 386 was significantly higher in capacity to renovate potassium from the effluent at the lowest rate of effluent application than NZ 1295. However at higher rates, the renovation capacity of PN 386 did not differ with the NZ 1295. The remaining potassium applied through effluent irrigation was possibly immobilised in the roots, fixed, precipitated or leached below the one metre root zone of the three SRF species.

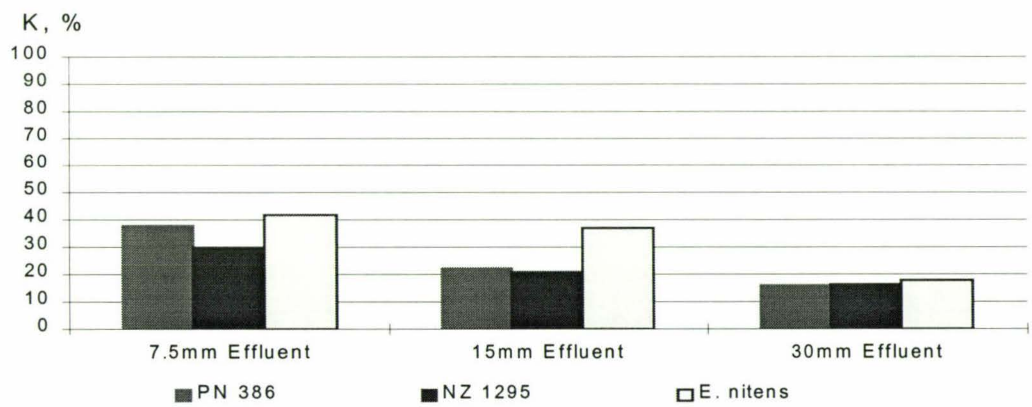


Figure 5.3 Percentage uptake by three SRF species of potassium applied per year from the effluent over for two growing seasons

5.3.4. Renovation of calcium

5.3.4.1 Soils

The percentage of exchangeable calcium in the soil under three SRF species is shown in Table 5.4. Only three depths of soils under PN 386 and *E. nitens* were included due to cost constraints, while six depths were included under NZ 1295. Equations 5.1, 5.2 and 5.3 (refer to section 5.1) were used to determine the calcium renovation capacity of the soil-SRF treatment system.

The soil-NZ 1295 treatment system applied with 15 mm of effluent achieved a total percentage of calcium renovation of 68.7 % (at three depths). The low percentage of calcium renovation in the highest effluent irrigation can possibly be accounted for by soil fixation, root uptake and leaching of the nutrient. The percentage of calcium renovation in all the six depths of soil under NZ 1295 at 30 mm of effluent irrigation showed 98.7% renovation of the soil-SRF treatment system. NZ 1295 immobilised 227 kg Ca ha^{-1} after two years in its above ground biomass renovating 1.4% of total Ca from the effluent and soil (using equation 5.4).

The uptake by the trees was higher than the amount of calcium applied through effluent irrigation but the exchangeable calcium in the soil during the second year increased (Figure 4.4). The amount of calcium added through effluent irrigation, and the capacity of calcium in the soil solution to maintain the state of equilibrium with exchangeable calcium possibly contributed to the increase of exchangeable calcium after year 2.

Table 5.4 Renovation of calcium in a soil-SRF species treatment system before and after two years of effluent irrigation

Species	Soil Depth	Pre-treatment Ca of Soil, kg ha^{-1}				Post treatment Ca of soil, kg ha^{-1}				% Renovation			
	cm	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent
PN 386	0-5	687.5	687.5	687.5	687.5	602.7	731.6	798.6	816.0	3.6	4.4	4.76	4.84
	5-10	693.0	693.0	693.0	693.0								
	10-15	704.0	704.0	704.0	704.0								
	15-30	1955.1	1955.1	1955.1	1955.1	2192.4	1866.9	2265.6	1837.5	13.1	11.2	13.51	10.90
	30-60	5208.0	5208.0	5208.0	5208.0								
	60-100	7436.0	7436.0	7436.0	7436.0	8236.8	6588.8	7219.2	6944.0	49.4	39.4	43.05	41.21
	Effluent		42.0	84.0	168.0								
	Plant Out					210.6	182.1	215.2	287.5	1.3	1.1	1.28	1.71
Total		**16683.6**	**16725.6**	**16767.6**	**16851.6**								
NZ 1295	0-5	687.5	687.5	687.0	687.5	607.6	744.0	762.3	888.0	3.6	4.5	4.55	5.27
	5-10	693,0	693.0	693.0	693.0				738.1				4.38
	10-15	704.0	704.0	704.0	704.0				756.4				4.49
	15-30	1955.1	1955.1	1955.1	1955.1	1612.8	2028.0	1725.0	2046.0	9.7	12.1	10.29	12.14
	30-60	5208.0	5208.0	5208.0	5208.0				4941,0				29.32
	60-100	7436.0	7436.0	7436.0	7436.0	8008.0	8351.2	8860.8	7043.2	48.0	49.9	52.84	41.80
	Effluent		42.0	84.0	168.0								
	Plant Out					125.2	125.3	165.4	227.1	0.8	0.8	0.99	1.35
Total		**16683.6**	**16725.6**	**16767.6**	**16851.6**				**16639.8**				**98.74**
Unaccounted Ca									**211.8**				
E. nitens	0-5	687.5	687.5	687.5	687.5	533.2	644.8	512.4	677.6	3.2	3.9	3.06	4.02
	5-10	693.0	693.0	693.0	693.0								
	10-15	704.0	704.0	704.0	704.0								
	15-30	1955.1	1955.1	1955.1	1955.1	1900.8	2200.8	1702.8	2380.8	11.4	13.2	10.16	14.13
	30-60	5208.0	5208.0	5208.0	5208.0								
	60-100	7436.0	7436.0	7436.0	7436.0	7207.2	6978.4	8694.4	6929.6	43.2	41.7	51.85	41.12
	Effluent		42.0	84.0	168.0								
	Plant Out					155.6	166.1	262.1	296.2	0.9	1.0	1.56	1.76
Total		**16683.6**	**16725.6**	**16767.6**	**16851.6**								

The same trend was evident in the soils under PN 386 and *E. nitens*. This increase was possibly the effect of the equilibrium state that influenced the availability of exchangeable calcium in the soil. McLaren and Cameron, (19960 and Vogeler, (1997) reported that the exchangeable calcium in the soil was maintained at an equilibrium for every cation taken up by the plant or held up in the exchangeable site by the indigenous calcium of the soil.

Equations 5.5, 5.6, 5.7 and 5.8 were used to quantify unaccounted amount of total calcium which can possibly be attributed to the root uptake and leaching of the nutrient. The soil-NZ 1295 treatment system when irrigated at 30 mm of effluent recorded an unaccounted total amount of 211.8 kg ha^{-1} of calcium (1.3%) (Table 5.4) that can possibly be stored in the roots of the tree or was leached below the one metre depth.

5.3.4.2 SRF species

The uptake of calcium by the three SRF species exceeded the amount of calcium applied through the three different rates of effluent irrigation during the two growing seasons. The supply of calcium from the effluent increased with increasing rate of irrigation. The application of 30 mm of effluent application during the first growing season supplemented 58.43, 73.8 and 59.5 % of the calcium uptake of PN 386, NZ 1295 and *E. nitens*, respectively. At 7.5 mm of effluent irrigation, the percentage of calcium supplied by the effluent were 23, 33.5 and 25.3 % for PN 386, NZ 1295 and *E. nitens*, respectively. The SRF species probably uptake the nutrient supplied by the indigenous calcium reserve in the soil to supplement the nutrients from the effluent.

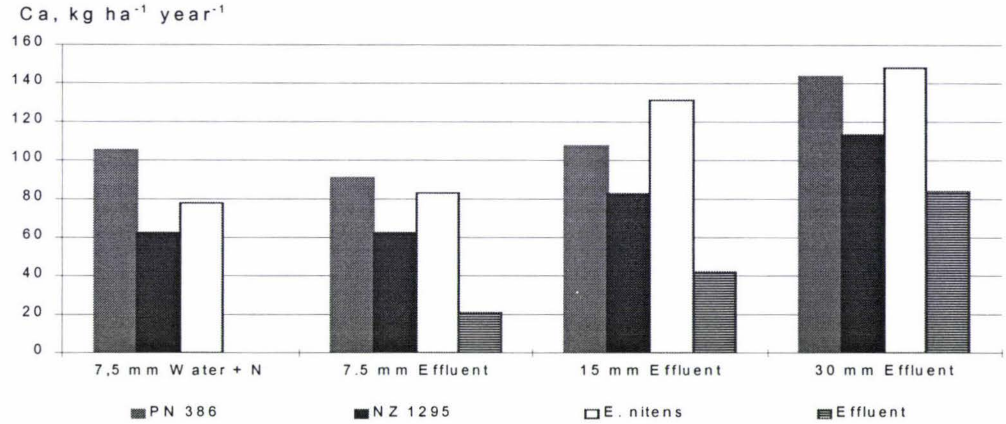


Figure 5.4 The yearly amount of calcium supplied by the effluent and taken up by the SRF trees over two growing seasons

5.3.5 Renovation of magnesium

5.3.5.1 Soils

The exchangeable magnesium in the soil under the three SRF species is shown in Table 5.5. Only three depths of soils under all the other treatments except NZ 1295 were included due to cost constraints. Six depths were included under NZ 1295 only at 30 mm of irrigation treatment. Equations 5.1, 5.2 and 5.3 (refer to section 5.1) were used to determine the potassium renovation capacity of the soil-SRF treatment system.

The three depths of soil (0-5, 15-30 and 60-100 cm) investigated in this section showed an increasing trend of exchangeable magnesium renovation with increasing effluent except for PN 386 when irrigated with 30 mm of effluent. The magnesium renovated by the soil- NZ 1295 treatment system (total of three depths only) when irrigated at 15 mm of effluent was 92.1 %, equivalent to 1540.94 kg ha^{-1} after two growing seasons. The lowest renovation occurred in the soil under PN 386 at 30 mm of effluent irrigation. The low renovation percentage can possibly be attributed to the uptake by the tree and downward movement of nutrients below the root zone. Exchangeable magnesium accommodated by the soil-SRF treatment system might have been replaced by the magnesium in the soil solution to maintain equilibrium state of the soil nutrient.

Table 5.5 Renovation of magnesium in a soil-SRF species treatment system after two years of effluent irrigation

Species	Soil Depth	Pre-treatment Mg of Soil, kg ha^{-1}				Post treatment Mg of soil, kg ha^{-1}				% Renovation			
	Cm	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent	7.5mm W +N	7.5 mm Effluent	15 mm Effluent	30mm Effluent
PN 386	0-5	72.2	72.2	72.2	72.2	68.0	133.4	146.3	122.5	4.2	8.1	8.7	7.1
	5-10	69.7	69.7	69.7	69.7								
	10-15	66.9	66.9	66.9	66.9								
	15-30	172.1	172.1	172.1	172.1	172.3	206.0	282.3	211.9	10.6	12.5	16.9	12.3
	30-60	510.4	510.4	510.4	510.4								
	60-100	729.9	729.9	729.9	729.9	931.5	807.6	884.2	769.0	57.5	49.0	52.9	44.6
	Effluent		26.0	52.0	104.0								
	Plant Out					77.1	78.2	89.8	116.4	4.8	4.9	5.4	6.8
	Total	1621.1	1647.1	1673.1	1725.1								
NZ 1295	0-5	72.2	72.2	72.2	72.2	88.2	136.4	135.3	131.3	5.4	8.3	8.1	7.6
	5-10	69.7	69.7	69.7	69.7				102.9				6.0
	10-15	66.9	66.9	66.9	66.9				81.5				4.7
	15-30	172.1	172.1	172.1	172.1	177.3	251.2	248.4	180.9	10.9	15.3	14.8	10.5
	30-60	510.4	510.4	510.4	510.4				344.5				19.97
	60-100	729.9	729.9	729.9	729.9	924.5	973.2	1035.4	621.2	57.0	59.1	61.9	36.0
	Effluent		26.0	52.0	104.0								
	Plant Out					77.0	95.0	122.0	187.0	4.8	5.7	7.3	10.9
	Total	1621.1	1647.1	1673.1	1725.1				1649.8				95.6
Unaccounted Mg									**75.4**				
E. nitens	0-5	72.2	72.2	72.2	72.2	67.1	107.0	114.9	137.5	4.1	6.5	6.9	8.0
	5-10	69.7	69.7	69.7	69.7								
	10-15	66.9	66.9	66.9	66.9								
	15-30	172.1	172.1	172.1	172.1	192.5	241.2	333.9	296.3	11.9	14.6	20.0	17.2
	30-60	510.4	510.4	510.4	510.4								
	60-100	729.9	729.9	729.9	729.9	827.2	799.4	702.1	883.5	51.0	48.5	42.0	51.2
	Effluent		26.0	52.0	104.0								
	Plant Out					71.5	83.9	126.6	156.6	4.4	5.1	7.6	9.1
	Total	1621.1	1647.1	1673.1	1725.1								

5.3.5.2 SRF species

Magnesium uptake by the three SRF species exceeded the amount of magnesium supplied through effluent irrigation. At 30 mm of effluent, the NZ 1295 accumulated the highest amount of 93.5 kg ha^{-1} year^{-1} of magnesium more than that supplied by the effluent (Table 5.4). A deficit of 41.5 kg ha^{-1} year^{-1} of magnesium was not supplied through effluent application. Probably the NZ 1295 had taken the nutrient from the natural magnesium reserve of the soil. At 30 mm of application, the supply of magnesium through effluent application was short of 23.61 and 4.21 kg of magnesium ha^{-1} year^{-1} for *E. nitens* and PN 386, respectively.

The three SRF trees showed increased uptake of magnesium with increasing effluent application. The NZ 1295 can accommodate the magnesium supplied by 30 mm of effluent. The PN 386 removed the least amount of magnesium at 58.2 kg ha^{-1} year^{-1} which almost equalled the supply of magnesium through 30 mm of effluent application at 52 kg ha^{-1} year^{-1}.

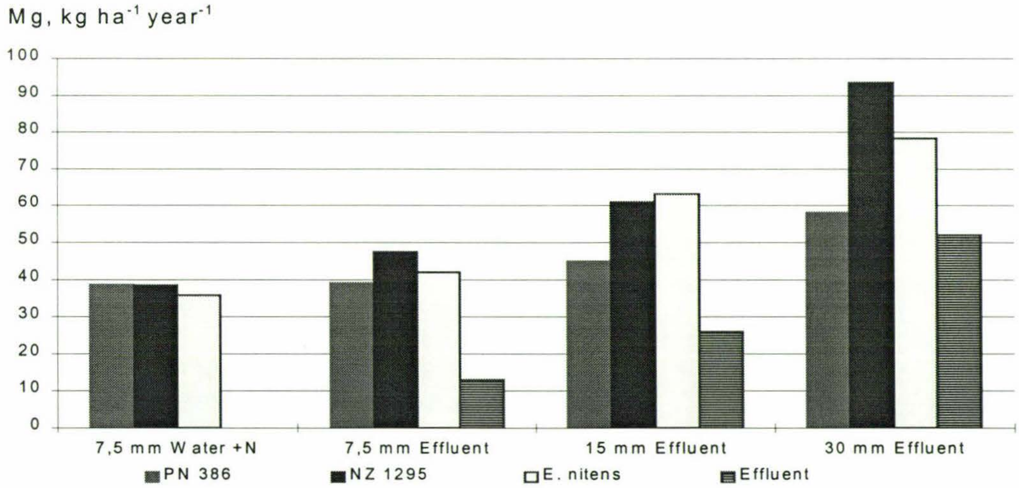


Figure 5.5 The yearly amount of magnesium supplied by the effluent and taken up by the SRF trees over two growing seasons

5.4 Conclusions and recommendations

The renovation of soil-SRF treatment systems increased with increasing load of TN added. The soil-*E.nitens* treatment system was the most efficient treatment system which renovated 96.45% (17212 kg ha^{-1})over two years of TN from the soil and 30 mm of effluent. The least application of effluent (7.5 mm) to PN 386 resulted in a higher percentage of renovated TN from the effluent which gave an average of 99.5% per year over two growing seasons.

The soil-PN 386 treatment system was the most efficient treatment that renovated 92.72% (6446.9 kg ha^{-1}) over two years of TP from the soil at 7.5 mm of effluent. The renovation of TP by the SRF species alone decreased as the application of effluent increased. PN 386 renovated the highest amount of TP (80%) from 7.5 mm of effluent

Only the soil-NZ 1295 treatment system was evaluated in its renovation of cations from the soil and effluent due to cost constraints. The soil-SRF treatment systems can be efficient as shown by the soil-NZ 1295 that renovated 99.51%, 98.74% and 95.63% per year of K, Ca and Mg, respectively, over two growing seasons from the soil and 30 mm of effluent.

The renovation capacity of the three SRF species alone decreased as effluent application increased. *E. nitens* renovated the highest percentage of K at 41.87% (148 kg ha^{-1} $year^{-1}$) which was supplied by 7.5 mm of effluent (394 kg ha^{-1} $year^{-1}$) after two years.

The amount of calcium and magnesium taken up by the three SRF species exceeded the supply from the effluent. PN 386 was best in renovated most Ca from the 30 mm of effluent and NZ 1295 was best in renovating Mg from the 30 mm of effluent.

CHAPTER 6

EFFECT OF DAIRY FARM-POND EFFLUENT IRRIGATION ON THE EVAPOTRANSPIRATION OF THREE SELECTED SHORT ROTATION SPECIES

6.1 Introduction

The use of rapidly growing trees, like willows and eucalyptus is gaining popularity as a component of a land treatment scheme. Water supply is essential to support the rapid rate of growth and biomass accumulation of these short rotation forestry crops. Dairy farm-pond effluent is a good source of both water and nutrients to maximise biomass production. The use of the effluent is environmentally ideal to treat dairy farm-pond effluent if applied in a volume which does not exceed the nutrient or water requirement of the trees. Knowing the water use of these trees through evapotranspiration studies is essential to determine the optimum application of waste effluents on to the trees without polluting the groundwater or waterways.

Evapotranspiration is the process whereby water in the liquid phase at the earth-atmosphere boundary is converted to the vapour phase by vaporisation both from the upper soil layers (evaporation) and from water taken from the soil and precipitation as interception by the plants (transpiration). Rijtema (1965) reported that in a forested land or plant-covered plantation, the evapotranspiration rate of crops is influenced by:

- the transport of water vapour from the air layers closest to the evaporating surface to higher air layers;
- the amount of energy available for the vaporisation of water;
- the aperture of the stomata in connection with the diffusion of water vapour through them;
- the rate of the supply of water to the evaporating surface.

The first two factors are dependent on the meteorological conditions and the last two factors are dependent on the physiological properties of the plants and soil physical properties. Similarly, Landsberg (1997) confirmed that the rates of water use by plantations are:

- determined by the interactions between transpiration
- driven by radiant energy and atmospheric humidity, and soil moisture, and
- dependent upon the water balance between inputs from rainfall and losses by runoff, drainage and evaporation.

Evapotranspiration from a forest is difficult to determine due to the size and variability of the vegetation and the variation of soil type. Holmes and Colville (1979) mentioned that evapotranspiration varies with respect to crop type. Jensen (1990) discussed the major soil and crop factors affecting evapotranspiration when moisture is not limiting plant the growth. These are:

- wetness of the surface soil with little or no crop cover;
- transpiration as influenced by the leaf area and characteristics of the leaves as the crop cover develops;
- transpiration as the crop matures.

Wright (1985) disclosed that the basic factors controlling the evapotranspiration process for irrigated crops are similar to those for other plant communities, except that the water requirement is largely satisfied by irrigation rather than precipitation.

Persson and Lindroth, (1994) estimated the high evapotranspiration rates of Salix stands using the Penman formula even exceeded those estimated for open water surfaces. Stewart et al. (1988) selected a crop factor between 1.4 to 1.9 (multiplied by the evaporation) to estimate the tree evapotranspiration rate in Australia. While in South Africa, Steynberg (1994) selected a crop factor of 0.9 to 1.0 for grass land during half of the growing season.

Evapotranspiration can also be associated with plant growth. Landsberg (1997) stated that plant growth is driven by the amount of photosynthetically active radiation absorbed by the foliage and the (photosynthetic) efficiency with which the leaves use that radiation (photon flux) to produce carbohydrates. McNaughton and Jarvis (1983) showed that forest absorbs more solar radiation-reflection than does short vegetation. It is possible that SRF species evapotranspire more than pasture and other crops.

However, information regarding the capability of SRF trees to evapotranspire dairy farm-pond effluent is not well established. The main objectives of this study was therefore to:

- determine the effect of dairy farm-pond effluent irrigation on the evapotranspiration of three SRF species by monitoring it during a short period of the growing season;

- determine the influenced of climatic factors on the evapotranspiration of effluent-irrigated *Salix kinuyanagi* (PN 386), *Salix matsudana X alba* (NZ 1295) and *E. nitens.*

6.2 Methodology

6.2.1 Climatic regime of the experimental area

The ten-year mean monthly climatic conditions measured on the experimental site at HortResearch Aokautere are presented in figures 6.1, 6.2 and 6.3. The rainfall and evapotranspiration rates are given in figure 6.1. From the month of October to March of the New Zealand growing season, the mean monthly evaporation is higher than the rainfall in the area. This condition indicates the need to supplement water supply through irrigation to meet the water demand and ground conditions for optimum crop growth and biomass production. The highest evaporation data was 168 mm for the month of January, and the lowest 24 mm for June. During the growing season, based on precipitation input and pan evaporation data, 332 mm of water is required to meet the evaporative demand alone at the experimental site at HortResearch, Aokautere, Palmerston North.

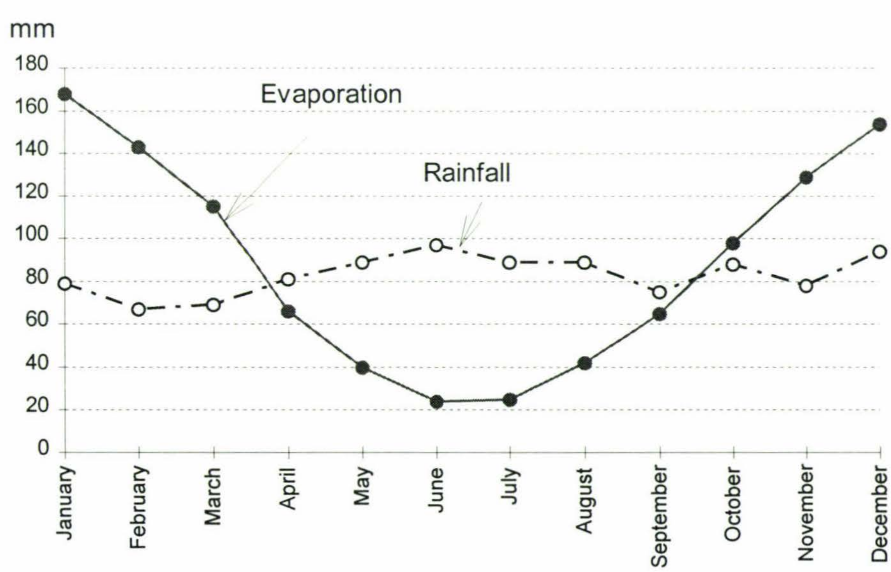


Figure 6.1 Ten-year mean monthly evaporation and rainfall in the experimental area at HortResearch, Aokautere, Palmerston North

The ten-year mean monthly temperature (°C) and vapour pressure deficit (mb) of the plantation are presented in figure 6.2. The mean monthly maximum air temperature of the plantation ranged from 15.9 to 27.1 °C. The vapour pressure deficit of the plantation site ranged from 8.9 to 15.3 mb. The highest mean vapour pressure was recorded in February and the lowest in July. Based on the ten-year mean monthly data, the vapour pressure of the area increased with increasing air temperature. The months of the growing season starting in October to March have higher air temperatures and vapour pressure deficits than the rest of the months. The highest mean monthly temperature was 27.4°C in February and the lowest 15.9°C in July. The air temperature range and vapour pressure ranges of the plantation site indicate the time of the year for plant growth.

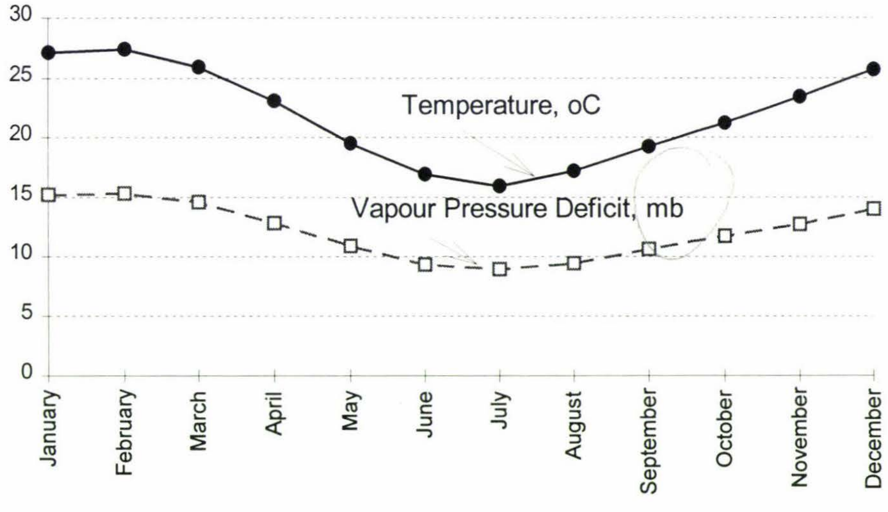


Figure 6.2 Ten-year mean monthly maximum air temperature and vapour pressure deficit in the experimental area at HortResearch, Aokautere, Palmerston North

Figure 6.3 shows the ten-year monthly mean daily wind run and the sunshine hours received at the plantation site. The wind run in the plantation ranged between 200 and 282 km per month with an average of 243 km per month during the year. The highest wind run was in November and the lowest was in July. Higher wind run and sunshine hours were receive during the growing period from October to March. The amount of sunshine received by the plantation is an important determinant for plant growth. The amount of total sunshine received by the plantation ranged between 94 to 209 hours per month giving an annual total of 1794 of sunshine hours.

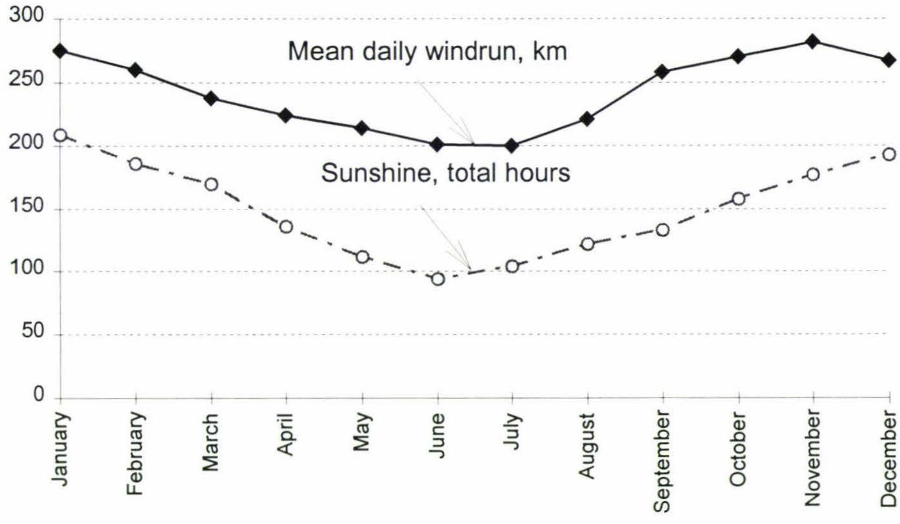


Figure 6.3 Ten-year mean monthly daily wind run and sunshine hours at the experimental area HortResearch, Aokautere, Palmerston North.

6.2.2 Selection of SRF species and instrumentation

From the field trial of ten species, three species of SRF trees irrigated with the highest (30 mm) and lowest (7.5 mm) rates of dairy farm-pond effluent per fortnight were selected for monitoring the evapotranspiration rates of the trees. Three representative trees were selected from each replicated plot. Heat pulse measurement using a custom heat pulse velocity data logger as described by Edwards et al. (1986) was set up to measure sap flow. The technique was governed by the principle of the Penmann-Monteith equation to determining the evapotranspiration rate of crops. Thermistors were impregnated into the stem of the trees to be monitored. The sensed sap flow data was recorded in a data logger that was provided for each plot monitored. The monitoring was conducted for a period of twelve days in January during the second growing season. The diameters of the trees were measured as a factor to determine the evapotranspiration rates. The climatic condition of the site was also monitored during the period of sap flow measurement. A micro-meteorological station was established at the plantation site to record the following climatic data: wind speed (km hr^{-1}), global radiation (W m^{-2}), rainfall (mm), wetness (%) and vapour pressure deficit (mb). Analyses were made to relate this climatic data to the evapotranspiration rates when irrigated with either high or low rates of effluent.

6.3 Results and Discussion

6.3.1 Evapotranspiration and climatological factors

The cumulative evapotranspiration rates of the three species irrigated with either 30 or 7.5 mm effluent during the two growing season is shown in figure 6.4. The rate of trees varied with the rate of effluent irrigation and species.

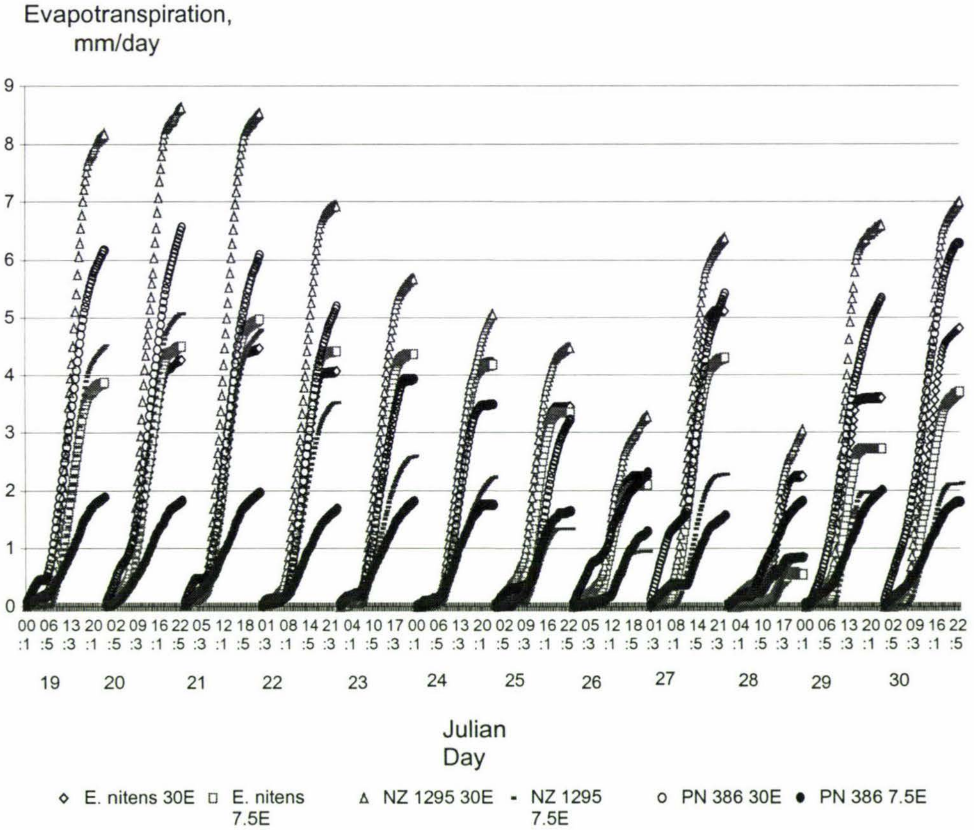


Figure 6.4 Cumulative daily evapotranspiration over a 12 day summer period of three SRF species that were irrigated with either 30 or 7.5 mm of dairy farm-pond effluent (E) per fortnight

The cumulative evapotranspiration was taken as the sum of evapotranspiration per unit of time interval measured from the 0 to 24th hour of the day. Each monitoring day achieved cumulative amount of evapotranspiration for each treatment

The SRF trees irrigated at the higher rate of effluent (30 mm per fortnight) had significantly higher ($p > 0.05$) cumulative evapotranspiration rates than the trees irrigated with 7.5 mm of effluent per fortnight.

The NZ 1295 salix trees irrigated at 30 mm per fortnight showed significantly higher cumulative evapotranspiration rates ($p > 0.05$) than the other treatments during the entire monitoring period. This result is similar to the findings of Lindroth et al. (1994) regarding higher evaporation from Salix stands than from agricultural crops and traditional forest.

E.nitens, however showed higher transpiration rates at the rate of 2.96 mm day^{-1} over the two other species when irrigated with 7.5 mm of effluent. The cumulative evapotranspiration (Figure 6.4) varied daily during the monitoring period due to daily variation in climatic conditions.

Climatic conditions (Figure 6.5) of the plantation influenced the evapotranspiration of the three SRF trees. During two cloud-free days (Julian Days 20 and 21), with no rain (figure 6.5c), 0% humidity (figure 6.5b), peak temperatures between 26 to 29.5°C (figure 6.5d) during the day, peak vapour pressure deficit with a range of 19 to 23 mb (figure 6.5e), and peak global radiation from 1200 to 1300 W m^{-2} (figure 6.5f) during the day, peak evapotranspiration of the NZ 1295 when irrigated at 30 mm resulted (Figure 6.4). The cumulative evapotranspiration of the species irrigated with lower rate of irrigation (7.5 mm of effluent per fortnight) were also at a peak during these cloud-free days.

The trees evapotranspired at lower rates during cloudy days such as Julian days 26 and 28 with, peak temperatures of between 16 to 20°C, peak vapour pressure deficit between 2 to 5 mb and peak global radiation of 300 to 700 W m^{-2}.

Day 24 had a high wind speed with a peak value of 0.085 m s^{-1}, peak temperature of 21°C, vapour pressure deficit of 7.5 mb and peak global radiation of 1000 W m^{-2}. The evapotranspiration of this day was low compared to evapotranspiration rates of the five previous days due to the higher wind speed.

According to Rijtema (1965) and Whitehead and Jarvis (1981), increasing wind speed is a key climatic factor that reduces the evapotranspiration rate of plants. Landsberg (1997) also indicated that exchange processes between leaves and air are inversely related to the wind speed. He further added that leaf shape and arrangement are also factors in determining the leaf boundary layer conductance, through which gaseous exchange takes place. This result was similar to the findings of Whitehead and Jarvis (1981) which were:

- increasing absorption of radiation increases transpiration;
- increasing wind speed decreases transpiration;
- increasing vapour pressure deficit increases evapotranspiration.

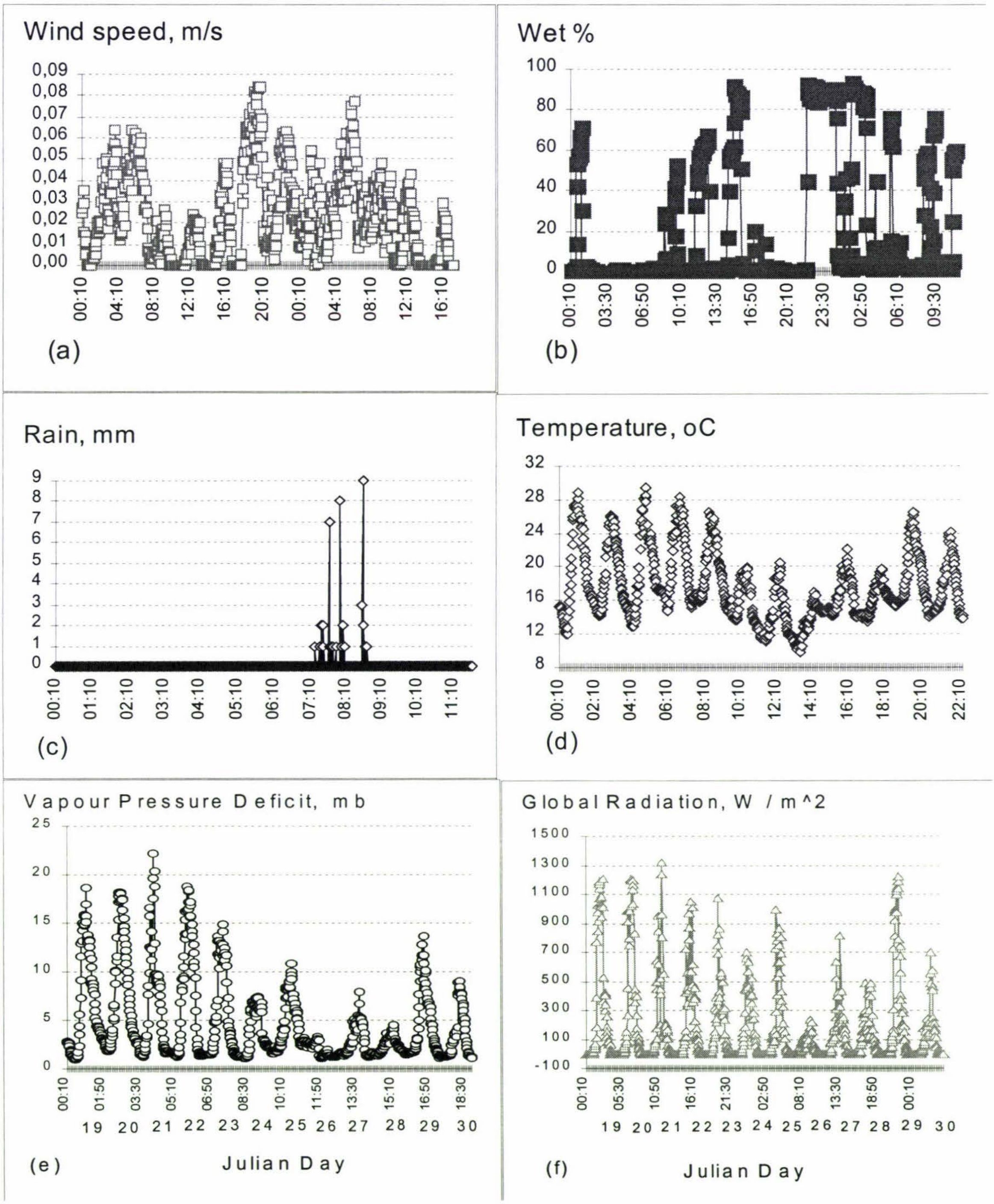


Figure 6.5. The wind speed (a), humidity (b), rain (c), temperature (d), vapour pressure deficit (e) and global radiation (f) of the SRF trees plantation taken during the 19th to the 30th day of the Julian calendar of the second growing season

6.3.2 Leaf area effect on evapotranspiration

The average cumulative evapotranspiration rates of the three SRF species during the period are shown in figure 6.6. Trees irrigated at the higher rates of effluent, 30 mm per fortnight, evapotranspired a significantly higher ($p > 0.01$) cumulative amount of water than those irrigated at 7.5 mm of effluent being 6.38, 4.84 and 4.00 mm day^{-1} for NZ 1295, PN 386 and *E. nitens*, respectively. Eucalyptus nitens when irrigated at 7.5 mm of effluent evapotranspired a cumulative average of 2.96 mm day^{-1}, while PN 386 and NZ 1295 evapotranspired at 1.65 and 2.71 mm day^{-1}, respectively. The variation in the evapotranspiration rate was attributed to the amount of water supplied through irrigation. This confirmed the work of Cienciala et al. (1993) who disclosed higher seasonal transpiration rates in irrigated trees than in non-irrigated trees. Whitehead and Jarvis (1981) also reported that transpiration rates are constrained by the closure of stomata associated with increases in vapour pressure deficit, and, to a lesser extent, as a result of water stress.

The variation in the evapotranspiration rates was also influenced by the species of the SRF trees. The physiological structure of the trees such as leaf architecture, sapwood and branch architecture influenced the transpiration regime. Stomatal responses to characteristics to meteorological factors also affected the transpiration rates. This result confirms the findings of Holmes and Colville (1979) that evapotranspiration varies with respect to crops. Mcnaughton and Jarvis (1983) also suggested that stomatal response characteristics are likely to be complex and varied.

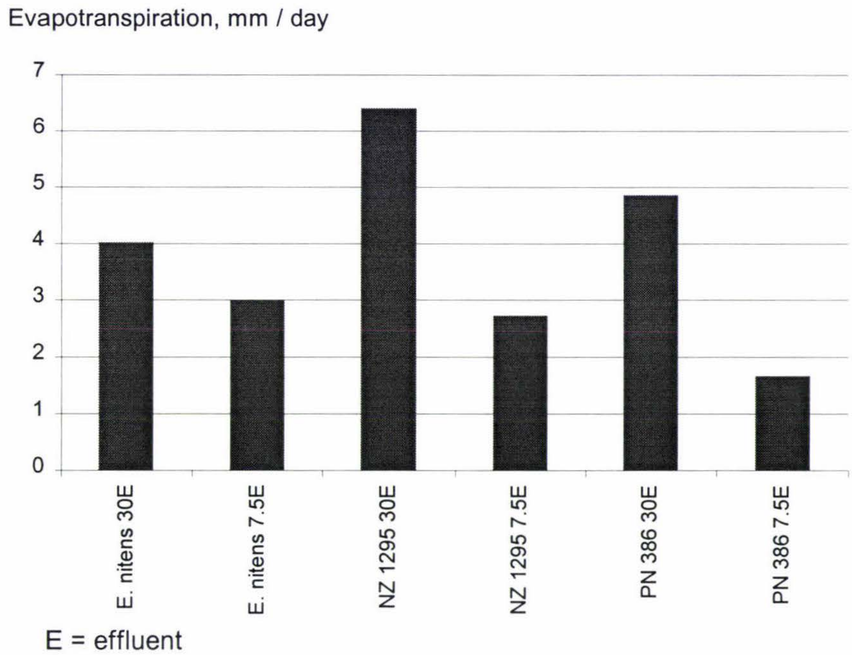


Figure 6.6 Average cumulative evapotranspiration of three SRF species irrigated with either 30 or 7.5 mm of dairy farm-pond effluent during the month of January of the second growing season

The average leaf area of the three SRF species is shown in figure 6.7. Trees irrigated at 30 mm of effluent per fortnight had a greater leaf area than those trees irrigated at the lower rate. The availability of sufficient water and nutrients through effluent application at 30 mm per fortnight. Beadle (1997) found that irrigated eucalyptus had a greater leaf area index compared with those only rainfed. At 7.5 mm effluent rate the low development of the leaf canopy resulted from an insufficient amount of water and nutrients. This had caused stress and lead to the cessation of leaf development of the trees. *E. nitens* when irrigated at 30 mm of effluent and NZ 1295 three produced more leaf area compared with PN 386.

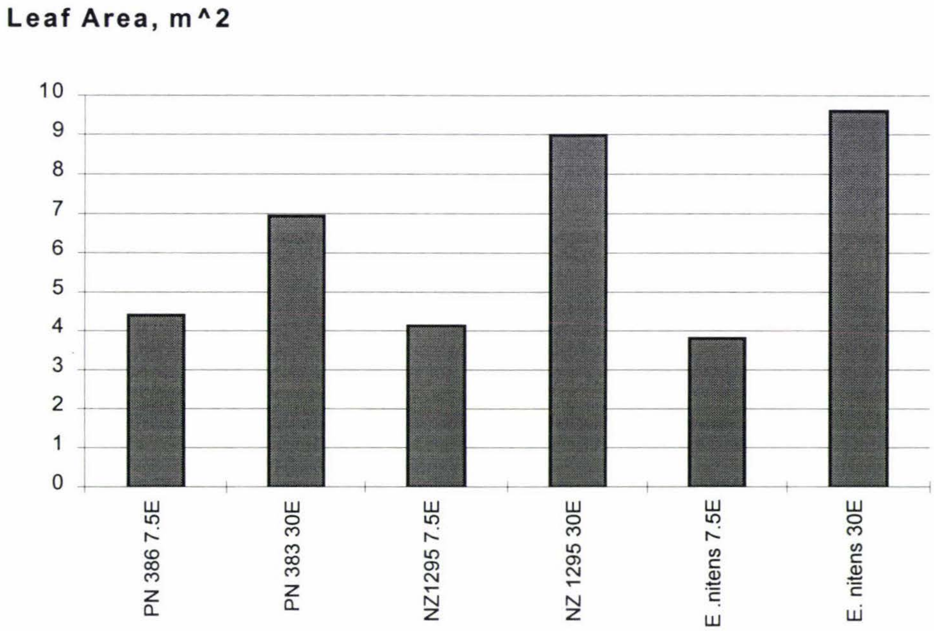


Figure 6.7. Average leaf area during the summer of the second growing season of three SRF species irrigated with either 30 or 7.5 mm of dairy farm-pond effluent per fortnight over two growing seasons

6.3.3 Leaf area in relation to evapotranspiration

The average cumulative evapotranspiration rates in relation to the leaf area of the three SRF are shown in figure 6.8. The evapotranspiration rates showed some correlation ($R^2 = 0.5873$) with the leaf area and increased with increasing leaf area.

McNaughton and Jarvis (1983) showed that a reduction in the leaf area index from 6 to 3 by thinning reduced the transpiration of forest trees by approximately the same proportion. Beadle (1997) reported that canopies with grouped foliage can achieve higher levels of leaf area index for a given level of light interception. Intercepted light affects the transpiration. The leaf structure of willows, particularly the tree willow, can be described as canopies with grouped foliage. The degree of clumping of the foliage of the trees in this study might have increased radiation interception through beam penetration which probably have influenced higher evapotranspiration rates in these trees.

Whitehead et al. (1984) stated that the transpiration of a tree is assumed equal to the volume flow rate of water passing through the stem of that tree. Trees irrigated at higher rates of effluent produce larger stem diameters than those irrigated at lower rates. Higher transpirational rates might therefore result from larger area of stems with proportionate phloem cells that conduct water from the roots to the foliage, causing higher transpirational rates.

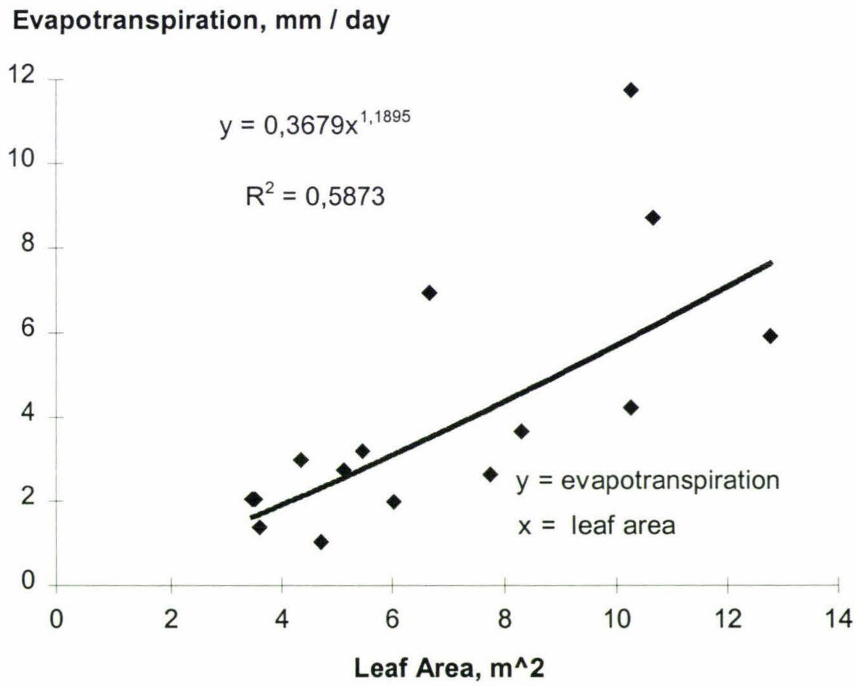


Figure 6.8 The relationship between the average daily cumulative evapotranspiration and the leaf area of three SRF species irrigated with either 30 or 7.5 mm per fortnight of dairy farm-pond effluent

6.3.4 Climatic impact on evapotranspiration rates

6.3.4.1 Evapotranspiration versus temperature

The evapotranspiration rate of SRF trees during the 12 day monitoring period was influenced by the air temperature of the plantation (Figure 6.9), correlated at $R^2 = 0.6015$. This result is similar to the findings of Rijtema (1965) who showed that transpiration increased with increasing temperature of the air. Evapotranspiration rate was zero during the night possibly due to stomatal closure which then resulted in clumped data on the temperature axis.

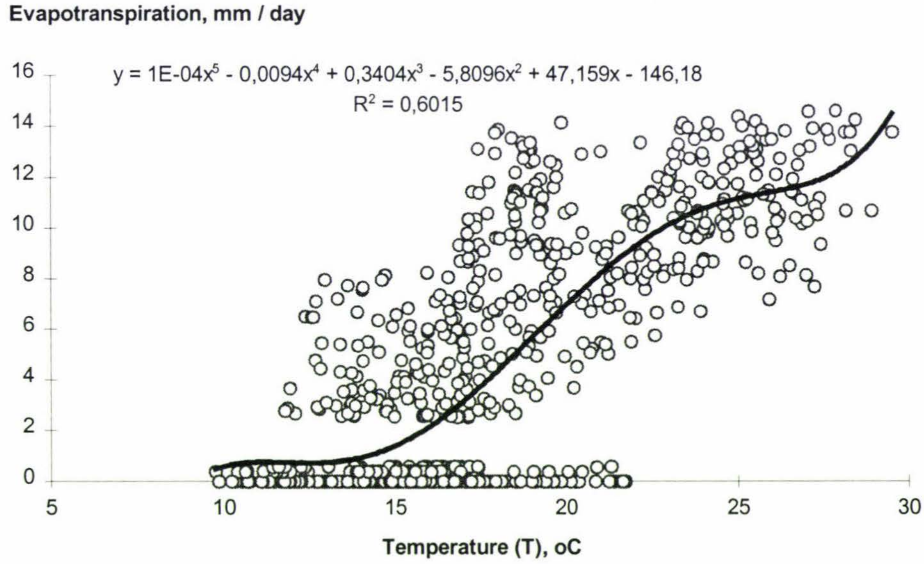


Figure 6.9. The relation between evapotranspiration rate of SRF trees and temperature in the plantation site at HortResearch, Aokautere, Palmerston North

6.3.4.2 Evapotranspiration versus the vapour pressure deficit

The relation between the evapotranspiration of the three SRF species and the vapour pressure deficit factor is presented in figure 6.10. The evapotranspiration is correlated to the vapour pressure deficit of the site ($R^2 = 0.6321$). However, as the vapour pressure deficit increased to more than 15 mb, there was negligible increase in evapotranspiration. This confirmed the results of Myers et al. (1996) that doubling the vapour pressure deficit (VPD) to 30 kPa only resulted in a 30 % increase in the transpiration of *P. radiata*. The clumping of data at zero were evapotranspiration rates during the night when possibly all the stomata close.

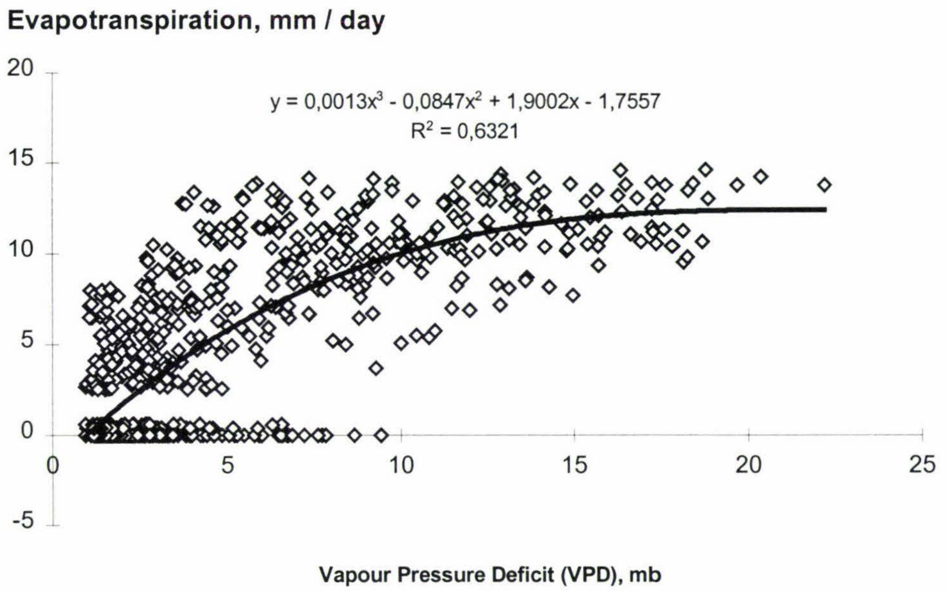


Figure. 6.10. The relation between the evapotranspiration rate and vapour pressure deficit (mb) in the SRF plantation

6.3.4.3 Evapotranspiration versus global radiation

The relation between the evapotranspiration of three SRF trees with the amount of global radiation received by the plantation is shown in figure 6.11. The evapotranspiration of trees is well correlated with the global radiation in the site with R^2 = 0.7913, producing the highest correlation value. This result is parallel to the statement of Jensen et al. (1990) that net radiation is the primary climatic factor controlling evapotranspiration when water is not limiting.

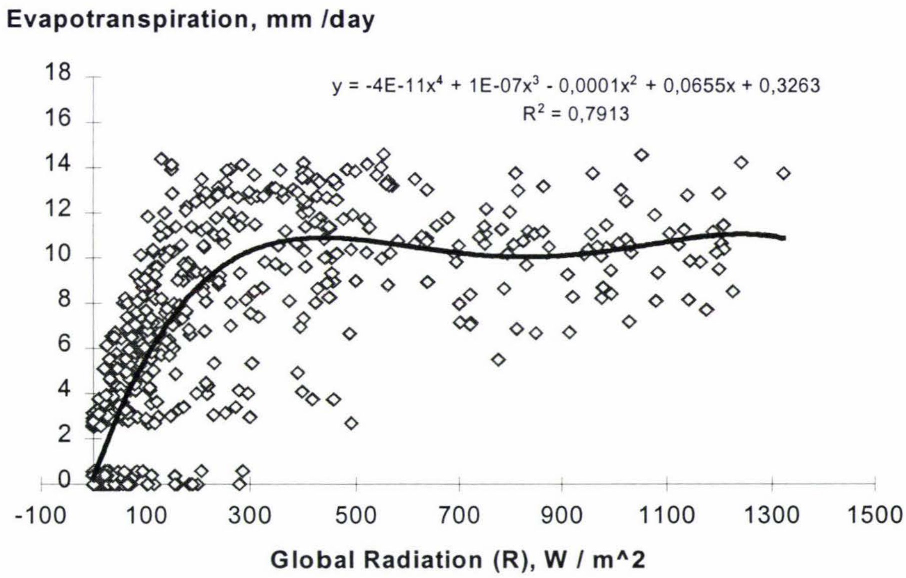


Figure 6.11 The relation between evapotranspiration rate and global radiation (W/m^2) in the SRF plantation

6.3.5 Water requirement of three SRF species

The amount of water required by the three SRF species per growing season is presented in Table 6.1. In a growing season, 332 mm of water is required to meet the evaporative demand alone at the experimental site (refer to section 2.1). NZ 1295 when irrigated with 30 mm of effluent (780 mm per season) can possibly evapotranspire 1148.4 mm per growing season. The rainfall for the growing season amounted to 475 mm, which added up to 1560 mm of rain plus effluent. This amount of transpired water (72.36% of the total applied as effluent and rainfall) can still possibly be insufficient to meet the water demand and deep percolation (depending on soil type) of soil-NZ 1295 treatment system. It is therefore possible to irrigate effluent to these three SRF species at rates matching their water requirement for optimum biomass production and effluent treatment system.

Table 6.1 Water balance for 2 years old three SRF species irrigated either at 7.5 or 30 mm of effluent for one growing season

Treatment	Irrigation mm	Evapotranspiration mm	Water Deficit mm
PN 386 1	195	300,3	437,3
PN 386 3	780	871	423
NZ 1295 1	195	487,8	624,8
NZ 1295 3	780	1148,4	700,4
E. nitens 1	195	532,8	669,8
E. nitens 3	780	720	272
Rainfall, mm		475	
Evaporation, mm		807	

1 = 7.5 mm Effluent 3 = 30 mm Effluent

6.4 Conclusions and recommendations

- The cumulative evapotranspiration rates of the 15 month old SRF trees irrigated at 30 mm of dairy farm-pond effluent per fortnight over two growing seasons were significantly higher than the trees irrigated with 7.5 mm of dairy farm-pond effluent. The NZ 1295 species had the highest average cumulative evapotranspiration rate of 6.38 mm day^{-1}, followed by PN 386 and *E. nitens* at the rates of 4.84 and 4.0 mm day^{-1}, respectively.
- The cumulative evapotranspiration rate of SRF trees that were irrigated with either high or low rates of dairy farm-pond effluent per fortnight reached peak levels during a cloud-free day of the monitoring period when global radiation, vapour pressure deficit and temperature were also at their peak.
- Trees irrigated with higher rates of dairy farm-pond effluent produced higher leaf areas than trees irrigated at lower rates. NZ 1295 and *E. nitens,* when irrigated at 30 mm of dairy farm-pond effluent produced leaf areas of 9 and 9.5 m^2, respectively, which were greater than for the other treatments.
- The cumulative evapotranspiration rate per day was correlated with the leaf area (R^2 = 0.59) of SRF trees. Trees with larger leaf areas evapotranspired higher cumulative amounts of water per day.
- Evapotranspiration was correlated with global radiation, vapour pressure deficit and temperature as measured at the plantation site during the monitoring period (R^2 = 0.79, 0.63 and 0.61, respectively). These climatic factors can be predictive values of evapotranspiration of 2 year old stands of SRF trees with the global radiation data as the best predictive factor.
- The evapotranspiration rates of the three SRF species can be used to determine irrigation levels of effluent to the trees. The NZ 1295 treatment system, when irrigated at 30 mm of effluent, can evapotranspire 1148.4 mm per growing season

which accommodated 72.36% of the total of water applied in the effluent and rainfall during the growing season.

CHAPTER 7

POT TRIALS OF HIGH RATES OF EFFLUENT IRRIGATION ON TO SHORT ROTATION FORESTRY CROPS

7.1 Introduction

Dairy farm-pond effluent is rich in nutrients like phosphorus and nitrogen. Various studies have shown that this effluent is a valuable fertiliser capable of stimulating pasture growth as discussed in section 2.1.2 (Yeates, 1978, Goold, 1980 and Cameron, 1995). Discharging this effluent to waterways can result in the depletion of dissolved oxygen, eutrophication, salinity and chemical toxicity.

Eutrophication and salinity are major waterways problems which require high redemption costs (Cullen, 1996) and can impact on the coastal or inland aquatic ecosystems. Therefore, the discharge or use of effluents to land is a major consideration as a treatment system.

Three selected short rotation forestry species, *S. kinuyanagi* (PN 386), *S. matsudana x alba* (NZ 1295) and *E. nitens* were identified in a field trial (section 3.2.1) as suitable for the treatment of dairy farm-pond effluent because of their fast growth. SRF trees usually grow rapidly when irrigated with effluent (Stewart et al., 1988). The fast growing regimes of these species are important features to give an efficient vegetative filter of wastewater. Doyle et al. (1996) reported the effectiveness of forest buffer strips and the soil system when intercepting nutrients and contaminants from cattle manure as shown by the improved water quality of the runoff collected from the disposal site.

Feigen et al (1990) showed that several crops including forest trees were evaluated as nitrogen scavengers. Smith and Evans (1977) disclosed that sewage effluent could contribute to renewing the wood fibre resources, while at the same time solving waste recycling problems. However, the planting of appropriate tree species and employment of management practices are considerations for the success of a land treatment scheme.

The purpose of this study was to determine the response of three selected SRF species to high rates of dairy farm-pond effluent irrigation greater than the 30 mm per fortnight uses in the field experiment (chapter 3). The specific objective was to determine the maximum irrigation level of dairy farm-pond effluent that could be tolerated by SRF species seedlings were grown in pots and compared for maximum growth, biomass production and nutrient accumulation.

7.2 Methodology

Three high yielding species of short rotation forestry crops irrigated with dairy farm-pond effluent in a field trial were used in the pot trial (refer to section 3.2.1). PN 386, NZ 1295 and *E. nitens* were planted in small pots with a diameter of 13 centimetres filled with a litre of air-dried Manawatu fine sandy loam soil. Each pot contained one tree.

The potted SRF crops were grown in a ventilated glasshouse with a maximum daily temperature of 32°C and minimum nightly temperature of 25°C. The potted trees with an initial diameter of 2 cm were grown to a height of 12 cm before irrigation treatment commenced. At the start of irrigation, each pot had 25 mm freeboard to prevent applied effluent or water from spilling. The irrigation started on 15 December 1995 and continued at two weekly intervals until 25 February 1996. The three SRF species were irrigated with 30mm, 60mm and 90mm of water as control treatments and by 30mm, 60mm and 90mm of effluent.

The effluent was as used for irrigating the SRF crops in the field experiment (section 3.1) and was taken from the oxidation treatment pond of Massey University Dairy Farm No.4. Each load of effluent was sampled and analysed to determine the chemical characteristics. The three levels of irrigation were applied every fortnight over a 10 week period to the potted trees. The lowest level of irrigation (30 mm/application) was based on the highest application rate applied in the field trial (Tungcul et al., 1996). The growth of potted SRF crops was monitored during the ten week period. Destructive assessment of the oven dry biomass yield and nutrient uptake determination of the trees was carried out after ten weeks. Root, stem and leaf biomass were determined separately. Accumulated total nitrogen, total phosphorus, potassium, calcium and magnesium were analysed for each, root, stem and leaf biomass components. Soil pH, total nitrogen and total phosphorus levels of the soil were also assessed after the termination of the trial. Exchangeable cations were not monitored due to financial constraints.

The efficiencies of the potted soil-SRF treatment systems in removing nutrients from the effluent were evaluated using equation 7.1.

$$PTR = \frac{TNO}{TNI} * 100 \qquad \text{(equation 7.1)}$$

where:

PTR = percentage of nutrient renovated by the potted soil and SRF treatment system

TNO = differential amount of nutrient in the potted soil after treatment and accumulated in the biomass of the SRF species

TNI = amount of nutrient input from the effluent and from initial nutrient level in the soil

The capacities of each selected SRF species to renovate nutrients from the effluent were also determined using equations 7.2 and 7.3.

$$SRF_R = NO_E - NO_w \qquad \text{(equations 7.2)}$$

where: SRF_R = amount of nutrient from the effluent renovated by the SRF species

NO_E = amount of nutrient that accumulated in the biomass of the SRF species after effluent treatment

NO_W = amount of nutrient in the biomass of the SRF species irrigated with water equivalent to the application rate of the effluent

$$PR = \frac{SRF_R}{NO_E} * 100 \qquad \text{(equation 7.3)}$$

where: PR = percentage of nutrient from the effluent renovated by SRF species

7.2.1 Chemical characteristics of effluent

The chemical characteristics of the dairy farm-pond effluent at the time of each of the 5 applications taken from the oxidation pond of Massey University Dairy Farm No.4 are presented in table 7.1.

Table 7.1 Chemical characteristics of dairy farm oxidation pond effluents

Parameters	Irrigation Event					
	1	2	3	4	5	Mean
PH	7.6	7.8	7.6	8	7.8	7.8
Electrical Conductivity (mS m^{-1})	215	220	230	218	230	222.6
Suspended Solids g m^{-3}	185	188	190	196	196	191
Chemical Oxygen Demand (g m^{-3})	618	615	620	625	622	620
Total Nitrogen (g m^{-3})	118	110	145	150	130	130.6
Nitrate Nitrogen (g m^{-3})	16	18	15	18	20	17.5
Ammoniacal Nitrogen (g m^{-3})	102	92	130	132	110	113.2
Total Phosphorus (g m^{-3})	25	28	24	26	27	26
Dissolved Reactive Phosphorus (g m^{-3})	19	20	18	20	20	19.4
Total Potassium (g m^{-3})	168	180	188	200	210	189.2
Total Calcium (g m^{-3})	23	24	25	23	23	23.6
Total Magnesium (g m^{-3})	15	14	18	17	16	16

The volumes of effluent applied to the potted SRF crops at each of the five irrigation schedules were 2000, 4000 and 6000 ml pot^{-1} to give the desired the applications of 30, 60 and 90 mm, respectively. Table 7.2 shows the total amount of nutrients supplied to the SRF crops through effluent irrigation over the ten week period. The effluent or water was applied to the SRF trees at 8:00 a.m at each irrigation event. Any effluent or water that drained through the pots was collected in a plate beneath the pot and re-added the same day.

Table 7.2. The total amount of nutrients applied to SRF crops for ten weeks

Nutrients	30 mm	60 mm	90mm
	mg pot^{-1}	mg pot^{-1}	mg pot^{-1}
Total Nitrogen	261	522.4	783.60
Total Phosphorus	52	104	156
Total Potassium	378.4	756.8	1135.2
Total Calcium	47.2	94.4	141.6
Total Magnesium	32	64	96

Figure 7.1 Potted SRF species irrigated with effluent and water over ten week period with five irrigation application

7.3 Results and discussions

7.3.1 SRF biomass yield

The oven dry biomass yield of *E. nitens* and PN 386 responded positively to increased application rates of effluent whereas NZ 1295 showed maximum biomass production at 60 mm fortnight^{-1}. PN 386 gave the highest significant average total biomass yield of 27 g pot^{-1} when irrigated with 90 mm effluent per fortnight ($p > 0.05$), followed by *E. nitens* at 18.5 g pot^{-1} (Figure 7.2). The application of effluent increased the biomass of SRF crops substantially to more than three times the biomass of the control plants. This can possibly be attributed to the continuous application of effluent rich in nutrients that supported the continued growth of the trees throughout the growing period. The control

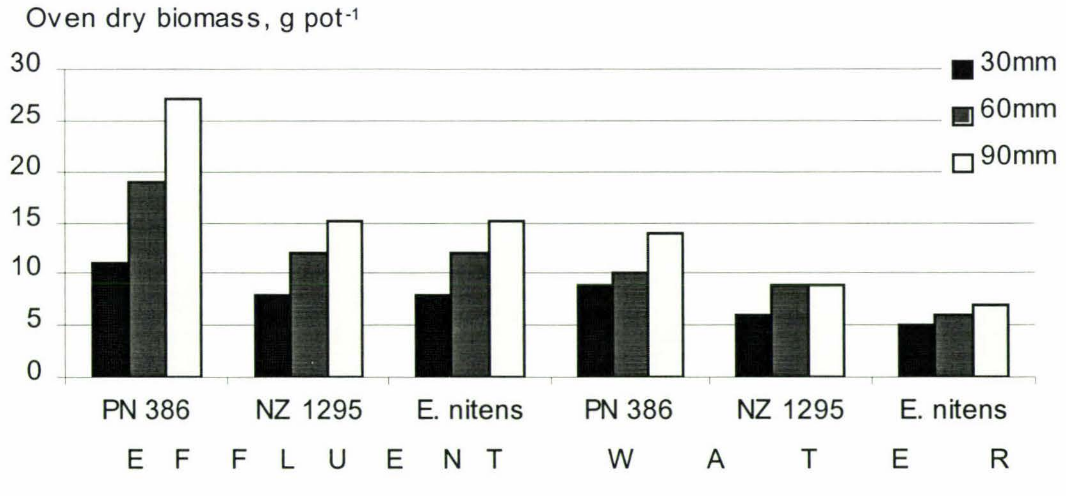


Figure 7.2 Total oven dry biomass of three pot grown SRF species seedlings irrigated either with effluent or water per fortnight for ten weeks ($LSD_{0.05} = 1.15$)

pots, SRF species irrigated with water produced lower biomass than the equivalent effluent irrigated species. This is comparable to the findings of Hasselgren (1996), Kutera et al. (1995) and Thomsen (1990) who also showed an increase of biomass of SRF crops as a result of continuous application of effluent giving good utilisation of nutrients during the growing period.

The leaf area of the three selected SRF species is shown in figure 7.3. The leaf area varied significantly with species of SRF trees and level of irrigation. *E. nitens* was significantly higher in leaf area ($p > 0.05$) when irrigated with 90 mm of effluent than all seedlings in the other treatments. The nutrients and water in the effluent at 90 mm of application might possibly have caused the *E. nitens* to produce a larger leaf area than the other treatments. In all cases the SRF species irrigated with effluent developed a larger leaf area than when irrigated with water alone at the same volume. The bigger area of leaves could intercept more light for the process of photosynthesis which might have resulted in higher biomass yields (figure 7.2).

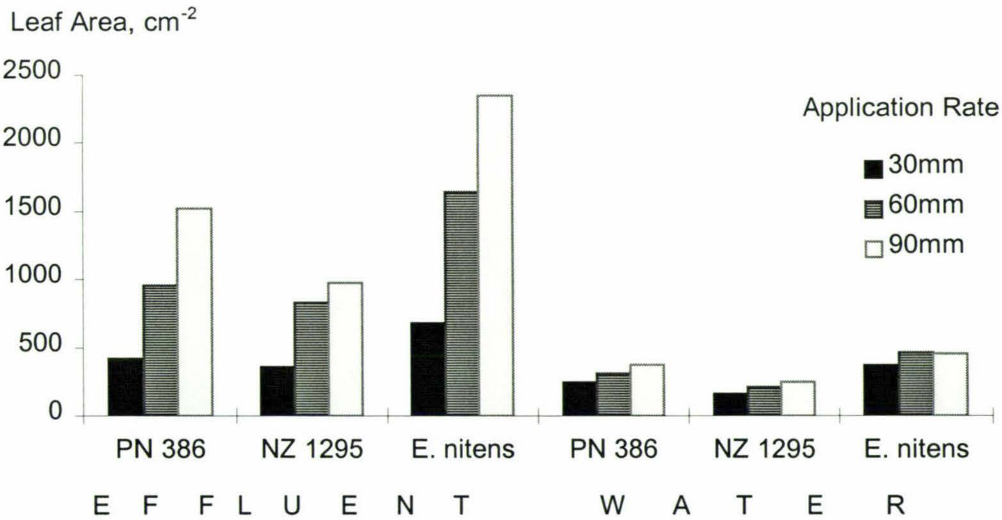


Figure 7.3 Leaf area of three pot grown SRF species seedlings irrigated either with effluent or water per fortnight for ten weeks ($LSD_{0.05}$ = 17.0)

7.3.2 Nutrients in the biomass

Nutrient content of leaves, stem and roots were determined separately. The results in this study are presented as the sum of nutrients in the total biomass of trees to assess the total capacity of each SRF species to remove nutrients from the disposal site.

7.3.2.1 Nitrogen

Nitrogen (N) is considered to be the main limiting nutrient for growth and production of forest crops (Stegemoeller and Chappell, 1990; Mengel and Kirkby, 1979). The amount of nitrogen in the biomass of SRF crops increased with increasing rates of effluent application except for NZ 1295 which levelled off at 60 mm per fortnight (Fig. 7.4). *E. nitens* and PN 386 accumulated significantly more nitrogen compared with NZ 1295 ($p > 0.01$) at rates of 367 and 353 mg N plant $^{-1}$ when irrigated with 90 mm of effluent per fortnight for ten weeks. This result is comparable to the findings of Petersen (1996) on the increased nitrogen uptake of crops when applied with increasing rates of slurry and mineral nitrogen fertiliser.

The amount of total nitrogen accumulated in the biomass of NZ 1295 was reduced from 238 mg TN seedling^{-1} to 232 mg TN seedling $^{-1}$ when the amount of effluent application per fortnight was increased from 60 mm to 90mm.

SRF crops irrigated with tap water showed lower concentration of nitrogen in their biomass than trees applied with effluent. This trend is similar to the results reported by Rytter et al.(1993) who showed that irrigated and fertilised stands of willows had higher N concentrations than unirrigated and unfertilised trees.

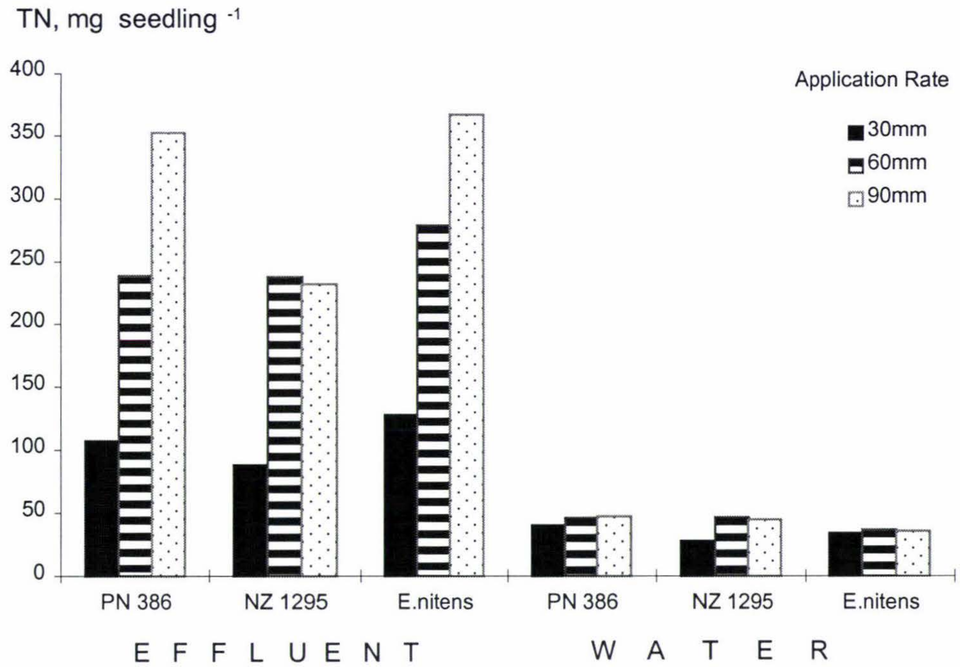


Figure 7.4 Total biomass nitrogen content of the three selected potted SRF species irrigated with either effluent or water every fortnight for ten weeks ($LSD_{0.05}$ = 17.68)

The nitrogen accumulated by the three selected SRF species was highly correlated with the total oven dry biomass (R^2 = 0.66). The relationship between the nitrogen and oven dry biomass of potted SRF species is shown in figure 7.5. Higher biomass production of the three SRF species denoted higher accumulation of nitrogen in the biomass of the tree.

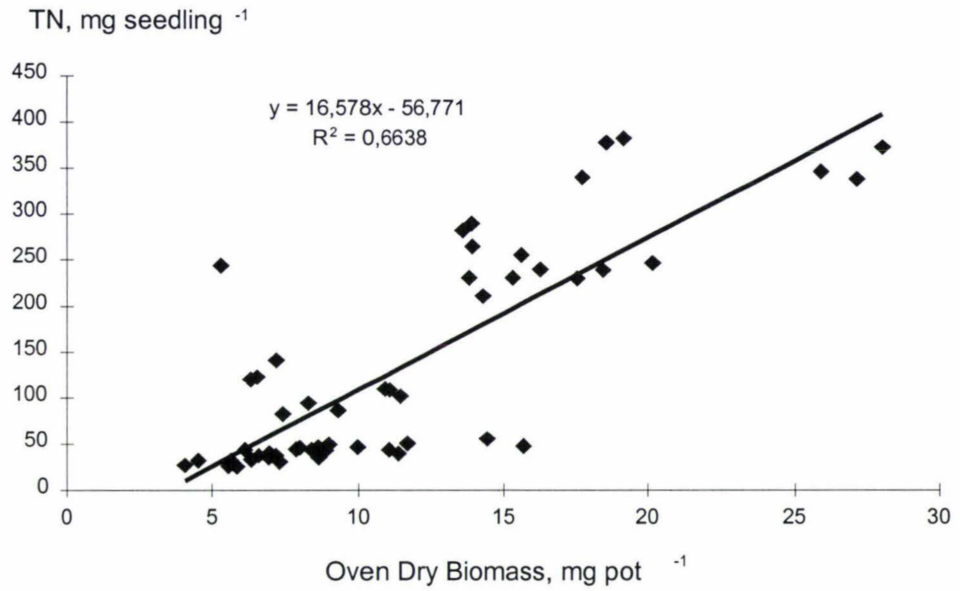


Figure 7.5 The relationship between the biomass and total nitrogen in the biomass of three selected pots grown SRF species irrigated with effluent or water per fortnight for ten weeks

7.3.2.2 Phosphorus

The amount of phosphorus in the biomass of the three selected SRF species increased with increasing rate of effluent applied (Figure 7.6). Phosphorus in the biomass of PN 386 was significantly higher than in the other treatments ($p > 0.05$) accumulating 35 mgP pot^{-1} when irrigated at 90 mm of effluent. NZ 1295 and *E. nitens* seedlings had uptake rates of 28 and 27 mg seedling^{-1}, respectively. The addition of phosphorus through the effluent irrigation favoured the phosphorus uptake of trees. Beier et al. (1995) reported that irrigation and addition of nutrients increased the P content of the foliage of trees. However, the phosphorus uptake of these trees was low compared to the standard capacity of fast growing crops which is at 1 kg P ha^{-1} day^{-1} (Mengel and Kirkby, 1979). The low phosphorus uptake of the SRF crops might have been influenced by the high pH of the effluent that ranged from 7.6 to 8. Similar observations were reported by Hendrix

(1967) and Hai and Laudelot (1966) regarding the declined phosphorus uptake of crops with increased pH.

The control SRF crops irrigated with water showed limited P content in its biomass that might have caused low biomass production. The phosphorus level in the soil alone was not sufficient to support the growth and biomass production of SRF crops.

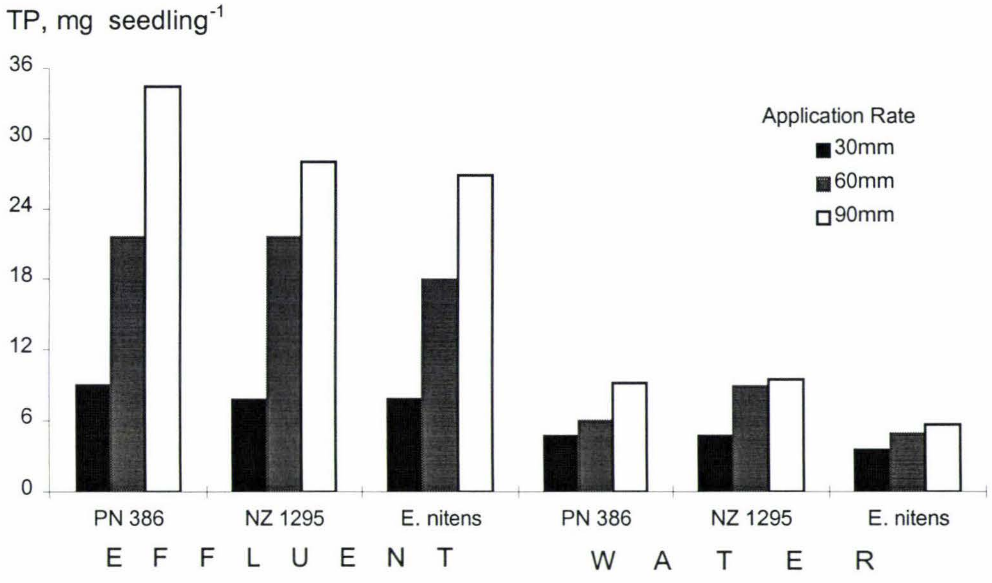


Figure 7.6 Total phosphorus content of selected three pot grown SRF trees irrigated with effluent or water per fortnight for ten weeks ($LSD_{0.05}$ = 2.14)

The amount of phosphorus that accumulated in the biomass of SRF crops was highly correlated with its biomass (R^2 = 0.7587). The amount of phosphorus added through effluent irrigation probably caused the accumulation of the nutrient in the biomass of the three selected SRF species. This result can be explained by the mobility of phosphorus in the plant and its translocation in an upward and downward direction (Hall and Baker, 1972).

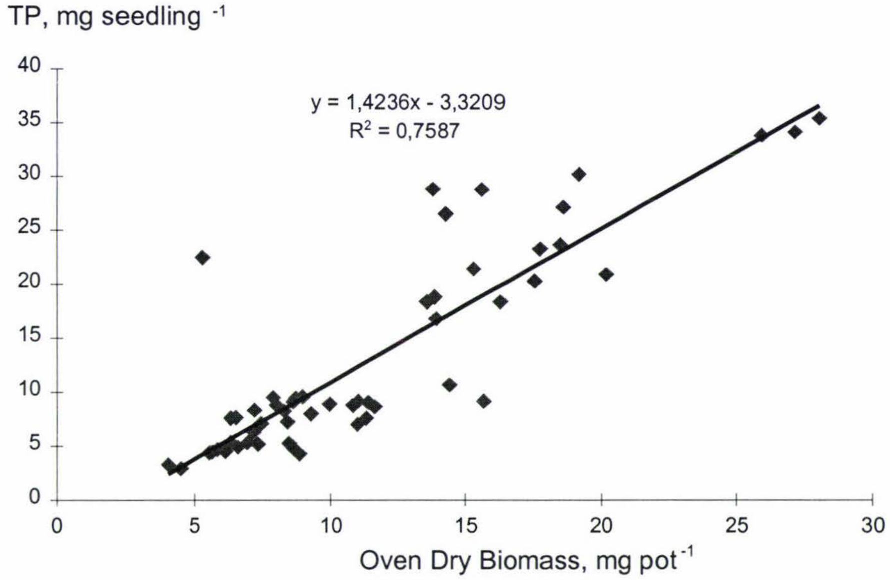


Figure 7.7 The relationship between the biomass and total phosphorus in the biomass of three selected potted SRF species irrigated with effluent or water per fortnight for ten weeks

7.3.2.3 Potassium

Potassium is an essential element for crop production. The three selected SRF species showed positive response of accumulated K in its biomass with the increased application rate of effluent except for NZ 1295. The SRF crops accumulated high amount of K probably as a result of large supply of K from the effluent. PN 386, when irrigated at 90 mm of effluent per fortnight, accumulated highly significant amount of K at 331 mg pot^{-1} compared to the other treatments ($p > 0.01$). The potassium in the effluent on top of other nutrients might have fuelled the biomass production of trees. Grant et al. (1996) disclosed that a high yield of crops is associated with the sufficient application of K nutrients. Mengel and Kirkby (1979) also reported that sufficient supply of K is necessary for crops to utilise nitrogen that enhance biomass production.

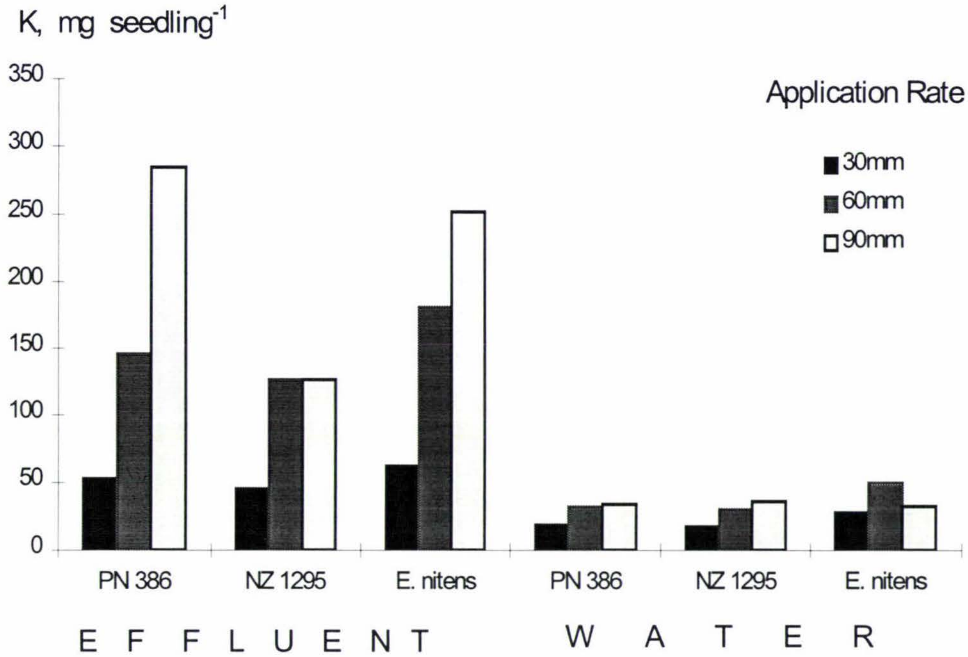


Figure 7.8 Potassium content of three selected pot grown SRF trees irrigated with effluent or water per fortnight for ten weeks ($LSD_{0.05}$ = 12.86)

Accumulated K in the biomass of the three SRF trees irrigated with water was very low compared with trees irrigated with effluent (Figure 7.8). The level of K in the soil alone cannot normally supply the potassium requirement of SRF crops over a long term. If the availability of K is poor, then probably, K uptake by the three SRF species was also low resulting in unsatisfactory biomass production.

Accumulated K in the biomass of the three SRF trees irrigated with water was very low compared with trees irrigated with effluent (Figure 7.8). The level of K in the soil alone cannot normally supply the potassium requirement of SRF crops over a long term. If the availability of K is poor, then probably, K uptake by the three SRF species was also low resulting in unsatisfactory biomass production.

The biomass of the potted SRF species and the amount of K taken up by the trees were highly correlated with each other (R^2 = 0.73). Figure 7.9 shows that the amount of K uptake by the three selected SRF species increased with increasing oven dry biomass of the trees.

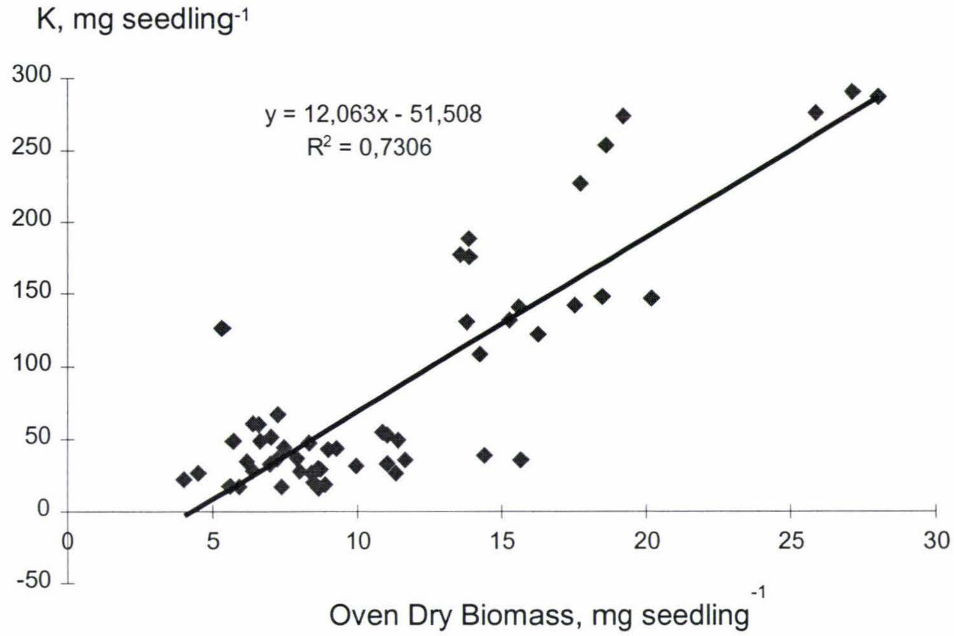


Figure 7.9 The relationship between the biomass and potassium in the biomass of three selected pots grown SRF species irrigated with effluent or water per fortnight for ten weeks

7.3.2.4 Calcium

The amount of calcium (Ca) in the biomass of the three selected potted SRF species increased with increased rate of effluent applied except for NZ 1295 (Figure 7.10). The calcium uptake of the trees was influenced by the non-limiting supply levels of Ca through effluent irrigation that might have influenced the favourable production of biomass. Cote et al. (1995) reported that application of fertiliser rich in Ca significantly increased the growth rate of SRF species by over 13 per cent.

In this present study PN 386 accumulated significant amount of Ca in its biomass compared to other treatments ($p > 0.05$), followed by *E. nitens* when irrigated at 90 mm of effluent per fortnight at rates of 195 and 138 mg Ca pot^{-1}, respectively. Nilson et al. (1995) reported that irrigation and liquid application of fertiliser enhance the Ca and other nutrient uptake of trees to 2-4 times higher than for unfertilised and irrigated Norway spruce trees. NZ 1295 showed maximum Ca uptake when irrigated with 60 mm of effluent accumulating 110 mg Ca pot^{-1} in its biomass. The optimum point of effluent application to NZ 1295 is important at which no further yield and nutrient uptake improvement can be further benefited by the addition of more effluent. Trees irrigated with water alone were relatively low in Ca particularly *E. nitens.*

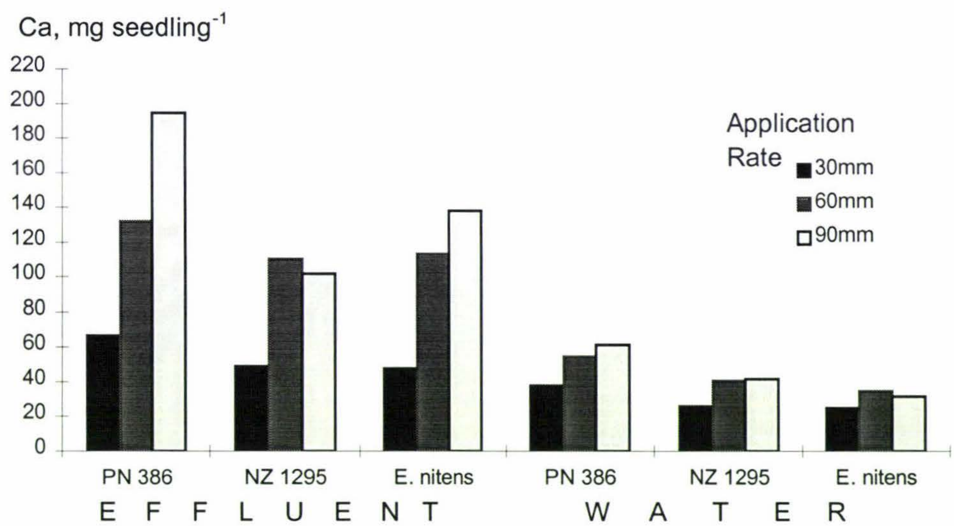


Figure 7.10 Calcium content of selected three potted SRF trees irrigated with effluent or water per fortnight for ten weeks ($LSD_{0.05}$ = 11.56)

The accumulated Ca of the potted plants was highly correlated with the biomass of the trees ($R^2 = 0.68$). Figure 7.11 shows the relationship between the amount of calcium taken up and the biomass accumulation of the three selected SRF species. The uptake of Ca by the three species increased with the yield of increasing oven dry biomass. The supply of calcium through effluent irrigation probably influenced the uptake of Ca by the trees which then enhanced their biomass production.

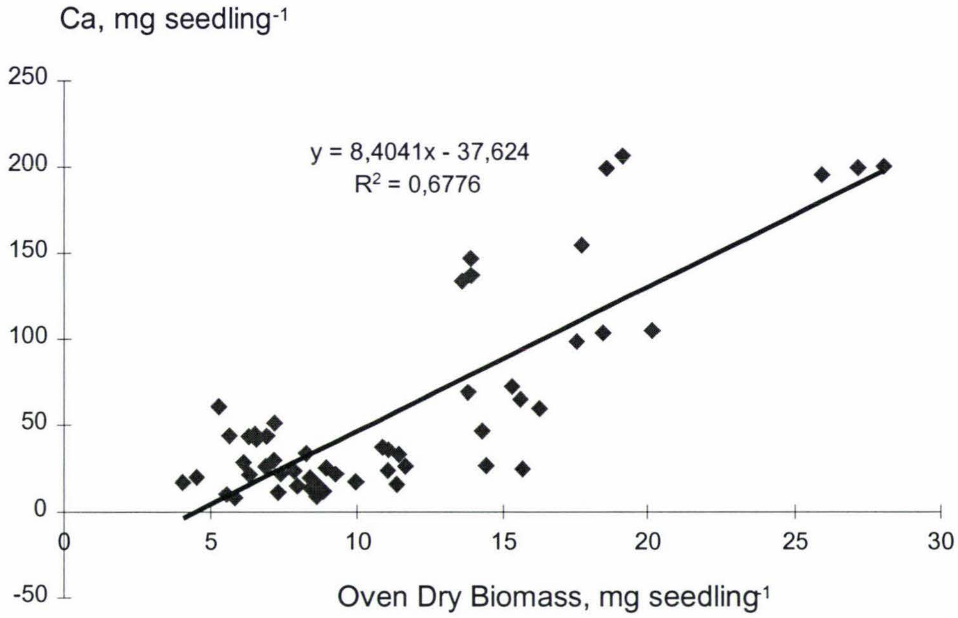


Figure 7.11 The relationship between the biomass and calcium in the biomass of three selected pots grown SRF species irrigated with effluent or water per fortnight for ten weeks

7.3.2.5 Magnesium

The three potted SRF species showed positive response of accumulated magnesium (Mg) with increased rate of effluent application. PN 386 and E. nitens when irrigated at 90 mm of effluent per fortnight accumulated highly significant amounts of magnesium ($p > 0.05$) (Figure 7.12) giving rates of 39.51 and 37.22 mg Mg pot^{-1}, respectively. The supply level of Mg through the effluent probably warranted the Mg uptake of trees that resulted into higher biomass production. This result confirmed the report of Katzensteiner et al.(1995) regarding the increased level of Mg content and improved the growth and vitality of the trees as a result. However, NZ 1295 once again showed optimum accumulation capacity of 21.88 mg Mg pot^{-1} when irrigated with effluent at 60 mm fortnightly. Increasing the effluent rate to 90 mm fortnightly decreased the amount of accumulated Mg in the biomass to 20.39 mg Mg pot^{-1}.

Trees irrigated with tap water showed lower levels of magnesium in its biomass. The amount of Mg from the soil alone is not sufficient to supply the needs of SRF crops that will enhance the production of biomass.

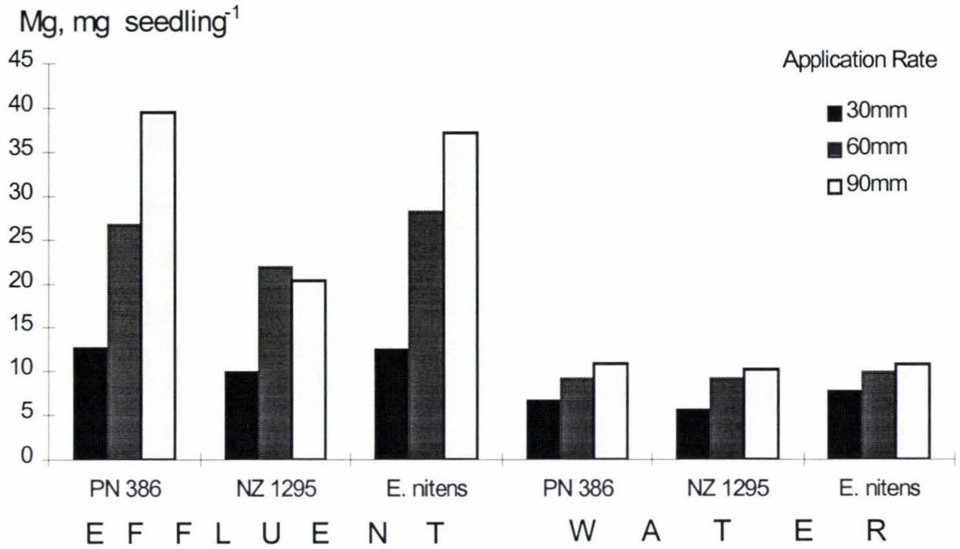


Figure 7.12 Magnesium content of selected three potted SRF trees irrigated with effluent or water per fortnight for ten weeks ($LSD_{0.05}$ = 2.4)

The amount of Mg accumulated by the three selected potted SRF species was highly correlated with the oven dry weight of the trees (R^2 = 0.754). Mg was found more in trees with higher biomass yields. The supply of Mg through the effluent probably caused the luxury uptake of this nutrient by the trees which might contributed to accumulation in the biomass.

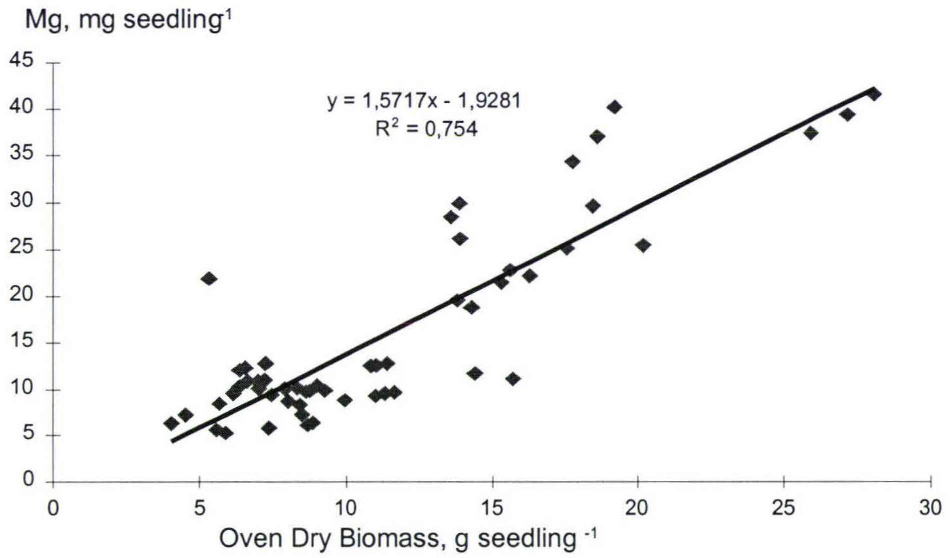


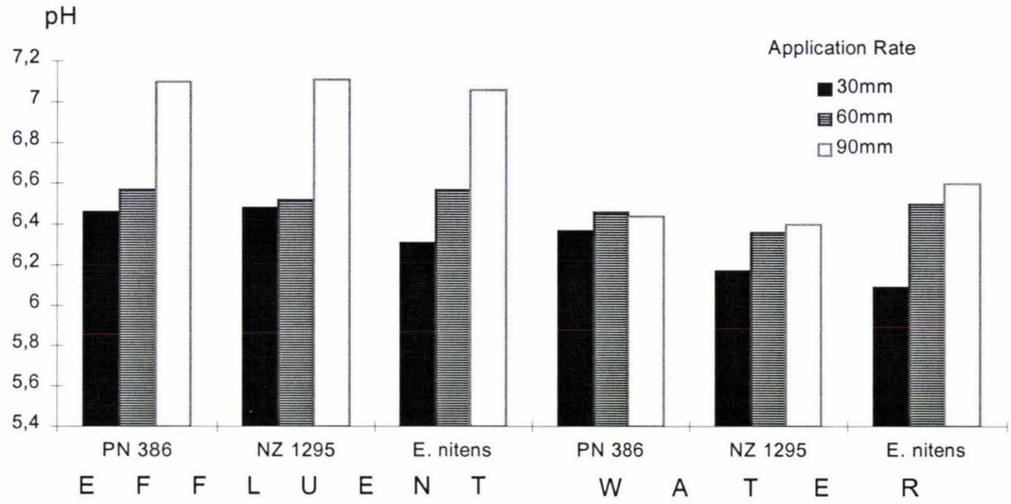
Figure 7.13 The relationship between the biomass and magnesium in the biomass of three selected pots grown SRF species irrigated with effluent or water per fortnight for ten weeks

7.3.3 Effect of effluent on the soils

7.3.3.1 Soil pH

The pH levels of potted soil grown with three selected SRF species and irrigated with either effluent or water for ten weeks are presented in figure 7.15. The soil pH significantly increased with an increasing amount of effluent. The three SRF species that were irrigated with 90 mm of effluent per fortnight had significantly higher pH levels than in the other treatments ($p > 0.05$) but were not different between the three SRF species.

The soil pH increased from 5.85 to 7.1 (21.3%), 7.11 (21.59%) and 7.06 (20.68%) units under PN 386, NZ 1295 and *E. nitens*, respectively, after ten weeks of applying 90 mm of effluent per fortnight. The considerable increase of the soil pH can be attributed to the high pH of effluent (Table 7.1) applied that ranged from 7.6 to 8.0.



$LSD_{0.05}$ = 0.18

Figure 7. 14 pH of potted soil under three selected pot grown SRF species irrigated with effluent or water per fortnight for ten weeks (pre-treatment soil pH = 5.85)

7.3.3.2 Nitrogen

Table 7.3 shows the total nitrogen (TN) in the potted soil under three SRF species irrigated with either effluent or water. The TN varied with both the rate of effluent irrigation and SRF species ($p > 0.05$). The soils under the three SRF species irrigated with effluent were significantly higher in TN than the soils irrigated with water. The soil under PN 386 irrigated with 90 mm of effluent was significantly higher in TN than in all the other treatments. The TN content of the soil increased from 230 mg pot^{-1} to 358.33 mg pot^{-1} which gave a TN renovation capacity of 69.80%. Around 29.20% of TN from the initial content of the soil and effluent was lost probably due to volatilisation, denitrification or leaching.

The increase in TN in the potted soils irrigated with effluent can be accounted for by the addition of nitrogen from the effluent. This is similar to the findings of Bernal et al. (1993) regarding the significant increase in soil N and P after eight months of pig slurry application at a rate that matched the calcareous soil in Spain.

The fate of TN in the effluent applied to potted SRF seedlings is presented in figure 7.16 (a, b and c). The amount of TN in the effluent was taken up by the SRF trees, adsorbed in the soil and lost through volatilisation. Figure 7.16b showed the highest percentage of TN accumulation in the biomass of the three potted SRF species when applied with 60 mm of effluent.

The amount of water and nutrient at 60 mm of effluent applied in a glasshouse environment possibly contributed to the accumulation of more TN in the biomass of *E. nitens* (53.4 %), the least amount of TN lost (30.8%) than the other SRF seedlings and adsorption of TN in the soil at 15.8%.

Figure 7.15 showed that the amount of TN lost increased as the level of effluent application increased from 30 to 90 mm of effluent. The highest TN lost was 64% occurred in the potted NZ 1295 when applied with 90 mm of effluent. This can be attributed to the lower threshold tolerance of NZ 1295 than the other seedlings to effluent application which also resulted to lower TN accumulation in the biomass (29.6 %) and lower TN in the soil (6.32 %).

The percentage of TN adsorbed in the soil decreased with increasing effluent application. More percentage of TN volatilised when more nutrients is applied through increased effluent application.

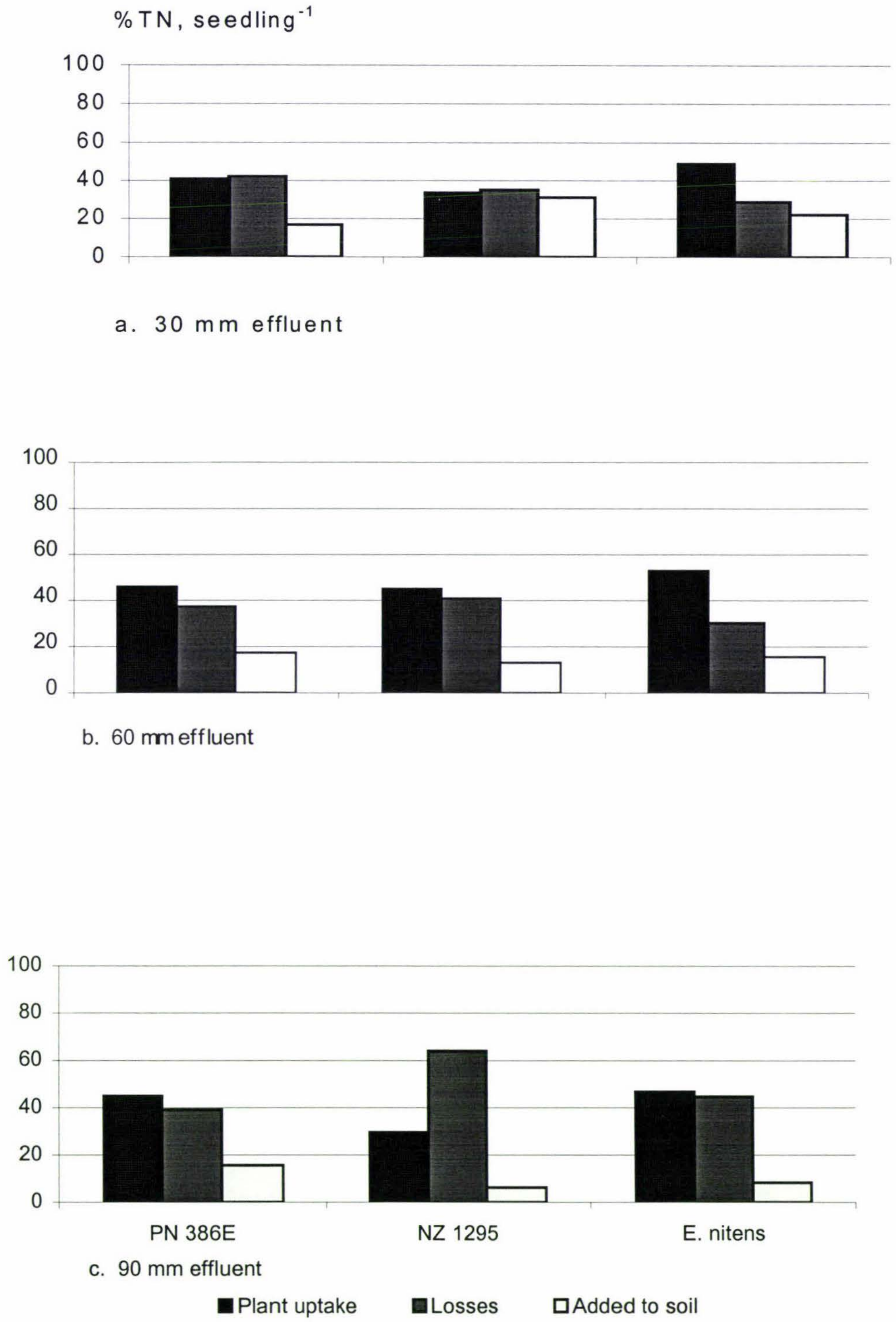


Figure 7.15 The fate of TN in the effluent in terms of percentage of total N applied to the three potted SRF seedling species at rates of (a) 30 mm (b) 60 mm and (c) 90mm per fortnight for ten weeks.

The percentage of TN renovation of the potted soil-SRF treatment system decreased with increased application of effluent from 30 mm to 90 mm. The potted soil-*E.nitens* treatment system, irrigated with 30 mm of effluent was significantly higher in TN renovation (84.79%) than all the other treatments applied with effluent (Table 7.3). The decrease in the percentage of TN renovation may be attributed to more volatilisation, denitrification and leaching of the nutrient when increasing the amount of nitrogen added through an increased rate of effluent application.

Table 7.3 Renovation of total nitrogen in a potted soil-SRF seedling treatment system

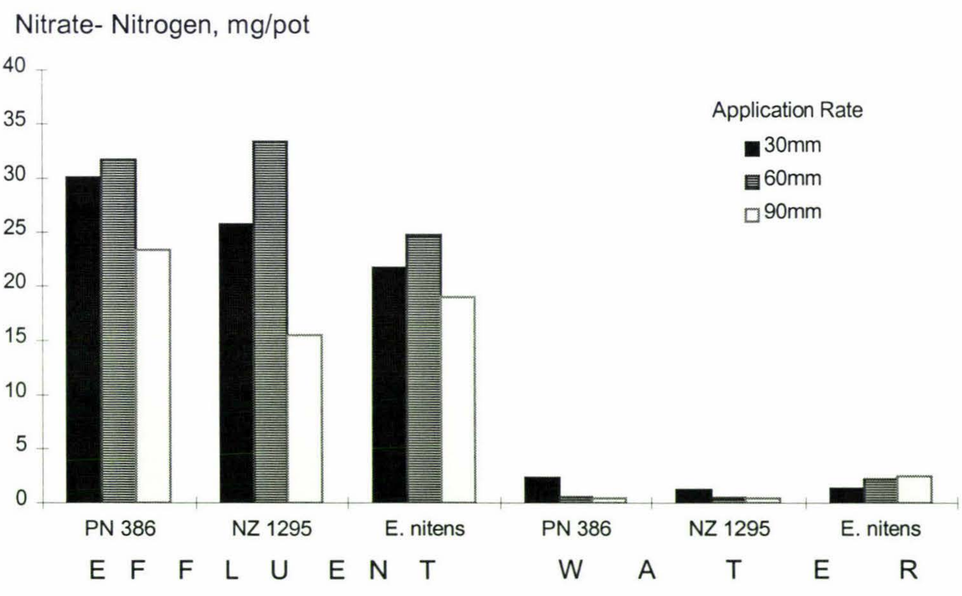
SRF Species	TN of potted seedling plus soil after 10 weeks of irrigation		
	30 mm Effluent	60 mm Effluent	90 mm Effluent
PN 386	279.00^{h} (77.77)	324.67^{b} (74.40)	358.33^{a} (69.80)
NZ 1295	316.67^{c} (81.53)	304.33^{d} (71.64)	284.50^{g} (50.74)
E. nitens	292.67^{f} (84.79)	317.67^{c} (78.78)	301.00^{e} (65.58)
	30 mm Water	60 mm Water	90 mm Water
PN 386	189.00^{i} (97.53)	187.00^{j} (99.14)	185.00^{k} (98.93)
NZ 1295	190.00^{i} (92.62)	186.00^{jk} (98.80)	188.00^{ij} (98.99)
E. nitens	189.00^{i} (95.00)	187.00^{j} (95.11)	186.00^{jk} (94.22)

( ) = % of TN Renovation of potted soil-SRF treatment system
Initial Soil TN = 230 mg pot^{-1}
Numbers with the same letters are not significantly different at 5%

The three selected SRF species renovated TN from the soil between 92.62 to 99.14% when irrigated with water. The initial level of TN in the soil was not sufficient as shown by the poor biomass production of the three selected potted SRF species (Figure 7.1).

7.3.3.2.1 Nitrate-nitrogen

The nitrate-nitrogen of the potted soils is shown in figure 7.16. The soils irrigated with effluent were significantly higher in nitrate-nitrogen than the soils irrigated with water. The soils under NZ 1295 at 60 mm of effluent irrigation were significantly higher in nitrate-nitrogen than all the other treatments. The accumulation of nitrates can be accounted to the addition of nitrogen through the effluent and uptake capacity of the specie. The optimum level of effluent irrigation to NZ 1295 was at 60 mm. Increasing the rate of effluent will not improve the biomass production and nitrogen renovation of the soil-NZ 1295 treatment system. The soils under SRF species irrigated at 90 mm of effluent were lower in nitrate-nitrogen probably due to plant uptake, volatilisation and leaching of the nutrient.



$LSD_{0.05} = 0.59$

Figure 7.16 Nitrate-nitrogen of soil under three selected pots grown SRF species irrigated with effluent or water per fortnight for ten weeks

7.3.3.3 Phosphorus

Table 7.4 shows the renovation of total phosphorus by the potted soil- SRF treatment system irrigated with effluent for ten weeks. The amount of TP renovated by the potted soil-PN 386 treatment system was significantly higher than all the other treatments giving 228.50 mg pot^{-1}. The TP renovation by both soil-salix treatment systems increased with increased rate of effluent irrigation. The TP in the potted soil-*E.nitens nitens* treatment system decreased in TP renovation from 101.50 to 98.00 mg pot^{-1} when effluent irrigation was increased from 60 to 90 mm, respectively. The soil-PN 386 treatment system renovated 99.61% of the TP from the soil and from the application of 90 mm effluent, which can be the preferred rate to the tree. For both soil-NZ 1295 and soil-*E. nitens* treatment systems, the TP renovation from 30 mm is not different from 60 mm effluent rate. The soil-NZ 1295 system renovated 98.87% of the TP from the soil and from the 60 mm of effluent, which can be an optimum effluent rate to the tree. *E. nitens* renovated 98.09% of TP from the soil and from the application of 60 mm effluent, which can be the preferred rate to the tree.

Table 7.4 Renovation of total phosphorus in a potted soil-SRF seedling treatment system

SRF Species	TP of potted seedling plus soil after 10 weeks of irrigation		
	30 mm Effluent	60 mm Effluent	90 mm Effluent
PN 386	149.50^{e} (99.06)	189.50^{e} (99.58)	228.50^{a} (99.61)
NZ 1295	152.00^{d} (99.87)	188.00^{c} (98.87)	220.00^{b} (93.94)
E. nitens	103.00^{f} (98.96)	101.50^{fg} (98.09)	98.00^{hi} (94.26)
	30 mm Water	60 mm Water	90 mm Water
PN 386	103^{f} (99.76)	98^{hi} (99.54)	97^{i} (99.23)
NZ 1295	103^{f} (99.77)	98^{hi} (99.01)	97^{i} (98.61)
E. nitens	103^{f} (98.66)	102^{fg} (98.98)	101^{g} (98.76)

( ) = % of TP Renovation of potted soil-SRF treatment system
Initial Soil TP = 40 mg pot^{-1}
Numbers with the same letters are not significantly different at 5%

The TP in the effluent was partitioned into the biomass of the SRF seedlings, adsorbed in the soil and some might had been lost as a result of tipping back the water that drained from the pots (Figure 7.17) with negligible amount.

Figure 7.17 shows that TP in the effluent was largely adsorbed in the soil. The percentage of TP accumulated in the soil decreased as the amount of effluent application increased. The potted soil under NZ 1295 irrigated at 30 mm of effluent adsorbed the highest amount of TP at 84.6 % and decreased to 71.8% at 90 mm. The supply of TP through effluent application possibly exceeded the capacity of the soil top adsorb the nutrient.

The percentage of TP taken up by the SRF seedlings increased with increasing amount of effluent applied except for NZ 1295 which showed maximum uptake at 60 mm. PN 386 accumulated the highest percentage of TP (22.1%) contained in the 90 mm effluent that was applied. Sufficient supply of moisture and TP in the effluent possibly influenced the SRF seedlings to uptake nutrients.

NZ 1295 and *E.. nitens* showed tolerance level at 60 mm of effluent application while PN 386 can tolerate up to 90 mm with regard to the uptake of TP. However, higher levels of effluent application may exceed the capacity of the soil to adsorbed and the plant to uptake the TP which might result to leaching of the nutrient.

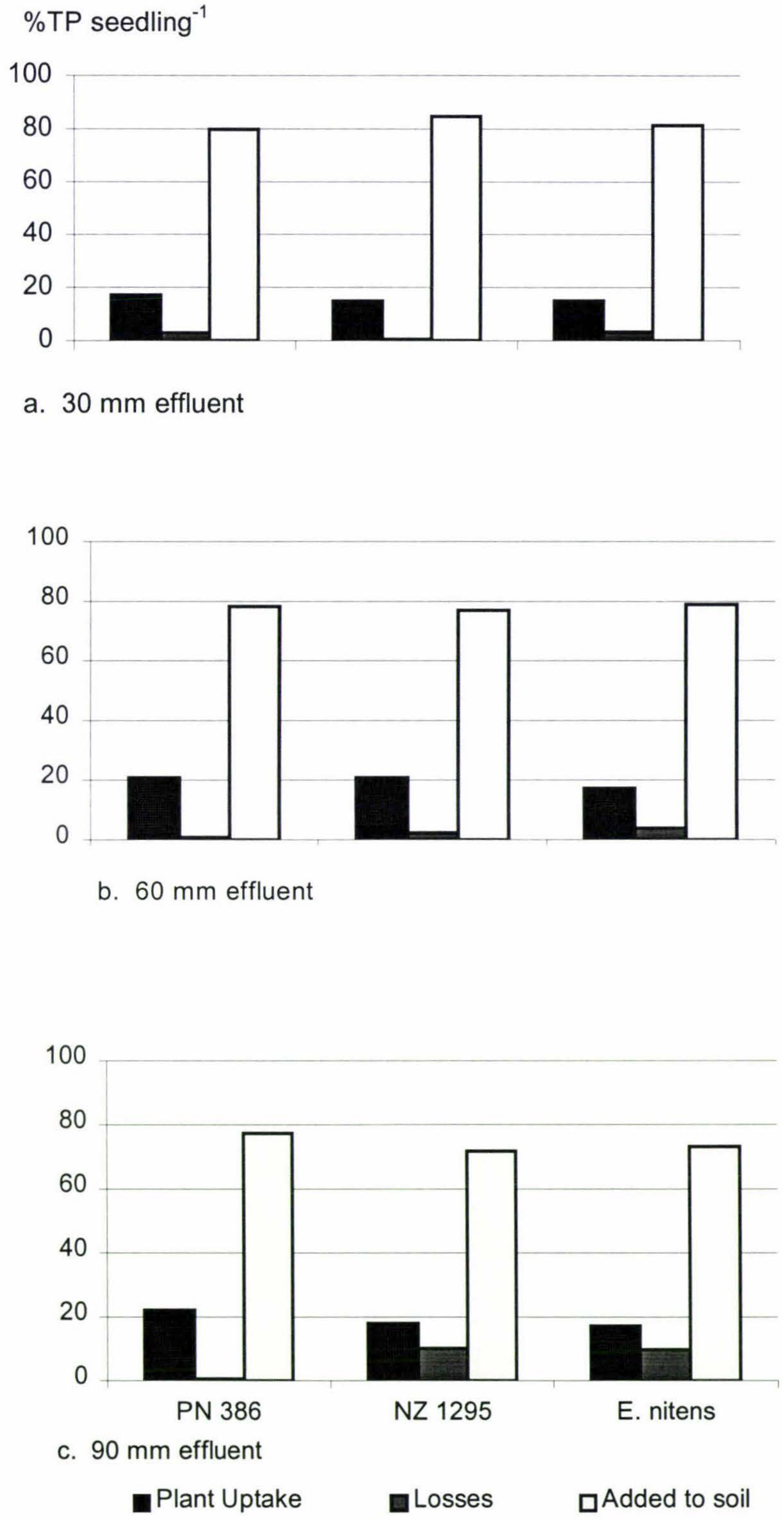


Figure 7.17. The fate of TP in the effluent in terms of percentage of total P applied to potted SRF seedling species at rates of a) 30 mm, b) 60mm and c) 90 mm per fortnight for ten weeks.

7.4 Conclusions and recommendations

Application of effluent up to 90 mm per fortnight fuelled the biomass production of PN 386 and *E. nitens* when grown in pots and producing 20.34 g seedling^{-1} and 18.5 g seedling^{-1}, respectively. The NZ 1295 produced optimum biomass of 15.30 g pot^{-1} when irrigated with 60 mm of effluent.

At 90 mm of effluent application, *E. nitens* and PN 386 accumulated more nitrogen in their biomass than all the other treatment at 367 and 353 mg TN seedling^{-1}. The latter accumulated more TP, K, Ca and Mg than *E. nitens* and NZ 1295.

The *E. nitens* alone renovated the highest amount of 331.6 mg TN seedling^{-1} from the 90 mm of applied effluent. Although the highest percentage of TN renovation occurred at 60 mm of effluent application at 53.4%. The potted soil-*E. nitens* treatment system renovated the highest percentage of TN (84.8%) from the soil and from the application of 30 mm of effluent per fortnight.

The PN 386 renovated the highest amount of TP which was 22.1% of the TP from 90 mm of effluent. The potted soil-PN 386 treatment system renovated the highest amount of TP from the soil and 30 mm of effluent giving 228.50 mg TP pot^{-1}.

The application of 90 mm of effluent is recommended for higher biomass production and higher accumulation of TN and TP in the biomass of potted PN 386 and *E. nitens*. For NZ 1295, 60 mm of effluent is recommended.

The application of 30 mm of effluent per fortnight to PN 386 is recommended for higher efficiency in the renovation of TN and TP in a potted soil-SRF treatment system.

CHAPTER 8

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The small plot field screening trial of nine species of Salix and one of Eucalyptus applied with three effluent irrigation treatments and 7.5 mm water + nitrogen fertiliser successfully identified four species better suited for use in a land treatment system of dairy farm-pond effluent.

All nine salix species responded positively to the highest rate of effluent application, whereas, *E. nitens* responded most positively to an application rate of 15 mm per fortnight which implied the 30 mm rate was over-loading the soil-plant system and therefore restricting the growth to some degree. NZ 1296, PN 386, and NZ 1295 irrigated with 30 mm of effluent per fortnight were the most suitable of the treatments evaluated, in terms of giving the highest biomass yield of 37.91, 37.87 and 37.58 ODt ha^{-1} $year^{-1}$, respectively. *E. nitens*, when irrigated with 15mm of effluent produced a comparable above ground oven dry biomass yield of 36.33 ODt ha^{-1} $year^{-1}$ and was the most suitable treatment for stem wood production that can be used for pulping or fuel.

The highest uptake of nitrogen, phosphorus, potassium, calcium and magnesium occurred as aresult of applying the highest (30 mm) effluent rate to the nine salix species. Once again maximum uptake by *E. nitens* resulted from the 15 mm effluent application. NZ 1296 irrigated with 30 mm of effluent accumulated the highest nitrogen, phosphorus and magnesium in its above ground biomass at rates of 196.02, 37.62 and 103.55 kg ha^{-1} $year^{-1}$ respectively. *E. nitens* irrigated with 15 mm of effluent accumulated the highest amount of potassium and calcium in its above ground biomass giving 145.42 and 148.08 kg ha^{-1} $year^{-1}$ respectively.

NZ 1296, NZ 1295, PN 386 and *E. nitens* were all identified as good performers from the ten species of SRF trees evaluated. This was reflected in their high biomass production and high amount of nutrient accumulation in the above ground biomass after being irrigated with effluent. It also justified the selection of NZ 1295, PN 386 and *E. nitens* for more detailed evaluations.

Both the chemical and physical compostions of the soil under the three SRF species were affected by the application of effluent (Chapter 2). A reduction of soil total nitrogen occurred from the original pre-treatment level to that reached after harvest at year 2 in spite of the addtition of N in the effluent. This indicates that the following processes occurred:

- a high uptake of total nitrogen by the SRF trees;
- some loss of total nitrogen during the process of nutrient transformation and volatilisation, and
- leaching of total nitrogen following rainfall or irrigation when soil water levels exceeded field capacity.

The application of 30 mm of effluent to the soil under the SRF species increased the total phosphorus (TP) levels in the top 5 cm depth. Below the 10 cm depth range, the total phosphorus for all the treatments decreased possibly due to tree root uptake. The application of 15 mm of effluent can be considered optimal to the soil under *E. nitens* due to the lower recovery of total phosphorus at 30 mm of effluent application.

Potassium was the limiting factor determining the effluent application loading rate. The level of exchangeable potassium in the soil under the SRF trees increased with increasing rate of effluent irrigation. Exchangeable soil potassium levels were highest under treatments of 30 mm of effluent application for the three SRF species, Salix NZ 1295, Salix PN 386 and *E. nitens* which were then studied in more detail.

The exchangeable calcium and magnesium levels in the soils under these three SRF species increased with increasing levels of effluent irrigation. The level of sodium in the soil increased after application of 30 mm of effluent but the sodicity limit remained below the risk level throughout all soil layers. The soils under NZ 1295 when irrigated with 30 mm effluent had the highest level of exchangeable sodium below the 30 cm depth layer.

The cation exchange capacity of the soils varied with the rate of effluent irrigation and the species. After two years of applying 30 mm of effluent reduced the average cation exchange capacity was reduced by 19.10, 25.81 and 43 % for *E. nitens*, PN 386 and NZ 1295, respectively. This suggests that the cations in the effluent were adsorbed onto the clay particles of the soil as indicated by the increased soil pH. The pH of the soil increased with increasing rate of effluent application being significantly higher under NZ 1295 when irrigated at 30 mm of effluent at all depths. The pH of soil under the NZ 1295 increased with increasing rate of effluent irrigation giving a soil pH ranging from 5.71 to 6.49 with depth.

The bulk density of the top 30 cm layer of the soil increased with the application of 30 mm of effluent. Both Salix species lowered the bulk density by 40% and *E. nitens* by 3.2%. The application of effluent also improved the infiltration rate of the soil under all three SRF species.

The soil-SRF treatment system effectively renovated the nutrients contained in the dairy farm pond-effluent. The renovation of the total nitrogen by the soil-SRF system in the field trial increased as the load of total nitrogen added from the effluent inreased. The soil-*E. nitens* treatment system was the best and renovated 96.45% (17.2 ODt ha^{-1} m^{-1}

depth) of the total nitrogen from the soil and from the application of 30 mm of effluent fortnightly after two growing seasons.

Nitrogen renovation by the three SRF species alone excluding the soil effect decreased as the effluent irrigation rate was increased. The lowest effluent irrigation rate of 7.5 mm applied to PN 386 showed the highest percentage of total nitrogen renovation from the effluent alone at 99.45 % (114.25 kg N ha^{-1} $year^{-1}$).

The soil-PN 386 treatment system showed the highest total phosphorus renovation capacity of 92.72 %(6.4 ODt ha^{-1} m^{-1} depth) after two growing seasons from the TP of initial soil and phosphorus that was applied in the 7.5 mm of effluent.

TP renovation by the SRF species alone decreased as the effluent rate was increased. PN 386 renovated 79.18% (35.60 kg P ha^{-1}) from 46 kg P ha^{-1} applied in the effluent at the rate of 7.5 mm over two growing seasons.

The soil-NZ 1295 treatment system renovated 99.5% of the potassium supplied by the soil and the 30 mm of effluent over two growing seasons. NZ 1295 renovated 7.52% (260 kg K ha^{-1}) and 17.50 kg K ha^{-1} (0.50%) can be accounted for by leaching, and root uptake of K that was supplied by the soil and effluent.

The potassium renovation capacity of three SRF species decreased as the effluent application increased. *E. nitens* renovated 41.87 % (148 kg ha^{-1}) of the K supplied in the 7.5 mm effluent treatment (394 kg ha^{-1}) after two growing seasons.

The amount of calcium taken up by the SRF trees exceeded the amount of calcium supplied by the effluent, even at the highest rate of irrigation. The application of 30 mm of effluent after two growing seasons supplemented 168 kg ha^{-1} of calcium.

Approximately 58.43 (287.48), 73.8 (227.06) and 59.5 % (296.16) of calcium was taken up by PN 386, NZ 1295 and *E. nitens*, respectively. The remaining percentage taken up by the SRF trees was supplemented by the calcium in the soil solution under the three SRF species.

The soil-NZ 1295 treatment system renovated 98.74% of the calcium supplied by the soil and 30 mm of effluent over two growing seasons. NZ 1295 renovated 227.06 kg ha^{-1} (1.35%) and 211.76 kg ha^{-1} (1.26%) of calcium which can be accounted to leaching, and the root uptake of K that was supplied by both the soil and the effluent after two growing seasons.

The amount of magnesium taken up by the SRF trees exceeded the amount of magnesium supplied by the effluent, even at the highest rate of irrigation. The application of 30 mm of effluent after two growing season supplemented 104 kg ha^{-1} of magnesium. Approximately 89.33, 55.61 and 66.40 % of the magnesium was taken up by PN 386 (116.42 kg ha^{-1}), NZ 1295 (187 kg ha^{-1}) and *E. nitens* (156.62 kg ha^{-1}), respectively. The soil supplemented 12.42, 83 and 52.62 kg ha^{-1} of Ca to PN 386, NZ 1295 and *E. Nitens* over two growing seasons.

The soil-NZ 1295 treatment system renovated 95.63% (1649.75 kg ha^{-1}) of the magnesium supplied by the soil and 30 mm of effluent over two growing seasons. NZ 1295 renovated 187 kg ha^{-1} (10.86%) and 75.38 kg ha^{-1} (4.37%) of magnesium which can be accounted to leaching, and root uptake of Mg that was supplied by both the soil and the effluent after two growing seasons.

The ability of the three selected SRF species to evapotranspire effluent was compared. The effects of the rate of effluent irrigation were measured using a heat pulse system technique (chapter 6).

The cumulative evapotranspiration rates of the 15 month old SRF trees irrigated at 30mm of dairy farm-pond effluent per fortnight over the two growing seasons were significantly higher than for trees irrigated with 15 mm or 7.5 mm of effluent. The NZ 1295 species had the highest average cumulative evapotranspiration rate of 6.38 mm day^{-1}, followed by PN 386 and *E. nitens* at the rates of 4.84 and 4.0 mm day^{-1}, respectively. The larger tree size of the NZ 1295 trees might have influenced the evapotranspiration of these SRF species although the leaf area was also a significant factor.

The cumulative evapotranspiration rate of the SRF trees that were irrigated with either the high or low rates of effluent reached peak levels during a cloud-free day of the monitoring period when global radiation, vapour pressure deficit and temperature were also at their peak.

Evapotranspiration of SRF irrigated with effluent was correlated with global radiation, vapour pressure deficit and temperature as measured at the plantation site during the monitoring period (R^2 = 0.79, 0.63 and 0.61, respectively). These climatic factors can be predictive values of evapotranspiration of 2 year old stands of SRF trees with the global radiation data being the best predictive factor.

The evapotranspiration rates of the three SRF species can be possible indicator of the desired irrigation level of effluent to the trees. The NZ 1295 treatment system when irrigated at 30 mm of effluent evapotranspired 1148.4 mm of moisture during the growing season which accommodated 72.36% of the total sum of water applied in the effluent and through.

The response and tolerance of the three selected SRF species to higher loading rates of effluent, were measured using a pot trial in greenhouse situation. Application of effluent up to 90 mm per fortnight increased the biomass production of potted PN 386 and *E. nitens*. The NZ 1295 produced optimum biomass at 60 mm of effluent application per fortnight. The glasshouse condition possibly influenced the positive response of *E. nitens* to higher loading rates of effluent compared to the field trial result. Rainfall, wind and temperature in the field trial possibly limited the *E. nitens* to produce more biomass at higher level of application than when grown in a glasshouse.

The amount of nutrients supplied to SRF seedlings through the application of effluent up to 90 mm per fortnight influenced the trees to uptake more nutrients in their biomass except for NZ 1295. When harvested, this would enable the removal and export of more nutrients from the disposal site.

Irrigation with dairy farm pond effluent can increase the total P, K and Mg levels and pH of the soil without detrimental effects as shown by the resulting soil pH at the highest application rates ranged from 6.31 to 7.11.

Establishing and monitoring a further field trial of SRF species with high rates (above 30 mm) of effluent irrigation is recommended to determine the dynamics of nutrients and sustainability of the treatment system at a higher volume of effluent disposal to land.

An evaluation of the use of different types of waste effluents such as sewage, tannery, piggery and industrial effluent to grow SRF species in a field trial is recommended to determine the most appropriate SRF-soil treatment system for each type of effluent, for any given soil and set of climatic conditions.

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