Nutrient Cycling in *Eucalyptus* Short Rotation Forests

Sustainable production linked with meatworks effluent land treatment

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ABSTRACT

Short rotation forests have the potential to provide a renewable energy source and thus reduce the demand for fossil fuels. They absorb CO_2 quickly during their rapid growth, which then is recycled during the energy conversion process. However, short rotation forests are highly nutrient-demanding, and cause great depletion of soil nutrients from the site after frequent harvests. Effluents, such as from meatworks, contain high levels of nutrients which could be irrigated on to land to aid crop productions in land treatment. In many instances, this is more acceptable than disposal to waterways. Application to short rotation forests is an ideal option as it may lead to a sustainable production system. The successful link between short rotation forests and effluent land treatment depends on good management based on knowledge of nutrient cycling in the system.

The objective of this study was to investigate the nutrient cycling in *Eucalyptus* short rotation forests linked with land treatment of meatworks effluent, through monitoring soil change, tree nutrient uptake, nutrient return via litter fall, and nutrient release via litter decomposition. A series of field experiments and one growth cabinet experiment were conducted from 1993 to 1997 at the Richmond Meat Processors & Packers Ltd. processing plant at Oringi, Dannevirke, and at Massey University, Palmerston North, New Zealand.

Application of meatworks effluent increased soil nutrient levels and enhanced tree biomass production. Compared with non-irrigated crops, biomass was increased by 17%, 25% and 80%, and nitrogen uptake by 15%, 64% and 77% among the three studied species (*E. botryoides*, *E. globulus* and *E. ovata*). *E. globulus* showed the best performance of the three species, whether without irrigation or irrigated with effluent. When *E. globulus* stands were irrigated with effluent, 90 oven dry t/ha of above ground total biomass was produced after 3 year growth with a total of 859 kg nitrogen uptake.

The amount of litter fall and nutrient return depended on the degree of biomass production and nutrient uptake in the stands. Up to 13.4 oven dry t/ha/y litter fall with up to 160 kg/ha/y of nitrogen was recorded. During the 3 year period, up to 20% of total above ground biomass produced fell as litter and up to 24% of total nitrogen uptake was returned to soil surface via litter. Litter decomposition and subsequent nutrient release from the litter were significantly influenced by internal factors (species, litter source, and the initial contents of cellulose, lignin and magnesium) and external factors (planting density, plantation age, effluent irrigation, water irrigation, temperature and light condition).

The concept of growing short rotation forest linked with effluent land treatment has good potential to provide both a sustainable renewable energy source and a sustainable effluent treatment system. If they are designed and managed rationally according to the nutrient cycling within the system, the environment will be protected. The system design and management include: species selection (on the basis of biomass production, nutrient uptake, litter characteristics), tree planting density, effluent irrigation, rotation length, time of harvest, and litter management.

Key words: nutrient cycling, short rotation forests, *Eucalyptus*, biomass production; effluent land treatment.

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1. GENERAL INTRODUCTION AND OBJECTIVES

It is no longer in dispute that global CO_2 levels, due to the activities of mankind, have increased during this century (Maclaren & Wakelin 1991). World-wide, carbon dioxide is the most significant greenhouse gas (Taylor & Lloyd 1992), which reputedly contributes about 40% to the "greenhouse" effect on the raising global temperatures (Hillis 1990). Its production is closely linked with economic activity through the burning of fossil fuels: coal or gas in power stations, factories or homes; or diesel and petrol in transport.

The atmospheric CO_2 level could be brought into balance by both reducing its emissions or increasing carbon sinks. For reducing the emissions, renewable energy, such as wind, solar, hydro and bioenergy, can be used to displace fossil fuels. Biomass must be regarded as one of the more promising options and considerable interest has been shown in the concept of short-rotation forestry (Neenan & Steinbeck 1979).

Natural and plantation forests are one of major carbon sinks. The rate of carbon absorption is closely related to tree growth rate. Short rotation forests can absorb CO_2 quickly due to their rapid growth characteristics and they have potential as a renewable source of energy. However, frequent harvesting of the trees can remove large quantities of nutrients from the soil, especially when harvesting all the above ground biomass which is usually the case when managing short rotation forest systems.

Much of the concern about the sustainability of short rotation forest systems focuses on the question of depletion of soil nutrients. This is heightened by the harvesting of whole-trees together with the short harvest cycles (Heilman 1992; Ericsson 1994). For sustainable land use, the nutrient loss must be remedied by fertilising. In addition, water stress is largely responsible for loss of forest tree productivity (Pereira & Pallardy 1989). Irrigation and fertilization are essential to high water and nutrient demand by vigorous young trees for high crop production in short rotation forests and to avoid site degradation for a long-term sustainable land use. Unfortunately, supplying them increases the input costs and hence the energy price from the biomass source.

Meat industry products are New Zealand's largest export income earner, accounting for around one dollar in every six earned overseas with $2,613 million in the June 1995 year (Anon. 1996a). Meat processing consumes energy and at same time generates large volumes of effluent. In the year ended March 1995, New Zealand's meat export industry consumed 4,620 TJ of energy (about 1.1% of total consumer energy) with 5.8 GJ per tonne of meat. It was estimated that 261,640 tonnes of CO_2 emission resulted from the energy production (Anon. 1996b).

The pollution problems of the meat industry are greater than those of the domestic sector since each of the major slaughterhouses in New Zealand contributes a pollution load equivalent to a city of 60,000 - 100,000 population (Cooper et al. 1979). Disposal of liquid effluent in relation to water quality, environmental pollution and public health is a cause of concern around the world. Industry and farm wastes (meatworks, milk products, dairy sheds, pig farms etc.) end up in waterways, pollute the environment and also oppose Maori cultural values on the waste disposal. The Resource Management Act (1991) has restricted the discharge of wastes into waterways in New Zealand. Land treatment has been reconsidered and gradually accepted by farmers and industries.

Effluent from meatworks contains high levels of nutrients which can replace commercial fertilizer and provide nutrients and water for crop production. Effluent land treatment could relieve the pressure of waste water disposal to the environment using waterways. Short rotation forest is an option in an effluent land treatment system as it has the advantages of high nutrient and water consumption. Many of the potential health problems associated with the recycling of effluents do not occur where trees are the crop being irrigated, as there is no risk of transmitting diseases to humans through a secondary animal host, nor is the crop consumed directly (Cromer 1980).

There is a common relationship between the concepts of land treatment of wastewater and silvicultural energy crop production (Sopper 1980). Fertilization and irrigation are required to maximize woody biomass production on an energy farm. By contrast, a prerequisite to a successful land treatment system is maximum uptake of nutrients by the vegetative cover. Thus, a combination of the two concepts provides for a beneficial cost-effective solution. On the other hand, harvesting short rotation forest trees removes nutrients more efficiently since young stands of trees take up nutrients to a greater degree than mature stands (Loehr et al. 1979b).

Quantifying rates of litterfall and nutrient return, and understanding the mechanism controlling the rates of litter decomposition and nutrient release, are essential for the informed management of both native forests and plantations (Attiwill et al. 1996). Therefore, nutrient cycling should be clearly understood for correctly managing short rotation forests either when linked with land treatment or not. The nutrient accumulation in the harvestable parts (i.e. the above ground biomass), nutrient return through litter fall, and nutrient release rate from the litter are all relevant. The nutrient balance can be controlled to give sustainable land use according to the objective of growing short rotation forests. Soil changes can influence land sustainable uses in land treatment systems. The changes will reflect physical and chemical characteristics, such as infiltration rate and nutrient accumulation in the soil profile.

Usually nutrient removal in a forest is considered non sustainable. The leaves and branches should be kept on site to return the nutrients to the soil for sustainable land use. However in land treatment systems, the nutrients should be removed as much as possible to give sustainable land use. The key factors in management of a land treatment system are how much nutrient can be taken up by the trees and removed by harvesting, and also how much and how quickly nutrients would be returned to soil via litter fall and released following litter decomposition. The present knowledge is insufficient to understand the above aspects to successfully manage a short rotation forest, especially when linked with effluent land treatment.

This thesis reports on a series of field experiments designed to examine the response of soil to tree planting and irrigation of meatworks effluent, biomass crop production, and nutrient cycling in *Eucalyptus* short rotation forests (Figure 1.1). The experiment reported in chapter 3 was a preliminary one for the whole study in this thesis, which used four existing treatment sites in the field. The environmental effects on soil changes, tree seedling growth and litter decomposition were also examined using growth cabinets.

The hypothesis was that when short rotation forests are irrigated with effluent in order to treat it and reduce the environmental impact from its disposal, nutrient removal from the site in harvested biomass and the leaf litter is essential to provide a sustainable system in the long term. To test this hypothesis the specific objectives of the study were:

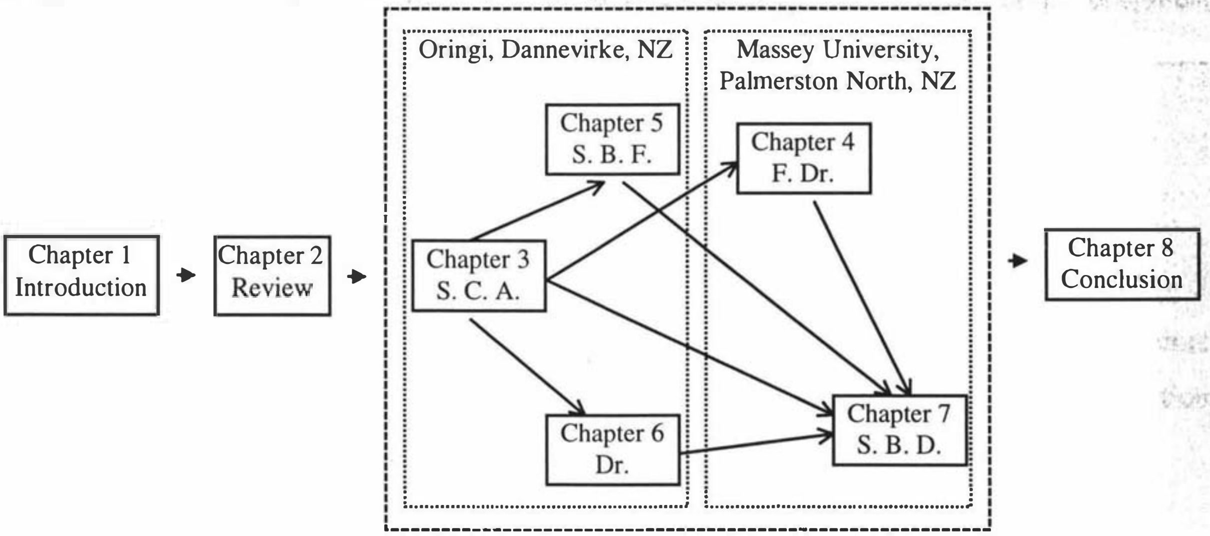

Figure 1.1 An outline of the structure in this thesis (all experiments were conducted in the field, except for the one in chapter 7 which was in growth cabinets; arrows indicate the relationships between chapters; A: litter accumulation; B: biomass production and nutrient uptake; C: nutrient concentration in plant parts; D: litter decomposition; Dr: litter decomposition and nutrient release; F: litter fall and nutrient return; S: soil).

1. to determine the effects of meatworks effluent applied to either pasture or eucalypt short rotation forests including the soil response to land use change and effluent irrigation, and the resultant response of pasture plants and trees;

2. to quantify biomass production of three selected eucalypt species for energy purposes, nutrient uptake by trees, and the distribution of biomass and nutrients in tree above ground components (i.e. leaves, branches, bark, wood);

3. to investigate nutrient return via litter fall under eucalypt short rotation forests;

4. to assess leaf litter decomposition and nutrient release rates varying with internal factors (species and the source of the litter investigated) and external factors (tree population density, plantation age, and effluent irrigation);

5. to compare environmental factors (temperature, water or effluent irrigation, and irrigation rate) on the soil changes and seedling growth, and environmental factors (light, temperature, water or effluent irrigation, and irrigation rate) on litter decomposition using growth cabinets; and,

6. to provide recommendations for designing and managing sustainable short rotation energy forests.

2. REVIEW OF LITERATURE

2.1 INTRODUCTION

Short rotation forestry systems are being developed for three principal reasons: as a means of producing a feedstock for energy and industry; as an alternative use for the land taken out of agricultural production; as a means to sequester carbon dioxide and hence relieve pressure on the accumulation of atmospheric greenhouse gases (Mitchell & Ford-Robertson 1992). Short rotation forestry is a version of the energy plantation using woody perennial tree crops, the idea being that forest plantations are grown for their energy content rather than for their fibre content value (White & Plaskett 1981). The available evidence suggests that short rotation coppice is the most economical way to produce energy from agricultural land (Hummel 1989). Burning of biomass fuels adds much less sulphur dioxide and nitric oxide to the atmosphere per unit of energy produced than the uncontrolled burning of coal and thus requires fewer pollution controls (Miller 1990). Therefore, production of energy forests to substitute for fossil fuels is more effective in the long term than carbon storage in either forests or forest products as these will eventually saturate with time.

Poor nutrient availability is often the major reason for plants not achieving their potential growth capacity (Mitchell & Ford-Robertson 1992). Intensive cropping of whole trees leads to depletion of soil nutrient reserves and a short rotation system is therefore really ‘tree farming’ and soil fertility problems resolve around the old classical agricultural problems of N, P, and K (White 1974). The shorter the rotation the greater will be the nutrient removal on an annual basis because maximum nutrient accumulation occurs during the early stages of stand development (Jorgensen et al. 1975). The concept of sustainable production generally connotes the absence of longer site degradation, with nutrient depletion being an important component of degradation (Wang et al. 1991). Thus, in a short-rotation, high-yield plantation system where nutrients removed in repeated harvests exceed natural rates of nutrient inputs, nutrient-use efficiency becomes an important concept.

The application of recycled waste water on to forests, especially plantation forests, is an attractive proposition because health considerations are not as demanding as those applying to a food crop (Smith & Evans 1977; Chakrabarti & Nashikkar 1994). The treatment of effluent need not include disinfection and treatment can be limited to primary treatment by sedimentation though secondary treatments are often practised. In addition, well-planned and managed projects in which trees are irrigated with recycled water can have important social, aesthetic and environmental benefits (Stewart et al. 1986). Short rotation forests are suitable vegetation filters with regard to removal of nutrient from municipal sewage sludge and wastewater. The benefit is three-fold (Perttu 1993):

i) purification of waste using natural circulation;
ii) production of biomass for energy purposes; and
iii) reduction of air pollution when burning wood instead of fossil fuels

This chapter reviews the information on soil responses to planting trees into agricultural land and effluent irrigation, forest biomass production, particularly the nutrient cycling (nutrient uptake via tree growth, return via litter fall, and release via litter decomposition) in forests, especially linked with effluent land treatment, and with a focus on eucalypt forests. Common study methods of biomass production, and nutrient cycling are described and discussed.

2.2 EFFLUENT LAND TREATMENT

The agricultural industry is a major waste producer in New Zealand (Vanderholm 1984). The pollution problems of the meat industry alone for example are greater than those of the domestic sector (Cooper et al. 1979). The organic constituents of effluent from a slaughter house come from four major sources: i) paunch contents; ii) faecal material; iii) suspended solids and fat; iv) blood and other soluble materials (Copper et al. 1979). Hence, the considerable volumes of organic effluent contain relatively high levels of nutrients, particularly nitrogen and phosphorus.

Disposal of liquid effluent in relation to water quality, environmental pollution and public health is a cause of concern around the world. Industry and farm wastes (meatworks, milk products, dairy sheds, pig farms etc.) often end up in waterways polluting the environment. In addition, Maori cultural values do not condone waste disposal into waterways in New Zealand. To the

Maori, water is the essential ingredient of life - a priceless treasure left by ancestors for the life-sustaining use of their descendants. Hence, water and associated resources confirm life to man, and thereby form a basis for his identification, his belonging, his mana (Taylor & Patrick 1987). Maori people regard rivers as a foodbowl, so to use it for sewage disposal is an affront (Patrick 1987). Therefore, land application of sewage is being adopted in order to meet Maori cultural values which require human waste to be returned to the land rather than be allowed to pollute natural water resources (Cameron et al. 1997).

The primary objective is to treat the wastes though side benefits may be realized, such as increased production of harvestable crops or recharge of ground water. The major function of the soil is to dissipate the wastes, to recycle them through the crops, or to purify them through filtering and adsorption (Witty & Flach 1977). Irrigation on to land transfers the environmental disbenefits of effluent discharge of surface waters to the soil, plants and groundwater. The groundwater and any crops grown must be safe for subsequent use (Russell et al. 1988).

In New Zealand land systems to treat effluent from meatworks, dairy farms, and milk processing plants have traditionally been irrigated on to pasture. However, grazing animals have several effects on the operation of an irrigation scheme (Russell et al. 1988):

i) pugging the soil to slow infiltration and create channels in the irrigation area;
ii) animals, particularly cattle, destroying earthworks, especially borders in border dyke systems; and
iii) recycling approximately 90% of the nitrogen they consume back to the pasture.

Marecos do Monte et al. (1989) reported that the nitrogen content of municipal wastewater could replace the nitrogen from commercial fertilizers and without significant crop composition changes being noticed. However, accumulation of some trace elements in plant tissue may cause an increase in their level in the food chain. Resultant phytotoxicity is an important barrier to the use of trace element-enriched plant material for food (Feigin et al. 1991).

For examples, meatworks effluent irrigation raised the ryegrass plant levels of N and K; there was little change in P and Ca; but it lowered levels of B, Mn, and Sr (Wells & Whitton 1970). The irrigation of ryegrass pasture with meatworks effluent stimulated growth by supplying water and nutrients, increased N, P, and Na contents, decreased K and Ca, but there were no effects on

Mg. And nitrate-nitrogen levels in the pasture were elevated by the irrigation, which may cause nitrite toxicity problems to animal, but the other elements in the herbage should not (Russell et al. 1988).

2.3 SHORT ROTATION FORESTS

Some of the increasing plantation areas of fast growing trees are being established for their social value. This is dependant on the interactions between environmental improvement (erosion control, shelter *etc.*), growth rate and total value of the products (firewood, cash crops *etc.*) (Hillis 1990). Recently, interests have also arisen on linking effluent land treatment with short rotation forest production.

A key to maximum biomass production is rapid establishment and early utilization of the total growing capacity of the site. Short-rotation energy plantations are usually grown at close spacings to give high tree densities. Annual biomass production will be greatly influenced by rainfall and therefore irrigation may be required to ensure maximum production. In addition, after some time, the accelerated harvesting of the short-rotation plantations may deplete the site of plant nutrients and require fertilization to maintain maximum production. The need to both irrigate and fertilize might increase forest production costs considerably.

The three major factors required for plant growth are sunlight, water, and nutrients (Jorgensen et al. 1975). The last two factors can be manipulated through irrigation and fertilization to optimise crop production. Sometimes, they are combined as fertigation, providing nutrients through the irrigation system. A possible economic solution to these two requirements (irrigation and fertilization) and to maximize biomass production might be to utilize effluent. Wastes are now looked upon as a resource since some wastewaters provide good quality irrigation water and has an appreciable concentration of nutrients, such as nitrogen, phosphorus, potassium and organic matter (Chakrabarti & Nashikkar 1994) without high levels of heavy metals or toxins.

Generally speaking, effluent irrigation is more likely to increase growth in young trees, either plantation or natural forests, than in larger trees. Since growth rate is a major determinant of nutrient uptake and assimilation, young trees will contribute more than old trees to the treatment (Cooley 1982) as young stands of trees take up nutrients to a greater degree than mature stands (Loehr et al. 1979b). There was a consistent downward trend in nitrogen concentration with age in all tree components (Cromer & Williams 1982). Hence, high nitrogen wastewater should not be applied to forests with little or no net accumulation of biomass, such as predominantly evenly-aged stands of mature trees (Brockway et al. 1982) because the irrigation in older forests resulted in excessive leaching of nitrate to groundwater (Burton 1982).

However, uptake in very young plantations of any species is low because they do not fully occupy the site (Brockway et al. 1982). The maximum nutrient accumulation occurs about the time and shortly after the stand closes and fully occupies a site because nutrient demands on the soil are high while the tree crown is expanding. Once full canopy closure is achieved, about two-thirds of the nutrient requirement for one annual flush of foliage may be met by nutrients recovered from old foliage before it is discarded (Jorgensen et al. 1975; Miller 1989). Hence, the demands made by forest on the soil nutrient capital fall markedly after canopy closure (Miller 1986).

Therefore, the canopy closure in forests is the key for the maximum nutrient accumulation, and it is affected by tree planting density and tree age. The site can be quickly and fully occupied under the high tree density. The trees should be harvested soon after the canopy closure for their nutrient demands fall markedly thereafter. Hence, short rotation forest should be one of good choices in effluent land treatment due to their high tree density and the short rotation.

2.4 SPECIES SELECTION

There are many highly productive tree species in the world, such as *Populus*, *Salix*, *Robinia*, *Acacia*, and *Eucalyptus*. For an energy crop aim is to optimise heating value (MJ/ha/y), which depends partly on energy content, but also on biomass yield. The differences in biomass yields and ecological tolerances are more important in species selection than in any variation in their heating values (Neenan & Steinbeck 1979).

Gambles & Zsuffa (1988) listed the characteristics desired in species to be used in short rotation forestry. These included rapid juvenile growth; ease of reproduction and plantation establishment; and efficient use of water and nutrients which was evaluated in tonnes of dry matter produced per unit of water and nutrients provided. Conversely, when linked with effluent land treatment, the efficient consumption of water and nutrients should be considered as one of the key characteristics.

The considerable advantage of coppice management is that subsequent rotations do not involve site preparation or replanting operations (Nicholas 1993, cited in EECA 1996). Field trials of various species, planting densities, time of harvest and rotation length have established that *Eucalyptus*, *Salix* and *Acacia* are suitable species for energy plantations in New Zealand because of their fast early growth, coppicing ability and high wood density (Miller 1993, cited in EECA 1996).

In theory, a “better” species should achieve high yields, remove more or less nutrients at each harvest to maintain optimum ecosystem nutritional equilibrium, and be a better choice for specific site management, to meet grower objectives (Wang et al. 1991).

In normal short rotation forests, deciduous trees, such as *Salix*, can conserve nutrients on-site if they are harvested after the leaves have fallen and returned to the soil, and significant amounts of leaf, branch and stem nutrient components have been translocated to the root systems for winter storage (White et al. 1996). If the objective of growing the plantation is to remove nitrogen or some other nutrients from the soil, the selection criterion should be high dry matter productivity, but not rate of nutrient uptake because the large amount of N uptake was due to their very high production other than their ability to take up nitrogen (George et al. 1986). In addition, deciduous trees are less suitable than evergreen trees for they have a dormant period each year.

Total energy content of the hardwoods (*A. dealbata* and *E. regnans)* was about 50% more than that of *Pinus radiata* in 8 years old plantation. *Acacia spp.*, such as *A. dealbata*, are fast-growing evergreen trees with early fast growth, excellent for pulping, and fixing atmospheric nitrogen (Frederick et al. 1985a). They have good potential in short rotation forests. However they would be limited in a land treatment system due to their nitrogen fixation. Martin & Focht (1977) indicated that the amount of N fixed by a nodulated legume crop will vary from about 60 to 600 kg/ha/y. If inorganic N is present, the plants will utilize the soil supply and the amount of gaseous nitrogen fixed will be reduced. Even with such a reduction of nitrogen fixing, *Acacia spp*. are not recommended in a land treatment system in order to avoid any extra nitrogen input.

Furthermore, nitrogen fixation is an energy-expensive process, requiring about 18.8 g carbon/g N fixed (Gutschick 1978), which reduces the net biomass produced by photosynthesis.

In temperate regions interest centres on species or cultivars of *Salix*, *Populus* and *Alnus* but in more favoured climates *Eucalyptus* species are likely to be preferred in short rotation forests (Miller 1989). Eucalypts with other fast growing young trees remove more carbon dioxide from the atmosphere each year than does a mature forest (Hillis 1990). They are prime candidates for woody biomass plantations because of their rapid growth rate, which can yield as much as 40 oven dry (OD) t/ha/y on wide range of sites (Sachs et al. 1980).

Serious problems have been attributed to *Eucalyptus* plantations: they have a reputation for excessive site nutrient depletion and for a substantial reduction of total water yields, especially when planted in semi-arid water area (Madeira 1989). At Karnataka in India farmers have been blaming eucalyptus for falling water tables, and decreasing soil fertility. While the pine tree consumes 760 mm of water a year, eucalyptus consumes 1200 mm (Wright 1990). The cumulative water uptake by the *Eucalyptus* trees was 1882 mm during a ten month period (Zohar & Schiler 1998).

On the other hand, in most places where they are planted the eucalypt growth is limited by available water (White et al. 1994). Irrigation on to young *E. globulus* resulted in a 3.3-fold increase of biomass production and a 2.3-fold increase in leaf area index. The leaves in the irrigated plants had a greater surface area per unit of biomass than those of the non-irrigated plants (Borralho et al. 1989). Hence, eucalypt trees have a good potential in land treatment systems due to their high water and nutrient demand.

Eucalyptus grew faster than virtually all native tree species in peninsular Florida, giving thema considerable advantage for nutrient accumulation and water use in remediation systems (Rockwood et al. 1996). Some eucalypts are preferred for short rotation forests irrigated with waste water in New Zealand because they have the characteristics of fast growing (consuming more nutrients and water); whole year round growth; coppicing ability, and evergreen, which is ideal for harvesting whole above ground biomass to strip nutrients from a land treatment site.

There exist significant variations in eucalypts for different purposes in plantation forests as there are more than 500 species in this genus (Boland et al. 1992). The species of the *Symphomyrtus* subgenus (e.g. *E. botryoides*, *E. globulus*, *E. nitens*, and *E. ovata*) are usually the choice due to the early investment in leaf area, and thus maximum light interception, which leads to a more rapid increase in canopy photosynthesis than with the *Monocalyptus* (Hillis 1990).

E. botryoides showed promise under sewage irrigation in northern Victoria (Turnbull & Pryor 1978) and is one of the preferred species for planting in the land treatment of effluent for it can tolerate clay soils and where soils are moist (Knight & Nicholas 1996).

E. globulus was the most extensively planted eucalypt in the world (FAO 1979). It is a promising tree species of cool humid region of Victoria and Tasmania in Australia and is known for its remarkable adaptability and performance (Negi & Sharma 1984). Despite its poor performance from early plantings in New Zealand, it warrants re-evaluation following the control of the foliage-damaging beetle *Paropsis charybdis* (Knight & Nicholas 1996).

Tree planting may have effects on sustainable land use as it will change soil properties and deplete nutrients from site through continued harvesting. Therefore, good knowledge about soil change and nutrient cycling in the system is important to plantation management.

2.5 SOIL RESPONSE

Sustainable land use is of concern, in relation to soil properties, such as soil physical and chemical changes. Any degradation, e.g. reducing crop production, will not be sustainable.

2.5.1 Soil physical change

When effluent is applied, the soil permeability influences the length of time liquid wastes remain in the soil and potential loading rates. If permeability is high, liquid wastes and soluble components are not adequately dissipated, especially during periods of high rainfall. On the other hand, if permeability is low permissible application rates could be too low to be practical, or anaerobic conditions would be induced (Witty & Flach 1977).

Cook & Thorne (1990) found that the infiltration rate dropped by 50% from 7200 mm/day to 3550 mm/day after three years of effluent application. Not only were the large pores affected, as indicated by the substantial change in infiltration rate, but there may have been changes in the pore structure over a large range of pore sizes.

Mathan (1994) found the physical properties of sandy loam soils were improved by using sewage irrigation water and continuous use of progressively improved the hydraulic conductivity, bulk density and porosity. The longer the period of irrigation, the lower the soil bulk density value, and the influence could be up to 600 mm depth after 15 years. Tipler et al. (1996) reported a similar finding that soil bulk densities fell by approximately 20% from 0.984 to 0.867 g/cm^3 after ten years of meatworks effluent irrigation. After irrigation of sewage water for 70 years, the soil texture changed from sandy to loamy-sand, soil organic matter and clay minerals increased, giving greater cation exchange capacity and improved structure (Abd Elnaim et al. 1987).

Comparing with natural *Quercus suber* forests, *E. globulus* planting reduced water infiltration rate from 10 mm/min to 1.7 and 3.3 mm/min (Madeira 1989). This could be affected by the increase of soil bulk density. It may also have some relationship with soil organic matter as the matter in the soil is the prime agent for maintaining the infiltration rate (Loehr et al. 1979a).

Overall, the soil change is affected by effluent irrigation, and also by the land use change (e.g. planting trees into pasture) and different crops.

2.5.2 Soil chemical change

Soil pH

A side effect of the application of sewage effluents to soil is the production of acid in the nitrification reactions (Gilmour et al. 1977):

$$\mathrm{NH_4^+ + 2\,O_2 \rightarrow NO_3^- + H_2O + 2\,H^+}$$

$$\text{Organic N} \rightarrow \mathrm{NH_3};\quad \mathrm{NH_3 + 2O_2 \rightarrow NO_3 + H_2O + H^+}.$$

Waly et al. (1987) found that the pH value of the surface layer decreased gradually in soil treated with sewage water, but this tendency was less pronounced in the lowest layers. This fall could be attributed to the production of CO_2 and organic acids by soil micro-organisms.

Irrigation with meatworks effluent on to pasture decreased the soil pH, which may be due to the higher ammonium ion concentration of this effluent displacing cations from the soil and the oxidation of ammonia to nitrate (Russell et al. 1988). However, irrigation of pasture with organic-rich effluents from meatworks for 15 years had little change in soil pH (Wells & Whitton 1970). Soil pH increased in a plantation of two tree species (*P. radiata* and *E. grandis*) irrigated with secondary-treated effluent sewage effluent after two and four irrigation seasons (Falkiner & Smith 1997). Therefore, variations on pH change exist following effluent irrigation.

On the other hand, tree planting of different species and nitrogen fertilization also affect the soil pH. For example, in 8 year old plantations, the pH of the mineral soil (0-200 mm) was lowest (5.2) under *E. regnans*, highest (6.0) under *P. radiata* and medium (5.5) under *A. dealbata* (Frederick et al. 1985a). Soil pH decreased linearly with increasing urea application (Belton & Goh 1992).

Soil pH reduction could be harmful to a lot of crops in the long-term. For example, *Salix* roots do not grow in low pH soils (Ericsson & Lindsjo 1981, cited in Elowson & Rytter 1986). However, some species have tolerance to soil pH reduction. For example, grey alder (*Alnus incana*) was less sensitive to soil pH values below 5 (Elowson & Rytter 1986). Therefore, species selection is important to the site with the potential pH reduction following land use change, effluent irrigation and fertilization.

Soil nutrients

Fast growing trees consume soil nutrients quickly. For example, the total quantity of nutrients in the soil decreased from 7165.7 kg N/ha, 301.4 kg P/ha, and 5330.3 kg K/ha in a 2-year-old plantation to 7091.8 kg N/ha, 226.5 kg P/ha and 4401.1 kg K/ha in an 8-year-old plantation (Bargali et al. 1992b).

Effluent irrigation can improve the nutrient level in the soil. In effluent land treatment systems, nutrients (e.g. N) in the effluent become part of the soil nutrient cycle as soon as they reach the soil (Feigin et al. 1991). Irrigation of pasture with organic-rich effluents from meatworks for 15 years raised nitrogen levels and increased base saturation of the topsoils (Wells & Whitton 1970). Surface irrigation of pasture with meatworks-fellmongery wastes increased the nutrient status of the soil to the point where most of the applied nutrients, with the exception of phosphorus, were lost in drainage water and eventually reach the saturated zone (Keeley & Quin 1979). Ten year meatworks effluent irrigation raised soil organic matter content by 40% (from 4.9 to 6.75), Olson P by 120% (from 17 to 37 ppm) and the nutrient holding capacity by 15% (from 16.6 to 19) (Tipler et al. 1996).

The changes in the soils receiving effluent were attributed to nutrient input rather than to additional water loading (Schipper et al. 1996). Total and soluble nitrogen, as well as available phosphorus in the soil, increased with prolonged application of sewage water. The greatest accumulation was in upper layers of the soil (Waly et al. 1987). The top soil is the key layer responding to land use change and effluent irrigation, especially in short term. On the other hand, fine roots are concentrated in the litter layer and surface soil in forests (Attiwill & Adams 1993) for consuming nutrients and water.

In summary, soil chemical changes can be caused by effluent irrigation, different crops, and various managements. The top soil is more obvious to reflect whether the soil changes are sustainable to land use or not.

2.6 FOREST BIOMASS PRODUCTION AND NUTRIENT CYCLING

Biomass refers to the total quantity of organic matter present in the ecosystem at a stated time and may relate to particular organisms or groups of organisms (Ovington 1962). Newbould (1967) considered biomass to be the total amount of living matter present at a given moment in a biological system (in this case the photosynthetic plants making up the woodland stand) and it is taken to include heartwood and bark (which may no longer be alive). Kerruish & Rawlins (1991) defined biomass as the weight of living organisms on a site. Hence, these above definitions are more like a total living biomass.

Miller (1990) indicated that biomass is organic plant matter produced by solar energy through photosynthesis. Hence, biomass can be defined as any recent organic matter, originally derived from plants as a result of the photosynthetic conversion process, which is destined to be utilised as a store of chemical energy (EECA 1996). The annual litter production should be added to biomass value to give the annual net production (Toky & Ramakrishnan 1983a). Therefore, biomass in a forest system should be defined as all organic matter recently produced via photosynthesis, including the living parts and dead parts, such as trees (living parts and the parts which may no longer alive) and litter on the forest floor (dead parts). Hence, the total biomass production is the biomass accumulation and the total litter fall in the stands throughout the whole rotation.

The forest nutrient cycle has three segments: an input, an intracycle or system within which nutrient movement takes place, and an output (Jorgensen et al. 1975). The general model of nutrient cycling in forests embraces the following (Attiwill & Adams 1993):

i) Inputs to, and outputs from, the forest. Nutrients come into the ecosystem in rain and dust and by biological fixation, and go out in stream-water and in gaseous forms (denitrification or volatilization by fire). The weathering of parent rocks releases nutrients in more available forms.

ii) Transfer of nutrients between plant and soil, including uptake and return to soil by leaching, in litter and root turnover, and by death of individuals.

iii) Internal redistribution of mobile nutrients such as nitrogen and phosphorus.

In managed forests, especially plantation forests, the input also includes the nutrient addition from fertilization or from waste disposal in land treatment systems.

Nutrients taken up by trees can be divided into permanent storage (wood and coarse roots) and labile storage (foliage, bark, branches, fine roots). The labile storage pool contributes significantly to the cycling of nutrients. In above ground biomass, the most concern was given to nutrient cycling by litter fall which includes leaves mainly, and then other components (i.e. twigs, branches, bark and production parts) increased with tree age.

The values of nutrient uptake are obtained by adding the amounts of nutrients retained in the annual increment of biomass to the amounts returned through litter fall and canopy wash (Negi & Sharma 1996). Hence, the total nutrient uptake includes its accumulation, return via litter fall and other outputs, such as throughfall (leaching from tree crown), stemflow (leaching from bole), consumption by herbivores *etc*. In forest studies, the first two parts (accumulation + return via litter fall) are mainly concentrated as the other outputs are usually beyond the control of management, even though it may lead to an underestimation of the total uptake.

2.6.1 Biomass and nutrient accumulation

Biomass and its distribution in tree components

In a 10 year old *E. globulus* plantation, the total above-ground biomass amounted to 77 OD t/ha of which 66% was contributed by wood, and the remainder by branches, bark, leaves and twigs (George & Varghese 1990a). Above ground biomass produced for six *Eucalyptus* species (*E. grandis*, *E. laevopinea, E. maculata*, *E. saligna*, *E. sieberi*, and *E. viminalis*) grown on rotations of ten years ranged from 110 to 162 OD t/ha (Wise & Pitman 1981).

From their study on very short rotation (2 years) and dense (10,000 and 20,000 plants/ha) *E. camaldulensis* plantations for energy, Dalianis et al. (1996) reported that dry matter yields, averaged across all treatments, were 25.6 OD t/ha/y at first rotation harvest, 24.2 OD t/ha/y at second and 35.2 OD t/ha/y at third rotations. The stem percentages of total biomass increased from the first to the third rotation.

In a similar study, the total dry biomass produced in two years was 16.0, 21.2, 18.8 OD t/ha/y for *E. globulus* and 19.6, 20.1, 22.2 OD t/ha/y for *E. camaldulensis*, at 20,000, 30,000 and 40,000 densities, respectively (Pereira et al. 1996).

Nutrient uptake and nutrient removal

Trees in a forest take up nutrients from the soil to support their growth. At same time, they return nutrients via litter fall. Kreutzer (1990) indicated that the yearly uptake of nitrogen by forest stands ranged between 30 and 90 kg/ha/y and about 10% were stored in the growing biomass, and the rest returned to the soil mainly by litter fall. The balance between nutrient uptake and return in the forest depends on the growth rate, which relates to the site, species, tree age, tree density *etc*. The annual uptake may be equal to the annual return in a mature forest or could be even higher than the return in an over-mature forest.

Judd et al. (1996) concluded that while nutrients tend to be more concentrated in foliage than in other components, their contribution to the total nutrient pool is comparatively small since foliage represents only a small percentage of total tree biomass, and decreases with age to about 2% in mature forests. Foliage in the tree is the component with the most nutrient concentration. In most trees, leaves are usually the shortest life components in the above ground biomass. The nutrients in leaves will be returned to the soil via leaf fall unless they are retranslocated before leaf abscission. Therefore, nutrient net uptake (uptake - return) in mature natural forests is in balance and should be relatively lower than in plantation forests, especially in young, fast growing forests.

When trees are harvested, nutrients in the harvestable above ground biomass will be removed from the site. Much of the concern about the sustainability of short rotation forests focuses on the question of depletion of soil nutrients which is heightened by the whole-tree harvests together with the short harvest cycles used. Options are available to reduce nutrient losses, including harvest during the dormant season when leaves are absent returning unwanted branches and bark to the soil, and planting species and clones that are most efficient in using nutrients for production (Heilman 1992).

The choice of when and what to harvest can result in large differences in nutrients removed from the site. As trees grow larger, the bark, the leaf and small branch fractions of the total biomass generally decline with tree size. Thus the size of the tree at harvest also influences the nutrient 'cost' of biomass, with the result that shorter rotations with small diameter size cuts have a higher nutrient 'cost' than do longer rotations. The role of size in determining nutrient-use efficiency suggests that the use of coppice or 'wood grass' harvest schemes, would be very 'expensive' from a nutrient perspective (Wang et al. 1991).

Smaller amounts of nutrients would normally be removed since the nutrient-rich upper parts of tree trunks and the bark are frequently left within the ecosystem and some tree boles are not harvested, and the total weight of elements removed in the forest crop is relatively small compared with that of agricultural crops. However, the long term loss from woodlands by harvesting is considerable (Ovington 1962). On average, 3.6 times more N and 4.6 times more P would be removed in a whole tree than in a traditional stem harvest of evergreen plantations, while 2.3 times more N and 2.2 times more P would be removed in a whole tree than in a traditional harvest of deciduous plantations (Son & Gower 1992).

The importance of the nutrient cycle within the plant is not unique to trees, but is perhaps most evident in tree crops because of both their longevity and the amount of nutrient that can be stored. A consequence is that when trees are small less nutrient can be stored against possible reuse. Retaining leaves for more than a year means that a greater mass of nutrients has to be accumulated by the tree, which is the normal case in broad-leaf evergreen trees. The evergreen habit can be regarded as a nutritional disadvantage during the early part of the rotation while the tree crown is being constructed, which should be an advantage for nutrient uptake in land treatment systems. Once the canopy is fully formed, however, evergreen species will have a considerably greater store of available nutrients than deciduous species. At this stage leaf longevity might provide a nutritional advantage (Miller 1986) and it could be a disadvantage in land treatment systems. The rotation length can be adjusted between these advantages and disadvantage according the objectives of growing plantations.

Rotation length is a major consideration in maintaining productivity of a site under whole-tree harvesting as a consequence of intensifying the harvest to include branches and foliage and hence the greater the demand for nutrients from the soil. When harvesting trees under shorter rotations, more juvenile wood and bark with its higher nutrient concentration is extracted from the site. When only the stem is removed, even short rotations have little effect on the nutritional status of the site. By defoliating trees before harvesting during the growing season, or by harvesting after foliage has fallen, nutrient removal can be reduced considerably (Gambles & Zsuffa 1988). By leaving the bark and leaves in the field of a 10 year old *E. globulus* plantation, the nutrients' loss was reduced by 27% for N, 20% for P and 23% for K whereas the reduction in the harvested biomass would be only 5 to 11% (George & Varghese 1991).

Apart from nutrient losses associated with actual wood removal, forest harvesting can also increase losses from volatilization, leaching and erosion. Harvesting allows additional light, heat and moisture to reach the forest floor and consequently decomposition activity is usually increased. These conditions accelerate losses of nitrogen by denitrification. More frequent harvests, which are involved in managing forests, intensively will increase nutrient losses caused by such mechanisms (Gambles & Zsuffa 1988). After a harvest disturbance nitrate leaching should be less from infertile sites than from more fertile ones, although the response time may be the same (Dyck et al. 1983).

For an equivalent site, the consequences of short rotation forests compared with traditional forests will be a quicker desaturation of the soil, if the output is not compensated by fertilization, followed by a destabilisation of the ecosystem function and establishment of a new equilibrium with a lower level of biomass production (Nys & Ranger 1990).

Fertilization

If large quantities of nutrients are removed, in any manner whatsoever, they must be replaced if vegetation is to grow at an acceptable rate (Jorgensen et al. 1975). Fertilization is one of the main ways to increase crop production, the main fertiliser elements being phosphorus and nitrogen for plantations of exotic tree species in New Zealand (Ballard 1978; Will 1985).

Cromer et al. (1975) found that the total above ground biomass of *E. globulus* (2196 stems/ha) ranged from 1 OD t/ha without fertilizer to 8.6 OD t/ha following the heaviest application rate (nitrogen 202 kg/ha, phosphorus 90 kg/ha) at age 2 and 6.3 OD t/ha to 30.3 OD t/ha at age 4. The nitrogen and phosphorus removed from the soil and held in the various above ground biomass ranged from 10.1 kg N/ha and 0.53 kg P/ha in untreated plots to 53.1 kg N/ha and 4.87 kg P/ha with the heaviest application rate at age 2 and 26.3 kg N/ha and 1.6 kg P/ha to 92.1 kg N/ha and 9.26 kg P/ha at age 4.

In *E. globulus* plantations, Cromer & Williams (1982) reported that it took 9.5 years for the unfertilized trees to reach a leaf biomass equal to that achieved by the heavily fertilized trees at 3 years of age (a difference of 6.5 years).

2.6.1.1 Methods of mensuration of biomass yield and nutrient accumulation

Comparing seven methods of above-ground weight estimation (the basal area ratio method, unweighted regression of weight on tree diameter squared, and 5 methods based on logarithmic regressions), the basal area ratio method gave the closest estimates to the measured plot weights and had the added advantage of being the simplest to apply (Madgwick 1983).

The mean tree method is commonly used for destructive sampling for the tree of mean basal area seems to be the best for even-aged stands of a single species (Carron 1968; Cromer et al. 1975; Parde 1980). The mean trees are usually selected according to mean diameter, height, and crown width. The biomass production is determined using the formulae as follow (Madgwick 1976; Frederick et al. 1985a, 1985b):

$$\text{Biomass of stand (OD t / ha)} = \frac{\sum \text{sample tree biomass (OD t)} \times \text{stand basal area (m}^2\text{ / ha)}}{\sum \text{sample tree basal area (m}^2\text{)}}$$

Tissue nutrient concentration is assessed by nutrient analysis of ground tissue sub-samples. The distribution of nutrients (kg/ha) in the stands is calculated by multiplying the nutrient percentage of different tree components by their respective biomass (Wise & Pitman 1981; Negi & Sharma 1984). Each nutrient accumulated in every tree component in the stands is estimated as follows:

$$\text{Nutrient (kg / ha)} = \text{nutrient concentration (\%)} \times \text{biomass (OD t / ha)} \times 1000$$

Nutrient accumulation by trees is estimated from the tissue nutrient concentration and biomass production as follows:

$$\text{Nutrient accumulation in the stand (kg / ha)} = \sum \text{nutrient in tree parts in the stand}$$

2.6.2 Litter fall and nutrient return

During establishment and growth of the vegetation, litter production equals net primary production minus increment of dry matter (Wild 1993). Litter fall is the primary mechanism for transfer of plant detritus from above-ground parts of forest ecosystems to the soil surface (Bray & Gorham 1964; Attiwill et al. 1978; Cuenca et al. 1983). Litter plays a major role in the transfer of energy and nutrients in woodland ecosystems and data on litter fall have been used to predict the productivity of ecosystems (Baker et al. 1990; Toky & Singh 1993).

Perman (1988) found that the energy (*Salix*) forest took up nitrogen much more effectively than corn. However, Sopper & Kardos (1973) commented that trees were not as efficient renovating agents as agronomic crops, whereas harvesting a corn silage crop removes 145% of the nitrogen applied in the sewage effluent, but harvesting trees only remove 39% most of which is returned to the soil by leaf fall.

Quantifying rates of litter fall and nutrient return, and understanding the mechanism controlling the rates of litter decompositionand nutrient release, are essential for the informed management of both native and plantation forests (Attiwill et al. 1996).

Many workers have attempted to quantify the rate of litter fall and decomposition as an important pathway for the transfer of litter mass and minerals to the soil surface in forest ecosystems. Intensive studies have been carried out in many parts of the world (Sharma & Ambasht 1987).

Litter fall

The eucalypt is normally an evergreen tree and because of this it is easy to obtain an impression that the leaves have a long life. In actual fact the average life of the leaves is short for an evergreen tree. Some leaves last for only a few months, whilst others may persist for four years or even longer in eucalypts (Penfold & Willis 1961). In a number of tests carried out on eucalypt species, the average leaf-life of forest trees was found to be less than eighteen months (Jacobs 1955). In addition leaves fall from rapidly growing crowns more quickly than from slow growing ones if other conditions are equal.

The age of the trees is important to litter fall only in very young stands, the amount of litter increases with increasing age, until the canopy becomes closed, and then the annual litter fall tends to remain fairly constant over a long period of time (Bray & Gorham 1964; Jensen 1974).

The annual litter fall in eucalypts ranged from 3.88 to 6.86 OD t/ha/y (Baker 1983). Similar figures (3.6 to 5.5 OD t/ha/y) were found under 45-60 years old *E. obliqua* stands (typical warm temperate forest, 704 to 976 stems/ha) in Australia (Attiwill et al. 1978).

The annual litter fall was 5.83 OD t/ha/y under a young coppicing *E. globulus* plantation (Lisanework & Michelsen 1994). Toky & Singh (1993) found that production of litter in 4 year old stands (14,933 stems/ha) of *E. tereticornis* reached 7.2 OD t/ha/y, whereas in 8 year old stands (1486 stems/ha) it was 9.1 OD t/ha/y.

In the more highly productive forests, up to 10 tonnes of litter of low nutritional quality is deposited annually on the forest floor (Attiwill & Adams 1993). Annual litter reached 14 OD t/ha in the Brazilian plantations of *Eucalyptus* (Penfold & Willis 1961). As high as 16.8 OD t/ha/y of litter fall was recorded under 20 year-old *E. camaldulensis* planted on fertile soil (Negi & Sharma 1996).

Nutrient return via litter fall

In *E. diversicolor* forests of varying age, litter fall is the major transfer mechanism for three of the nutrients, accounting for 89-93% of the N, 80-87% of the Ca, and 67-79% of the P reaching the forest floor each year, only about 28-38% of the K (O'Connell 1985). A similar trend in eucalypt forests was concluded by Attiwill et al. (1996) though there existed some variations in the percentage of the nutrients, 92% of the N, > 99.5% of the P, 92% of the Ca, 91% of the Mg and 60% of the K.

George & Varghese (1990b) reported 8.5 OD t/ha/y of litter produced under 10 year old *E. globulus* plantation. On an annual basis, the total return of nitrogen was 58 kg/ha/y, potassium 40 kg/ha/y and phosphorus 4.6 kg/ha/y.

In three *Eucalyptus* hybrid plantations of ages 5, 7 and 10 years, litter fall was 3.4, 3.8 and 6.2 OD t/ha/y, respectively, and the total annual return of nutrients was highest for Ca (40.2, 42.8 and 73.2 kg/ha/y), followed by N (29.8, 32.1 and 59.1 kg/ha/y), K (15.0, 17.5 and 30.6 kg/ha/y), Mg (5.0, 6.1, and 9.3 kg/ha/y), and P (1.6, 1.9 and 3.9 kg/ha/y) (George 1982). At 10 years old, *E. globulus* returned more nutrients than it retained, taking up 101 kg N/ha/y (retaining 43 kg/ha/y, returning 58 kg/ha/y), 7 kg P/ha/y (3, 4), 76 kg K/ha/y (36, 40) (George & Varghese 1991).

Frederick et al. (1985b) concluded that the rates of cycling of nutrients both through the tree-litter fall pathway and through litter decomposition were higher under highly productive New Zealand plantations than both natural Australian eucalypt forests and plantations in drier climates. They reported that the total annual litter fall ranged from 4.7 to 5.7 OD t/ha/y with 43.4 to 65.4 kg N/ha/y, 2.0 to 4.5 kg P/ha/y, 9.4 to 12.1 kg K/ha/y, 52.0 to 77.8 kg Ca/ha/y, 8.7 to 14.4 kg Mg and 2.3 to 5.9 kg Mn/ha/y. The litter fall and nutrient return were unrelated to stand age (4 to 17 years old).

The effects on the litter fall and nutrient return

Bray & Gorham (1964) indicated that fertile soils may cause higher litter fall in forests and litter production appeared to be little affected by differences in tree density within closed-canopy forests. Thinning reduced litter production, which was roughly proportional to the degree of thinning.

O'Connell & Grove (1993) found that annual accessions of litter to the forest floor were significantly increased by fertilizer additions. Application of N fertilizer increased *E. diversicolor* litter fall by up to 21%, and P fertilizer by up to 8% giving a maximum of 5.67 OD t/ha/y. Concentration of N in leaf litter was 9% to 23% greater on plots treated with N fertilizer compared to untreated plots and a similar trend was noted in P. However, the increase should be related to the more biomass production following the fertilization.

If old or moribund forests are excluded, there is generally a close correlation between the weight of leaf-fall and the growth rate in managed forests, irrespective of species (Miller 1984). High values of litter fall in plantations of *E. tereticornis* may be related to fast growth rates with net primary productivity of 29 OD t/ha/y at 4 years of age. Also self-shading in high density stands promotes litter fall (Zavitkovski 1981, cited in Toky & Singh 1993). The faster growing the species is, the more litter it will produce (Penfold & Willis 1961). The amount of foliage can be more easily correlated with current growth than with mean growth over the life time of a tree or forest and there is some correlation between litter fall and forest production (Bray & Gorham 1964). Fast tree growth can result in the higher litter fall (George & Varghese 1990b). Therefore, the negative correlation between litterfall in broad leaf forests and latitude observed by Vogt et al. (1986) may be caused by the effects of latitude on the forest production.

2.6.2.1 Litter components

The mean percentage of non-leaf litter from angiosperms is stated to be 21% in cool temperate climates and 23% and 42% in warm temperate climates in North America and Australia, respectively (Bray & Gorham 1964; Jensen 1974). On average, the percentage of non-leaf material in forest litter is 30% for angiosperms and 29% for gymnosperms (Williams & Gray 1974). However, the percentage also depends on tree age.

Even though the floor of a *Eucalyptus* forest is often covered with fallen bark (Bray & Gorham 1964), the bark fall is not a main component of the litter fall. Litter leaves provide the main litter component in the eucalypt forests (Hart 1995). Leaves made up more than 40% of the mass of annual litter fall in pole-stand *E. diversicolor* forest (O'Connell 1987) and in ten year old *E. globulus* plantations (George & Varghese 1991); 62% in 4 year old stands (14933 stems/ha) of *E. tereticornis*; and 58% in 8 year old stands (1486 stems/ha) (Toky & Singh 1993). Leaves accounted for 71-89% of the total litter fall in 5- to 20-year old plantations; in the 1-year old ones they were the only form of litter fall (Toky & Ramakrishnan 1983a). Leaf litter contributed 76, 66 and 75% in the three *Eucalyptus* hybrid plantations of ages 5, 7 and 10 years, respectively. The maximum amount of all nutrients was returned through leaf litter and lowest through bark (George 1982).

In an age series of *E. regnans* plantations, the percentage of leaf litter fall and nutrient return via leaf litter decreased with age (Figure 2.1). Therefore, in short rotation forests of *Eucalyptus* under 4 years old, leaf litter unlikely contributes less than 90% of the total litter fall, total nitrogen return and total phosphorus return via litter fall (Frederick et al. 1985b).

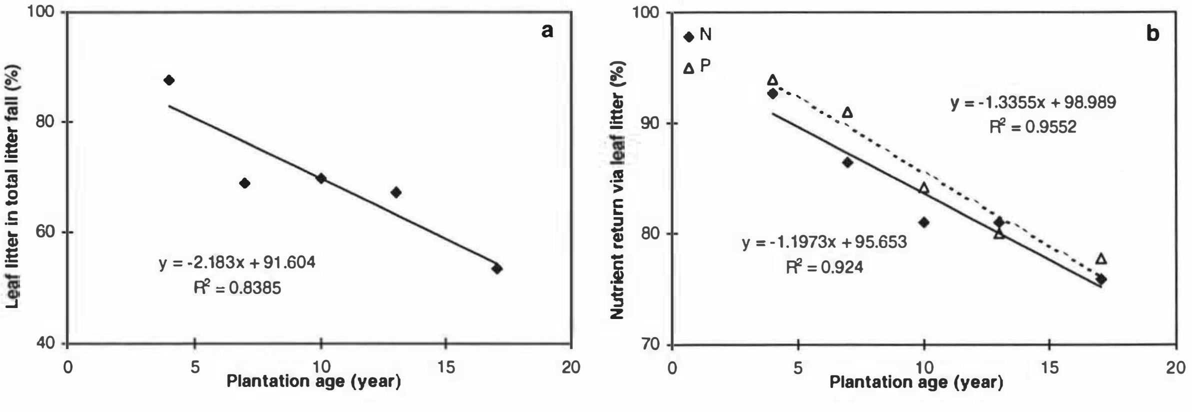

Figure 2.1 The effects of plantation age on: (a) the percentage of leaf in total litter fall, (b) nitrogen and phosphorus return via leaf litter (data from Frederick et al. 1985b).

2.6.2.2 Seasonal variations

If forest litter is ever to be utilized economically, it will be of importance to know the pattern of litter fall, whether distinctly seasonal, or more or less continuous (Bray & Gorham 1964).

At all seasons of the year there is a continual drop of leaves, twigs, branches, bark, flower buds, and fruit capsules from the eucalypt trees on to the forest floor (Penfold & Willis 1961). *Eucalyptus* forests in Victoria and Western Australia deposit leaf litter mainly in the warm, dry part of the year (Bray & Gorham 1964). Fifty percent of the litter fall occurred in the summer months in a *E. obliqua* forest, and seasonal rate of litter fall is dependent primarily on temperature (Attiwill et al. 1978). Leaf litter fell all year around with a summer maximum and winter minimum leaf fall (Frederick et al. 1985b). Similar results were also reported in other studies on eucalypts (Baker 1983; Toky & Singh 1993; Lisanework & Michelsen 1994; Hart 1995).

Concentrations of nitrogen and phosphorus in fallen leaves varied markedly between seasons but were consistently lowest at times of peak fall (Baker 1983). Highest concentrations of each element were found during mid-winter (July-August) when the amount of *E. diversicolor* leaf litter fall was smallest, and lowest in mid-summer (January-February) when litter fall was greatest (O'Connell & Grove 1993).

2.6.2.3 The methods for monitoring litter fall

For catching litter, the tray method (Newbould 1967) is widely used in studies on forest litter fall, even though the litter may be subject to considerable loss of weight while remaining in the trays as the result of leaching, microbial decomposition and feeding by animals. Usually, the tray is supported or hung up to a certain height (e.g. 100 - 300 mm above ground) to reduce the errors to under or over estimate litter fall in forest study. Swift et al. (1979) suggested that trays should be directly put forest floor under dwarf shrubs. Therefore, whether the trays should be put on the forest floor or suspended above the ground appears to depend on the height of the plants monitored.

There are various intervals used between collecting the litter from the trays, such as one week (Wieder & Wright 1995), two weeks (Proctor et al. 1983; Cuevas et al. 1991; Sampaio et al. 1993), 4 to 6 weeks (Frederick et al. 1985a, 1985b), two weeks and one month (Reiners & Lang 1987), two months (Prescott et al. 1993), and three months (Hart 1995). A one month interval was most widely used (Briggs & Maher 1983; Toky & Ramakrishnan 1983a; Lamb 1985; Sharma & Ambasht 1987; Singh & Singh 1991; Bargali et al. 1992a; Escudero et al. 1992; Toky & Singh 1993; Lisanework & Michelsen 1994).

2.6.3 Litter accumulation and nutrient pool on the topsoil

Litter can be defined as the material lying on the soil surface consisting of dead plant components and shed organs, but not standing dead plants (Bell 1974). The litter layer may be clearly distinguishable from an underlying mineral layer, but there may be no sharp boundary between a layer containing recognisable plant structures and a layer containing only amorphous organic material. Organic debris which has fallen as litter and the organic, decomposing layer on the surface of the mineral soil are together termed 'the forest floor' (Pritchett 1979).

Total litter accumulation includes all the forest-floor litter above the mineral soil (Gholz & Fisher 1982; O'Connell 1987; Baker et al. 1990). Litter is usually separated into three layers (Ashton 1975; Gholz & Fisher 1982, Sampaio et al. 1993): a top or L (O1) layer contained material mostly undecomposed and still identifiable; a middle or F layer with material mostly decomposed, consisting mainly of large leaf fragments; and a bottom or H layer, consisting mainly of unidentifiable organic material. Otherwise, the litter can be simply separated into two layers: fallen litter fall (L horizon) as well as decomposing organic matter (F and H horizons) (Vogt et al. 1986).

Sukardjo & Yamada (1992) found the accumulation of litter of 47.4 - 51.4 OD t/ha in a 7-year-old stand of *Rhizophora mucronata*. Jurgensen et al. (1986) reported that the weight of forest floor under *E. regnans* varied between 4.7 and 11.0 OD t/ha with little effect due to stand age (4 to 17 years old). Toky & Singh (1993) found that the stands had a minimum amount of litter accumulation during winter and a maximum amount during spring with 17.0 OD t/ha in four year old stands and 21.6 OD t/ha in 8 year old ones. O'Connell & Grove (1996) indicated that the build-up of litter is rapid following fire and can reach 23-30 OD t/ha within 8 years in *E. diversicolor* forests. They suggested that the predicted equilibrium mass of the forest floor (annual litter fall balance by decomposition) is approximately 40 OD t/ha. The litter accumulation in the forest floor under *E. regnans* forests closed to the above predicted equilibrium mass with 44 and 47.5 OD t/ha (Feller 1978; Feller 1980).

In 4 and 8 year old stands of *E. tereticornis*, the amount of N (179.5 and 222.5 kg/ha, respectively), P (14.2, 18.7), Ca (86.6, 114.9) and Mg (23.8, 31.6) accumulated in the litter layer (Toky & Singh 1993). In an 8 year old stand of *E. regnans*, litter accumulation reached 9.2 OD t/ha with 87 kg N/ha, 7 kg P/ha, 9 kg K/ha, 104 kg Ca/ha, 10 kg Mg/ha (Frederick et al. 1985a). In a natural *E. regnans* forest, nutrient accumulation in the 44 OD t/ha litter was 74.8 kg N/h, 7.0 kg P/ha, 17.6 kg K/ha, 88.0 kg Ca/ha and 22.0 kg Mg/ha (Feller 1978).

The amount of litter accumulation on the forest floor is dependent on the litter input from trees and the output by decomposition. Similarly, the amount of nutrients accumulated in the litter layer is dependent on the nutrient return via litter fall and nutrient release via litter decomposition.

2.6.3.1 Methods for measuring litter and nutrient accumulation on the top soil

Litter accumulation on the forest floor is usually estimated by randomly sampling with quadrats or corers (Gholz & Fisher 1982; Baker & Attiwill 1985; O'Connell 1987; Baker et al. 1990). Then, the total amount is calculated from the area of quadrats or corers and the sample weights. Total litter includes all forest-floor litter above the mineral soil (Gholz & Fisher 1982; O'Connell 1987; Baker et al. 1990).

2.6.4 Decomposition and nutrient release

The investigation of decomposition is an important aspect of the analysis of ecosystem function (Wieder & Lang 1982). Decomposition of the detritus on the forest floor provides the main source of energy and nutrients for soil and litter organisms, and is a major pathway for the recycling of nutrients to the plant community (Charley & Richards 1983). Processes of decay start from the very moment the leaf is formed, and the leaves are exposed to attack by micro-organisms and animals during their whole life, senescence and death (Jensen 1974). During the decomposition of litter, respiration releases carbon to the atmosphere, most of the nitrogen is conserved within microbial cells and their metabolites, which typically have a ratio of carbon to nitrogen (C:N ratio) of about 10 (Attiwill et al. 1996).

Decomposition processes play an important role in soil fertility in terms of nutrient cycling and in the formation of soil organic matter (Bargali et al. 1993). Litter decomposition is regulated by numerous factors, of which the most important are probably (i) the environment under which decay takes place and (ii) the physicochemical properties of the substrate (Gillon et al. 1994). Hence, the litter decomposition can be controlled by internal and external factors. The internal factors are the characteristics of litter itself (e.g. nutrient concentration, lignin content and tannin content, lignin:N, C:N, availability of N and P). They are affected by species, and the plant's growing environment. The external factors are the environment around the litter, such as temperature, light, soil moisture, soil fertility, soil fauna and micro-organism (Williams & Gray 1974; Nagy & Macauley 1982; Taylor et al. 1991; Attiwill & Adams 1993; Prescott 1996).

2.6.4.1 Internal factors

Adams & Attiwill (1986) concluded that the slow rate of decomposition of eucalypt forest litter, resulting in the storage of significant amounts of nutrients in the soil, has been recognised as a feature of this genus. *Eucalyptus* leaves decomposed more slowly than leaves of many European broad-leaved tree species (Wood 1974).

However, Penfold & Willis (1961) indicated that the eucalypt litter in Australia decays quite rapidly, and it is unusual to find a layer of undecayed litter on the ground more than a few centimetres thick. Jorgensen et al. (1986) reported that litter decomposition rates were clearly lower under *P. radiata* than under *E. regnans.* Briones & Ineson (1996) did not confirm this reputation of *Eucalyptus* as a recalcitrant litter for the decomposition of the eucalyptus paralleled that of the birch litter in terms of mass loss in their study.

Prescott et al. (1993) reported that the amount of N returned in annual above ground litter was greater in Douglas fir plots with sewage sludge applied and found no consistent evidence of more rapid turnover of N in litter fall on forest floors under stands treated with large quantities of N from either fertilizer and sewage sludge. Fertilization of these forests did not change the quality of the litter sufficiently to increase the rate at which it decayed and released nutrients to the forest floor.

The initial nutrient concentrations in the litter may play a special role in the variation on litter decomposition. The concentration of plant nutrients in litter material is important because of its influence both on the rate of decomposition of the litter and on the amount of nutrients liberated during the decomposition (Jensen 1974).

Significant positive linear relationships were found between the initial concentrations of N or P in the leaves and their loss in weight after 12 months in the field (Woods & Raison 1983).

Initial litter N and Mg showed a strong correlation with mass loss (Briones & Ineson 1996). Litter tissues with substrated quality of low carbon, low lignin and high nitrogen tended to decay the fastest (Bloomfield et al. 1993).

Meentemeyer (1978) proposed that the relative control by lignin over the decomposition rate is not uniform over different climatic regions. Generally, the greater the abundance of energy and moisture, as indicated by the actual evapo-transpiration (AET), the faster the decay rate for a given lignin content. The higher the lignin content, the more energy and moisture are required to cause breakdown to be accomplished in a unit time (e.g. a year). The decomposition is a tremendously complex process, and AET and lignin are surrogates for only some of the actual regulators of the decay rate.

Although in agriculture, C:N ratios are often used as indicators of decomposition and nitrogen release potentials, nitrogen release in forest litter was not well related to C:N ratio and decomposition rate was unaffected by a considerable decrease in C:N ratio (Jorgensen et al. 1980; Will et al. 1983). The C:N ratio of litter played a more important role in determining decomposition rates than did litter temperature or moisture. Nonetheless, the role of litter temperature and litter moisture was significant (Sharma & Ambasht 1987).

2.6.4.2 External factors

In general, litter tissues decaying under abiotic conditions of high temperature and high moisture tend to decay the fastest (Bloomfield et al. 1993). Provided that the soil moisture content is favourable for microbial activity, decomposition and mineralization of eucalypt leaves proceeds remarkably quickly with 30 to 50% weight loss occurring during the first year despite the sclerophyll nature (Ericsson et al. 1992).

Maximum rate of *Quercus leucotrichophora* leaf litter decomposition was observed in the rainy season and the minimum in the dry season (Pant & Tiwari 1992). The most rapid weight loss from *E. diversicolor* leaf litter occurred during the first wet season following placement on the forest floor (O'Connell 1987).

Among different age stands (7, 17, 30, 46, 56 years old plantations of *Alnus nepalensis*), litter decomposition rate was highest under the 30-year old stand being at the time of canopy closure, litter decomposition was largely controlled by the prevailing moisture, and temperature (Sharma & Ambasht 1987). Bargali et al. (1993) reported that rapid weight loss occurred in the 1 year old plantation and decreased with plantation age from their 1-8 year series of *E. tereticornis* plantations. However, Will et al. (1983) found that tree canopy density had little or no effect on litter decomposition rate or loss of nutrients.

The phosphorus addition increased the rate of dry weight loss of decomposing litter and the nitrogen addition decreased it (O'Connell 1994). Irrigation with sewage effluent significantly increased the rate of loss of organic matter and nutrients from *P. radiata* needles in litter-bags, which could have resulted from increases in nutrient and moisture availability and from greater solubility at higher pH of some organic fractions of litter (Baker et al. 1990).

Neuvonen & Suomela (1990) found that decomposition in acid treatments at less than pH 3.0, tended to be slower than in control (pH 6.0). Dursun et al. (1993) reported that pH reduction down to pH 3.0 had very little effect on the leaf litter respiration. Therefore, soil pH only has limited effects on litter decomposition.

2.6.4.3 The rate of litter decomposition and nutrient release

The most rapidly removed element from litter under pine forests was potassium and only 9.9% of it still remained after 2 years while the concentration of all of the other nutrients remained constant or was even slightly increased (Zielinski 1984). The relative loss rates were K > B > P > dry weight > Mg = Zn = Ca = Mn > N from *P. radiata* litter and there was little or no loss of nitrogen during the first 97 weeks (Will et al. 1983).

In rain forests, the rate of loss was K > Mg > Ca > dry matter > N > P, with K losing approximately 80% only in two months (Anderson et al. 1983). In a Beech forest, the rate of turnover varies for the nutrients -- K > Ca > Mg > P > N -- in a pattern which was consistent with the previous observations (Swift et al. 1979). Similar results were found from an *Alnus nepalensis* plantation where the relative elemental transfer from the decomposing litter showed potassium to be highly mobile and nitrogen least mobile (K > Ca > P > N) (Sharma & Ambash 1987).

The rate of nutrient element release and dry weight loss from *E. globulus* leaf litter was: K > Mg > Ca > dry weight > P = N, only 7.2% of dry matter being left after 24 months (Lisanework & Michelsen 1994). The order of mobility of the major nutrients was the same for *E. marginata* and *E. calophylla* leaf litter as for *E. diversicolor* leaf litter (K > Mg > S > Ca > N > P), and the low mobility of N and P was due in part to the high carbon:nitrogen and carbon:phosphorus ratios in the litter materials (O'Connell & Grove 1996).

Accumulation of nutrients, particularly P, was rapid reaching two and three times the initial N and P contents respectively, within the range of substrate compositions occurring in *E. diversicolor* forest litter (O'Connell 1988b).

2.6.4.4 Methods for monitoring litter decomposition

A common method used to monitor litter decomposition is to put a container with known litter mass and chemical composition on to the forest floor, and take it back after a period of time. The amount of change is as a result of the material decomposed during the time. Wire screening containers (Falconer et al. 1933; Gustafson 1943), gauze fabric and wood containers (Lunt 1933), metal cans (Jenny et al. 1949) had all been used to assess the litter decomposition rate until Bocock & Gilbert (1957) introduced the nylon mesh bag technique. The flexibility of the nylon permits the enclosed leaves to become embedded in the natural litter layer and in fact to become indistinguishable from it on casual observation. Thereafter, litter bags have been most widely used in studies of litter decomposition.

A number of authors have criticised the use of litter bags for studying decomposition (Wieder & Lang 1982). Some other techniques, e.g. wooden boxes covered with wire mesh (Attiwill 1968), glass or polythene tubes (Clymo 1965; Howard 1967), test-tube tops (Nagy & Macauley 1982), tethered leaves (Woods & Raison 1983), and litter baskets (Blair et al. 1991), have been used in monitoring litter decomposition. However, litter bags are still a widely used technique as Will et al. (1983) indicated. The bag method is also used in other areas using the same principle, e.g. to monitor the movement and behaviour of major and trace mineral elements within soils

(Berthelin et al. 1990). Cuenca et al. (1983) indicated that although the litter bag method introduces changes in the decomposition process which thus gives a dubious estimate of the decomposition, it gives a relative estimate of the effects of micro and macro-organisms.

Selection of bag mesh size depends partly on the size range of the fauna, but is a compromise between providing maximum access and minimising "fall-out" (Swift et al. 1979). Different mesh size bags have been used for monitoring litter decomposition: 10 mm (Bocock & Gilbert 1957), 7 - 10 mm with topside 20 mm (Anderson et al. 1983), 7.5 mm (Baker & Attiwill 1985), 8 × 3 mm (Woods & Raison 1983), 4 × 3 mm (Melillo et al. 1982), 3 mm (O'Connell 1988a), 2 mm (Kelly & Henderson 1978; Baker et al. 1990; Toky & Singh 1993), 1.5 mm (Briggs & Maher 1983; O'Connell 1987; Bloomfield et al. 1993; Prescott et al. 1993; Lisanework & Michelsen 1994; O'Connell 1994; Hart 1995; Prescott 1996), 1 mm (Will et al. 1983; Sharma & Ambasht 1987; Taylor et al. 1991; Bargali et al. 1993; Gallardo & Merino 1993; Gillon et al. 1994), 0.03 and 0.5 mm (Cuenca et al. 1983), and 0.04 mm (Anderson et al. 1983).

Increasing mesh size can let more soil fauna access the litter, at same time increase the fall-out which can cause over-estimating of the decomposition. Reducing mesh size can limit the fall-out, but reduce fauna access which can cause under-estimating. Swift et al. (1979) indicated the 5 mm mesh size allowed access to the entire soil and litter community including the largest animals present at these sites and was theoretically a measure of the total weight loss attributable to leaching, catabolism and loss of particles less than 5 mm diameter, following comminution. The 1 mm mesh excluded the larger soil animals such as millipedes, isopods and earthworms but allowed entry of mites, collembola nematodes and enchytraeids. The 45 μm mesh excluded all organisms except the fungi, bacteria, nematodes, protozoa and other very small members of the soil fauna.

Gallardo & Merino (1993) used 100 × 150 mm nylon bags with 1 mm mesh which they considered was small enough to prevent major losses of the smallest leaves, yet large enough to permit aerobic microbial activity and free entry of small soil animals.

Initially, a large number of bags are placed in the field and at each subsequent sampling date a randomly chosen set of bags is retrieved and analyzed for loss of mass and changes in the chemical composition of litter.

Litter bags are collected at different intervals in the different studies: daily (Briggs & Maher 1983), one month (Kelly & Henderson 1978; Briggs & Maher 1983; Pant & Tiwari 1992; Bargali et al. 1993; Toky & Singh 1993), two months (Anderson et al. 1983; Gallardo & Merino 1993), three months (Baker & Attiwill 1985; Lisanework & Michelsen 1994; Hart 1995), six months (Baker et al. 1990; Prescott et al. 1993), week 5, 11, 18, 30, 42, 51, 68, and 82 (O'Connell 1987), week 3, 5, 9, 19, 31, 45, 58, 71, 84, 97, 110, 123, and 128 (Will et al. 1983), month 1, 3, 6, 12 (Bloomfield et al. 1993), month 1, 6, 9, 12 (Melillo et al. 1982), month 1.5, 3, 6, 12, 24 (Zielinski 1984), and month 3, 6, 12, 24 (Sharma & Ambasht 1987).

Leaf-litter decomposition is most often studied because leaves are usually the main contributor to annual litter fall (O'Connell 1987; section 2.6.2.1). The bagged leaves in most studies are the freshly abscised leaves that are collected from the surface of the forest floor (Melillo et al. 1982; Nagy & Macauley 1982; Anderson et al. 1983; Will et al. 1983; Baker & Attiwill 1985; Baker et al. 1990; Bloomfield et al. 1993; Gillon et al. 1994) though in some studies senescent mature leaves before falling are used (Toky & Singh 1993; Lisanework & Michelsen 1994) or mature, nearly senesced (on the basis of colour) leaves but still attached (Bargali et al. 1993).

The bagged litter samples could be contaminated with soil. Anderson et al. (1983) removed the leaves from the litter bags and brushed them free of foreign material (including roots). Sharma & Ambasht (1987) removed them by gentle rinsing with tap water over a fine soil sieve. Hart (1995) carefully removed and discarded the soil and litter adhering to the outside of the mesh bags. He found a large amount of sediment was mixed with the litter inside the mesh bags and separated the litter from this by flotation.

Models commonly used to examine decomposition data are single exponential, double exponential, asymptotic, linear, quadratic, and power (Wieder & Lang 1982). In litter decomposition, the most suitable curves appeared to be those of shape (Grunda 1985):

$$y = a + bx + cx^2 + dx^3 \text{ and } y = e^{(a+bx+cx^2+dx^3)}$$

However, the single exponential model has been widely used in the litter decomposition studies (Jenny et al. 1949; Olson 1963; Meentemeyer 1978; Anderson et al. 1983; Will et al.

1983; Woods & Raison 1983; Bake & Attiwill 1985; Roberts et al. 1985; O'Connell 1987; Bloomfield et al. 1993; Gallardo & Merino 1993):

$$W_t = W_0 e^{-kt}$$

> where W_o is the initial litter dry weight, W_t the dry weight at time t, and k the instantaneous decay constant.

The constant k is used to compare the difference between decomposition rates in litter decomposition studies.

2.7 SUMMARY

Short rotation forests have good potential for biomass production, further recycling of carbon dioxide and protecting our environment. They also have good potential to link with effluent land treatment systems to relieve the pressure on the waterways. Usually nutrient removal in a short rotation forest is considered non sustainable. The leaves and branches should be kept on the site for sustainable land use. However in land treatment systems, the nutrients should be removed as much as possible to give sustainable land use. The common concern in short rotation forests, either when linked with effluent land treatment or not, is how much nutrient can be taken up by the trees and removed by harvesting. Therefore, managing such systems should be based on the knowledge of the short rotation forests, e.g. soil responding to land use change and effluent irrigation, the end products expected, nutrient removal in the harvestable biomass, litter fall and nutrient return, litter decomposition and nutrient release, and species variation.

Many studies in the above literature review have reported useful findings for managing short rotation forests, specifically:

i) soil responding to tree planting and effluent irrigation (Wells & Whitton 1970; Keeley & Quin 1979; Frederick et al. 1985a; Abd Elnaim et al. 1987; Waly et al. 1987; Russell et al. 1988; Madeira 1989; Cook & Thorne 1990; Bargali et al. 1992b; Mathan 1994; Tipler et al. 1996; Falkiner & Smith 1997);

ii) species selection (Turnbull & Pryor 1978; Negi & Sharma 1984; Hillis 1990; Knight & Nicholas 1996);

iii) biomass production and nutrient uptake (Cromer et al. 1975; Wise & Pitman 1981; Cromer & Williams 1982; Borralho et al. 1989; George & Varghese 1990a; George & Varghese 1991; Dalianis et al. 1996; Pereira et al. 1996);

iv) litter fall and nutrient return (Penfold & Willis 1961; Bray & Gorham 1964; Jensen 1974; Williams & Gray 1974; Attiwill et al. 1978; George 1982; Baker 1983; Toky & Ramakrishnan 1983b; O'Connell 1985; Frederick et al. 1985b; Vogt et al. 1986; O'Connell 1987; Sharma & Ambasht 1987; George & Varghese 1990b; George & Varghese 1991; Attiwill & Adams 1993; O'Connell & Grove 1993; Toky & Singh 1993; Lisanework & Michelsen 1994; Hart 1995; Attiwill et al. 1996; Negi & Sharma 1996); and

v) litter decomposition and nutrient release (Olson 1963; Jensen 1974; Williams & Gray 1974; Wood 1974; Meentemeyer 1978; Swift et al. 1979; Jorgensen et al. 1980; Nagy & Macauley 1982; Wieder & Lang 1982; Anderson et al. 1983; Will et al. 1983; Woods & Raison 1983; Baker & Attiwill 1985; Grunda 1985; Roberts et al. 1985; Adams & Attiwill 1986; Jorgensen et al. 1986; O'Connell 1987; Sharma & Ambasht 1987; O'Connell 1988b; Baker et al. 1990; Neuvonen & Suomela 1990; Taylor et al. 1991; Ericsson et al. 1992; Attiwill & Adams 1993; Bargali et al. 1993; Dursun et al. 1993; Gallardo & Merino 1993; Prescott et al. 1993; Gillon et al. 1994; Lisanework & Michelsen 1994; O'Connell 1994; Attiwill et al. 1996; Briones & Ineson 1996; O'Connell & Grove 1996; Prescott 1996).

However, a systematic study should be conducted on short rotation forests to assess soil response to land use change, biomass production, nutrient cycling and the mechanism to control nutrient cycling, particularly to the short rotation forests linked with effluent land treatment because limited data are available on above aspects for successfully managing such systems.

Therefore, this thesis focuses on the systematic study of short rotation forests from before tree planting to the end of the first rotation, especially on the mechanisms controlling or affecting nutrient cycling in short rotation forests. This includes species selection, the effects of effluent irrigation on tree growth, litter return, litter decomposition and nutrient cycling through these activities during the whole 3 year rotation. On the other hand, the findings in the field are tested for each individual external factor in the controlled environments.

3. THE EFFECTS OF MEATWORKS EFFLUENT APPLIED TO PASTURE AND EUCALYPT SHORT ROTATION FOREST

3.1 INTRODUCTION

Effluents from dairy farms, food processing industries, and municipal sewage treatment plants often contain high levels of nutrients, such as nitrogen and phosphorus, which are essential for crop growth. The application of effluent to land could provide nutrients and water for crop production, and at the same time relieve the pressure of waste water disposal to waterways.

Effluent has been irrigated to land as a replacement for commercial fertilizers (Marecos do Monte et al. 1989), and to increase crop yields (Sopper & Kardos 1973; Sopper 1980; Lowe 1994). Continued effluent irrigation can change soil properties such as soil infiltration rate, hydraulic conductivity, bulk density and porosity, soil pH and nutrient status (Waly et al. 1987; Cook & Thorne 1990; Mathan 1994). The above changes may influence the sustainablility of land use.

In New Zealand, land treatment systems using effluent from meatworks, dairy farms, and milk processing plants have traditionally been irrigated on to pasture. Recently, interest has arisen on irrigating forests for the benefits of this practice are two folds. Trees are not part of the human food chain, and there is no risk of soil compaction by grazing stock. The choice of crop for a disposal site must be determined by sustainable land use considerations and economic aspects, as well as its ability to take up the nutrients and water applied. This chapter outlines the effects of meatworks effluent irrigation on to soil, pasture and short rotation forests, and discusses the differences as land treatment systems.

The objectives of this chapter were to assess:

1. soil response to effluent irrigation and tree planting into pasture;
2. pasture and tree response to effluent irrigation; and
3. the potential of eucalypt short rotation forest linking with effluent land treatment.

3.2 MATERIALS AND METHODS

3.2.1 Site and effluent

The study field was at the Richmond Meat Processors & Packers Ltd. processing plant at Oringi, which is adjacent to the Manawatu River, located near Dannevirke, New Zealand. Longitude is 176°01'E and latitude is 40°16'S. The elevation is 200 m above sea level. Mean average annual rainfall is 1098 mm. The distribution of mean monthly rainfall ranges from 60 mm in February to 123 mm in December. Mean temperature is 11.2°C with a maximum of 17.4°C in February and minimum 7.8°C in July. Monthly distributions of rainfall and temperature are shown in Figure 3.1.

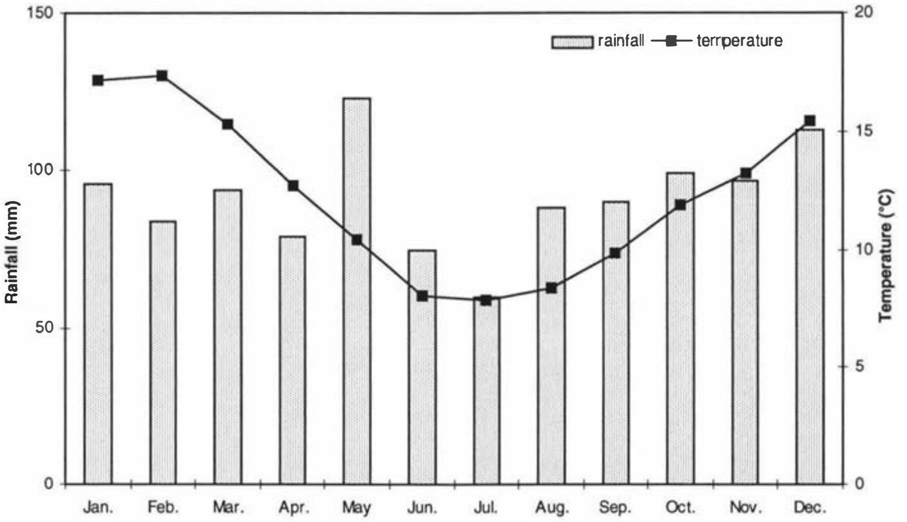

Figure 3.1 Ten year average monthly rainfall and mean temperature for Dannevirke, New Zealand.

The soils belong to the Dannevirke - Kopua soils from alluvial deposits, having textures of sandy loam overlying stony gravels, and mostly having medium to low natural fertility. They are very friable with low bulk density and good drainage (National Resources Survey 1971).

The maximum daily killing capacity of the plant is over 12,000 head of sheep. Approximately 1,100,000 m^3 of effluent is produced every year with chemical and biochemical characteristics are shown in Table 3. 1.

Effluent was applied to the land at a rate of 20 mm/week using flood irrigation. Species grown were ryegrass (*Lolium perenne*) pasture and *Eucalyptus botryoides* in a short rotation forest plantation with 3333 trees/ha.

Table 3. 1 Chemical composition of the meatworks effluent

Biochemical oxygen demand (g/m^3)	400	Phosphorus (g/m^3)	20
Chemical oxygen demand (g/m^3)	1060	Potassium (g/m^3)	90
Total Kjeldahl nitrogen (g/m^3)	200	Calcium (g/m^3)	25
Ammoniacal nitrogen (g/m^3)	150	Magnesium (g/m^3)	7
Nitrate nitrogen (g/m^3)	< 0.2	Manganese (g/m^3)	0.4
		pH	6.8

There were four treatments at four sites:

i) pasture without irrigation: no effluent disposal at any time (PN);

ii) pasture with effluent irrigated for 12 years since 1981 (PI);

iii) plantation without irrigation (TN): six year old trees without irrigation. Prior to the trees, this treatment had been in pasture which had received effluent irrigation from 1981 to 1987;

iv) plantation irrigated with effluent (TI): six year old trees irrigated with effluent. As for the TN treatment this area was previously in pasture and had been irrigated with effluent from 1981 to 1987.

3.2.2 Measurements and sampling

In February 1994, soil infiltration rates were measured and soil cores for bulk density were removed from the four treatment sites. Litter samples were only taken from the forest floor under the plantations as litter was not present in the pasture.

Infiltration rates were measured using double ring infiltrometers with two concentric cylinders of 205 and 510 mm in diameter (Anon. 1982). The outer cylinder was filled with water to approximately the same depth as the inner cylinder to ensure the water from the inner cylinder moves through the soil in a vertical direction. Three replicates were measured for each treatment. Bulk densities were determined by the core method (Blake & Hartge 1986). Five undisturbed soil cores were taken from each of two depths (topsoil 0 - 75 mm and subsoil 75 - 150 mm) at each treatment site. Twenty soil samples were obtained by random sampling with the corer at depths of 0 - 75 mm and 75 - 150 mm each site and then every four of them were mixed thoroughly to make five samples for chemical analysis. Litter on the forest floor, all the organic matter above the mineral soil, was randomly sampled in plantations using a 145 mm diameter corer (Gholz & Fisher 1982). Ten replicate cores were gathered. The depth of the litter layer was measured at the same time. The litter samples were separated into leaf, branch and decaying litter.

Plants were sampled for chemical analysis in March 1994. The above ground pasture components from treatments PN and PI were harvested using shears and a quadrat (100 mm × 100 mm). Five samples were randomly selected. Five trees from treatments TN and TI were randomly selected, harvested and dissected into samples of leaf, twig (diameter under 5 mm), branch (diameter from 5 to 40 mm), wood and bark (stems and branch diameter above 40 mm).

3.2.3 Laboratory and statistical analyses

Soil cores for bulk density were oven dried at 105°C. The soil samples for chemical analysis were separated into two parts: the fresh sample was used for available nitrogen (ammonium and nitrate) and the other one was air-dried at approximately 20°C, passed through a 2 mm sieve, then stored in polystyrene containers until required for further analysis. The samples of all plant components and litter were weighed following overnight oven dried at 80°C, but more than 3 days for wood, bark and branches, then ground to pass through 1 mm sieves for further analysis.

Total nitrogen and total phosphorus for soil and herbage samples were analysed using a Technicon Auto Analyser following Kjeldahl digestion:
i) weigh accurately 1 g finely ground soil samples (0.1000 to 0.1010 g herbage samples) and place in a pyres tube;
ii) add 4 ml of digest mixture (consisting of 250 g K_2SO_4 and 2.5 g selenium powder into 2.5 l H_2SO_4, heated over a gas ring for two hours) and heat it in an aluminium block at 350°C for 4 hours;
iii) cool the tubes, dilute with 50 ml of distilled water, and mix it thoroughly in a vortex mixture.

The fresh soil samples were analysed for ammonium and nitrate using a Technicon Auto Analyser following KCl extraction:
i) weigh 1.00 to 1.01g fresh soil sample and place in centrifuge tube (at same time subsample oven dried for soil moisture content);
ii) add 10 ml 2 *M* KCl and shake in an end-over-end shaker for 1 hour;
iii) centrifuge the solution at 8000 rpm for 3 minutes;
iv) filter the solution through Whatman No. 42 filter paper.

Soil Olsen phosphorus was analysed using a Technicon Auto Analyser following sodium bicarbonate extraction:
i) weigh accurately 1 g of air-dried soil into 50 ml polypropylene centrifuge tubes;
ii) add 20 ml of 0.5 *M* $NaHCO_3$ solution and shake tubes in an end-over-end shaker for 30 min;
iii) centrifuge the solution at 8000 rpm for 10 minutes;
iv) filter the solution through Whatman No. 5 filter paper.

Soil sulphate was analysed using a Technicon Auto Analyser following phosphate extraction:
i) weigh 4 g of air-dried soil into 50 ml polypropylene centrifuge tubes;
ii) add 20 ml of 0.01 *M* $Ca(H_2PO_4)_2{\cdot}H_2O$ solution and one drop of AR Chloroform;
iii) shake tubes in an end-over-end shaker for 30 minutes;
iv) centrifuge the solution at 8000 rpm for 10 minutes;
v) filter the solution through Whatman No. 41 filter paper.

Soil exchangeable potassium was analysed using an Atomic Absorption Spectroscopy (GBC 904 AA) following ammonium acetate extraction:
i) weigh 5 g of air-dried soil into 50 ml polypropylene centrifuge tubes;
ii) add 25 ml of 1 *M* NH_4OAc solution and shake tubes in an end-over-end shaker for 10 minutes;
iii) centrifuge the solution at 8000 rpm for 10 minutes;
iv) filter the solution through Whatman No. 40 filter paper;
v) dilute the extracts to 100 ml with 1 *M* NH_4OAc solution.

Potassium, magnesium, calcium and manganese for herbage samples were analyzed using an Atomic Absorption Spectroscopy (GBC 904 AA) following nitric acid digest for cation analysis:
i) weigh 0.1 g herbage into shorter 25 ml marked digest tubes;
ii) add 4 ml concentrate HNO_3 to each tube and place a small glass funnel on top;
iii) digest at 150°C until brown fuming stops;
iv) take funnels off and increase the temperature to 200°C to evaporate to dryness;
v) remove tubes from block while still warm and add 5 ml of 2 *M* HCl;
vi) top up to 25 ml mark with stock solution (0.4 *M* HCl solution containing 1000 ppm Sr and Cs).

All above methods were recommended by the Fertilizer and Lime Research Centre, Massey University.

Soil organic matter and herbage ash content were measured by ignition loss at 500°C for one hour, and soil pH was measured using a soil to water ratio of 1:2.5 according to Nicholson (1984).

Data from soil infiltration rates, soil bulk densities, soil nutrients, plant nutrient contents, litter weights and litter depths were analyzed using a linear model procedure to identify the effects of the treatments. All statistical analyses were performed using SAS GLM procedure (SAS Institute 1990).

3.3 RESULTS AND DISCUSSION

3.3.1 Soil properties

3.3.1.1 Soil infiltration rates

Effluent irrigation over 12 years significantly reduced the infiltration rates from 27 to 11 mm/min in pasture (Figure 3.2). Six year tree growth reduced the infiltration rate further to 5 mm/min. However, there was no such further reduction in the plantation irrigated with effluent.

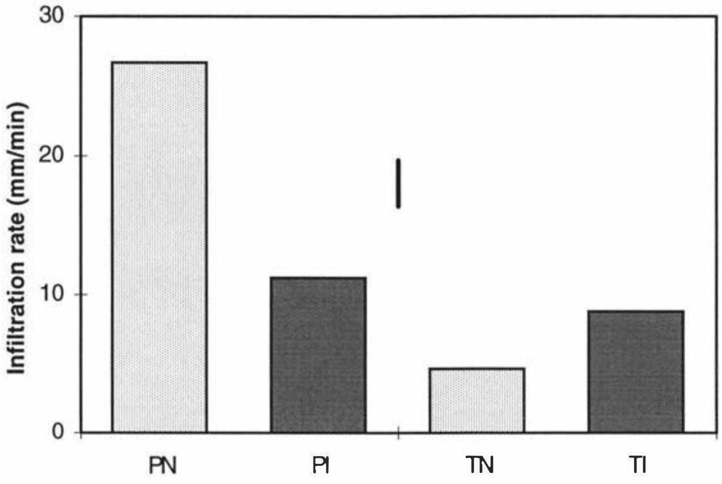

Figure 3.2 Soil infiltration rates in the four treatments (P = pasture; T = plantation; N = without irrigation; I = irrigated with effluent; n = 3; vertical bar indicates $LSD_{0.05}$).

The highest infiltration rates occurred in the soils under pasture without irrigation which in effect was the original soil. The average infiltration rate was 27 mm/min, which was much higher than the standard for agricultural topsoils ranging from 0 - 17 mm/min (Anon. 1982). Presumably, this is a consequence of soil texture, i.e. a shallow sandy loam soil overlying weathered gravels.

The infiltration rate was reduced by 60% following 12 years of effluent irrigation on the pasture site. Cook & Thorne (1990) also found the infiltration rate dropped by 50% from 5 mm/min to 2.5 mm/min after three years of treated domestic effluent application. They suggested that not only had the large pores been affected, but also there had been changes in the pore structure over a large range of pore sizes. In the soil studied here, treading damage caused by grazing stock could have a role in the reduction of the soil infiltration rates on PI. Sodium from effluent irrigation may also have played some role in the infiltration reduction under pasture. Neither of these possible caused were investigated further.

Madeira (1989) reported that soil infiltration rates were reduced by eucalypt planting from 10 mm/min to 2 - 3 mm/min, which may be due to the increase of soil bulk densities from 1.2 g/cm^3 to 1.40 - 1.45 g/cm^3. Tree planting also significantly reduced the infiltration rates in the current study (TN), but simultaneously reduced the soil bulk densities (next section). Lower soil infiltration rates and lower bulk densities under the plantations may have been caused by the litter accumulation under the trees, which provided organic matter to the topsoil following its decomposition, and thereby possibly modified soil structure and change the soil infiltration rates.

To consume the water and nutrients from effluent is one of the main aims for using plants in land treatment systems. Relatively low infiltration rates would be beneficial as it may give plants more time to absorb the water and nutrients before passing through to the groundwater. Conversely, low infiltration rates could increase the risk of ponding of the effluent if the application rates are excessive.

3.3.1.2 Soil bulk density

Irrigation of effluent on to pasture increased topsoil bulk density at 0 - 75 mm from 0.6 to 0.9 g/cm^3 over 12 years (Table 3.2). There was no such change for the bulk density values measured for the subsoil (75 - 150 mm). There were no significant differences in soil bulk densities at either depth between the six year old plantations without irrigation and irrigated with effluent. The topsoil compaction with higher bulk density following the irrigation of pasture may have resulted from grazing stock.

Mathan (1994) stated that the physical properties of sandy loam soils were improved by using sewage irrigation water, and its continued use progressively improved the hydraulic conductivity, bulk density and porosity of the soil. The longer the period of irrigation with effluent, the lower the soil bulk density value became. The depth of influence could be up to 600 mm over 15 years. In the current study, six years of tree growth reduced soil bulk density in the plantations both without irrigation and irrigated with effluent irrigation. The low bulk density in the soils under plantations may be a result of the increase in organic matter content rather than effluent irrigation.

3.3.1.3 Soil organic matter

There was little change in the soil organic matter content under pasture after 12 years of effluent irrigation (Table 3.2). Organic matter levels increased significantly following tree planting into the pasture. Under the plantations, organic matter levels were higher both in the topsoil and subsoil irrigated with effluent. Therefore in the current study, the difference in soil organic matter content was mainly due to the crops (pasture or trees) used in the systems, rather than directly from the organic matter in the effluent irrigated. The higher organic matter content in the soil under plantation irrigated with effluent than under plantation without irrigation could be results from the effluent irrigation leading to higher litter accumulation on the soil surface (Table 3.4).

The soil organic matter content had some direct influence on the soil nutrient levels (Table 3.2). Miller & Donahue (1990) indicated that the soil organic matter, from living or dead plant and animal residues, is a very active and important portion of the soil. It can be considered as a source and sink for nutrients (Killham 1994). As a source, it can help to maintain nutrient supply and increase crop production. As a sink, it could be good for effluent land treatment since it absorbs the nutrients from effluent and then releases them slowly instead of directly contaminating the ground water, or stream and rivers. It can also improve the soil structure and increase soil biota activity, which may indirectly help effluent land treatment and crop growth. However, as the soil holds large amounts of nutrients, there may be further environmental problems if the nutrients are released in a short time after some environment change, such as tree harvesting. Dyck et al. (1983) concluded that nitrate leaching after a disturbance may be more likely from fertile sites than from infertile ones though the response time may be the same. When a land treatment system is designed, these factors must be considered.

Table 3.2 Soil characteristics at two depths under pasture and eucalypt short rotation forest without irrigation and irrigated with effluent.

Site*	Depth (mm)	Bulk density (g/cm^3)	Organic matter (%)	pH	TKN** (%)	Ammonium (ppm)	Nitrate (ppm)	Total P (ppm)	Olsen P (ppm)	EK*** (meq/100g)	SO_4 - S (ppm)
PN	0 - 75	0.69 d	13.7 d	5.4 a	0.62 e	10.5 c	9.5 f	1320 f	40 f	0.50 e	21 c
	75 - 150	1.04 a	14.4 d	5.2 b	0.57 ef	14.4 a	13.2 e	1330 f	32 f	0.36 f	27 c
PI	0 - 75	0.96 b	13.4 d	4.7 cd	0.65 de	8.8 de	32.0 c	1535 e	96 cd	2.12 a	37 b
	75 - 150	1.00 a	13.1 d	4.4 d	0.53 f	9.4 d	43.6 a	1360 ef	77 e	1.59 b	36 b
TN	0 - 75	0.87 c	17.9 bc	4.7 cd	0.74 c	10.3 c	9.7 f	2520 c	101 c	0.93 d	73 a
	75 - 150	0.86 c	17.2 c	4.9 c	0.68 d	9.4 d	10.5 f	2325 d	89 d	0.92 d	71 a
TI	0 - 75	0.87 c	24.0 a	4.1 e	1.14 a	12.0 b	25.2 d	4060 a	298 a	1.42 c	73 a
	75 - 150	0.88 c	19.3 b	4.4 d	0.88 b	8.5 e	38.0 b	3235 b	182 b	1.34 c	71 a

*Site: P = pasture; T = plantation; N = without irrigation; I = irrigated with effluent;

**TKN = total Kjeldahl nitrogen; ***EK = exchangeable potassium;

Means with the same letter in same column are not significantly different by Duncan grouping (n = 5; $P < 0.05$).

3.3.1.4 Soil pH

Under pasture, pH in the topsoil was higher than in the subsoil, whereas under plantations, pH in the topsoil was lower than in the subsoil (Table 3.2). The soil became more acid after effluent irrigation under both pasture and the plantations even though the pH of the effluent was nearly neutral (Table 3.1). The soil pH was therefore not directly affected by the effluent, but possibly by microbial decomposition of organic matter. This tends to increase soil acidity through the production of organic acids (Killham 1994). Effluent application may raise this microbial activity and the pH reduction could be attributed to the production of CO_2 and organic acids by soil micro-organisms (Waly et al. 1987).

Herbert (1996) reported that the soil pH decreased after tree planting in natural grassland, which may be due to fallen litter decomposing and adding organic matter and organic acids to soil. However, the soil pH only had a little change after 6 year tree growth in the current study. Wenzel et al. (1995) reported that soil pH was higher in the soil without litter layer than in the soil with litter layer on soil surface. The lower pH in the topsoil should be the direct result of this litter decomposition. Trees continued to grow well in the study area even though the soil pH became as low as 4.0 - 4.5 under the plantation irrigated with effluent. Such low soil pH values can be found in soils under both natural and plantation eucalypt forests (Feller 1978; George & Varghese 1990b; Barros & Novais 1996; Herbert 1996; Turner & Lambert 1996). Therefore, planting eucalypts in effluent land treatment systems was a good choice for they are not sensitive to soil pH reduction following effluent irrigation.

3.3.1.5 Soil nutrients

In pasture, effluent irrigation increased Olsen phosphorus, nitrate, exchangeable potassium, and sulphate sulphur at both soil depths, and total phosphorus only in the topsoil, but reduced ammonium (Table 3.2). Tree planting increased total Kjeldahl nitrogen, total phosphorus, Olsen phosphorus and sulphate sulphur at both depths. Effluent irrigation further increased total Kjeldahl nitrogen, total phosphorus and Olsen phosphorus in the plantation, but not sulphate sulphur. It also raised soil nitrate at both depths under the plantation.

For plantation forests in New Zealand, the main fertiliser elements are phosphorus and nitrogen. New exotic plantings are fertilised annually (Ballard 1978). Fertilizer (mainly nitrogen and phosphorus) is usually essential for the successful establishment of eucalypts (Knight & Nicholas 1996) as it can significantly influence eucalypt growth (Messica 1990). In the current study, effluent irrigation significantly improved soil nutrient content, especially the available nutrients, i.e. available nitrogen, Olsen phosphorus and exchangeable potassium both under pasture and plantations. Hence, the irrigation should increase crop yield. The higher nitrate in the soil after effluent irrigation increased the risk of leaching to ground water. The risk may be reduced in plantation as the tree roots distributed much deeper than pasture roots.

Water has also been considered as one of the most important parameters in reducing tree growth (Pereira et al. 1996). Water stress is largely responsible for loss of forest tree productivity (Pereira & Pallardy 1989). Therefore, the supplement of nutrients and water by effluent irrigation instead of commercial fertiliser and conventional irrigation must be advantageous for forest production.

3.3.2 Plant nutrient composition

In trees, the ash content was reduced by effluent application in leaf, branch and bark, but there was little change in twig and wood components (Figure 3.3). A darker ash colour was found in all the components from trees irrigated with effluent. Further leaf ash chemical analysis by X-ray fluorescence analysis showed manganese was the main element to make the difference (Figure 3.4). Thereafter, manganese was included in the following studies.

Effluent irrigation on to pasture increased the content of nitrogen, phosphorus, potassium, and manganese, reduced ash content, but had little effects on levels of magnesium and calcium (Table 3.3).

In plantations, nitrogen levels were increased in leaf and twig by effluent irrigation, but not changed in the other tree parts. Phosphorus levels were increased in leaf, twig and bark components, but not changed in branch and wood. Potassium levels were increased in twig and branch, reduced in bark and wood, but not changed in leaf component. Calcium was reduced in all tree parts except wood. Magnesium was reduced in leaf, twig and branch, but not changed in bark and wood. Manganese was increased in all tree components.

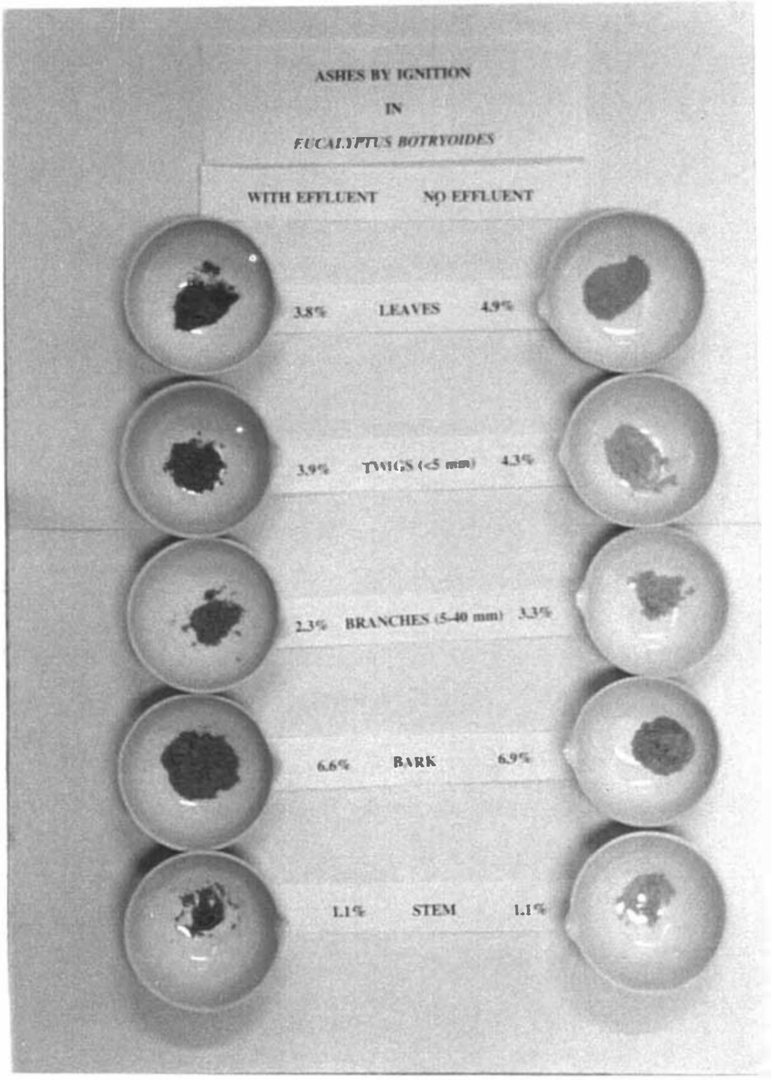

Figure 3.3 Ash content in tree components of *E. botryoides* without irrigation (right) and irrigated with effluent (left; note the darker colour).

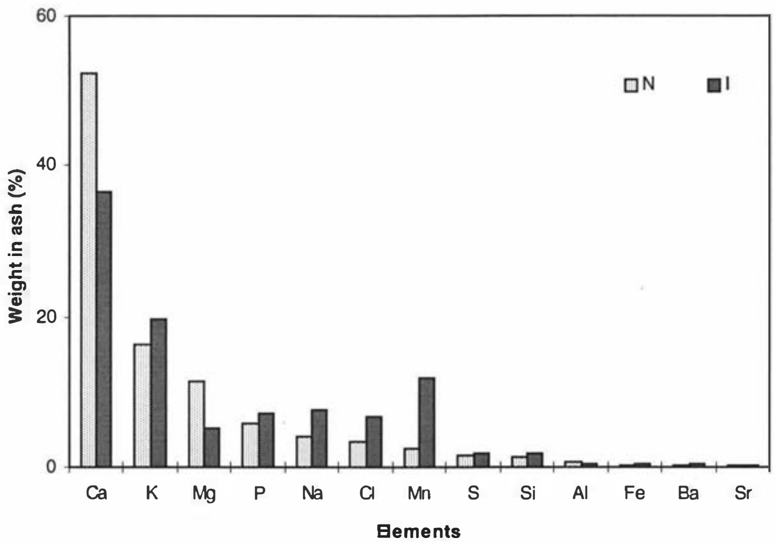

Figure 3.4 Element contents in *E. botryoides* leaf ash (N = without irrigation; I = irrigated with effluent).

The chemical composition of *E. tereticornis* seedlings varies according to the provision of resources in their environment, and this has direct consequences for the herbivores feeding on their leaves (Lawler et al. 1997). More birds were found in the plantation irrigated with effluent (data not shown). It may relate to the nutrient concentration change responding to nutrient supply from effluent.

Effluent irrigation changed the plant chemical composition. Whether these changes represent an increase or decrease in quality depends on the further use of the plant materials. Wells & Whitton (1970) reported that in ryegrass, irrigation with meatworks effluent raised the levels of nitrogen and potassium, lowered the level of manganese, but did not change the levels of phosphorus, magnesium and calcium. They stated that the resulting nutrient composition of the ryegrass plants irrigated with effluent was more favourable to animal health. In the present study, the effluent irrigation on pasture increased levels of nitrogen, phosphorus, potassium, and manganese, reduced the ash content, but had little influence on magnesium and calcium. This could also be favourable to animal health. Further study should be conducted on how much the change influences the grass quality, palatability, nutrient balance (including deficiencies or toxic levels), and even the quality of meat, wool, and milk products.

Table 3.3 The nutrient composition of pasture and tree components without irrigation and irrigated with effluent.

Plant	Part	Site*	Ash content (%)	Nitrogen (%)	Phosphorus (mg/g)	Potassium (mg/g)	Calcium (mg/g)	Magnesium (mg/g)	Manganese (mg/g)
Pasture	Above ground	PN	11.5 a	1.7 c	2.3 c	18.6 b	2.6 i	1.2 d	0.2 g
		PI	8.5 b	2.6 a	4.0 a	23.7 a	2.8 hi	1.2 d	0.3 f
Tree	Leaf	TN	4.9 d	2.1 b	1.3 e	7.4 e	8.7 d	2.5 a	0.9 c
		TI	3.8 ef	2.6 a	1.5 d	7.5 e	5.7 g	1.7 b	1.2 b
	Twig	TN	4.3 de	0.6 e	1.4 de	4.0 g	10.7 c	1.4 c	0.4 ef
		TI	3.9 ef	0.8 d	3.1 b	9.6 d	6.0 f	1.0 e	0.7 d
	Branch	TN	3.3 f	0.6 e	1.0 g	6.1 f	7.8 e	0.9 ef	0.3 f
		TI	2.3 g	0.6 e	1.1 g	9.4 d	3.6 h	0.7 g	0.5 e
	Bark	TN	6.9 c	0.7 de	0.4 h	12.2 c	20.8 a	1.0 e	0.6 de
		TI	6.6 c	0.8 d	0.9 g	7.7 e	16.9 b	0.9 ef	1.6 a
	Wood	TN	1.1 h	0.6 e	0.3 h	3.4 g	1.6 j	0.2 h	0.1 h
		TI	1.1 h	0.5 e	0.4 h	2.9 g	1.6 j	0.3 h	0.2 g

*Site: P = pasture; T = plantation; N = without irrigation; I = irrigated with effluent;
Means with the same letter in same column are not significantly different by Duncan grouping (n = 5; $P < 0.05$).

Compared with trees without irrigation, less ash content was found in the trees irrigated with effluent in all tree parts except the wood. The ash content of biomass used for energy purpose can influence the heating value (Lewandowski 1996). The ash, although representing only a minor proportion by weight, appears to be a major determinant in the combustion behaviour of a material (Krigstin et al. 1993) . The quantity of ash, as well as its chemical and physical properties, will affect the seriousness of the problem to foul equipment and atmospheric pollution (Heilman 1992). As the ash content reduces the heat of combustion, species of high ash content are less desirable for industrial fuelwood (Singh & Khanduja 1984).

If all above ground biomass is to be harvested and used for energy production, the biomass with less ash content from trees irrigated with effluent could be preferable than the biomass from trees without irrigation, even though the increased content of some elements may not be beneficial to certain energy conversion equipment. After effluent irrigation, the nutrient concentration of nitrogen, phosphorus and manganese in the tree leaves increased, while calcium and magnesium decreased and little change occurred in potassium. Overall, the nutrient concentrations in tree leaves were still within the range of values given for plantation eucalypts (Judd et al. 1996) though magnesium was less than the typical range, and nitrogen and manganese in the leaves from trees irrigated with effluent were above the typical range.

Any difference in nutrient contents of plant components between without irrigation and irrigated with effluent could be directly attributed to the addition of nutrients from the effluent, or indirectly from other changes following effluent irrigation. For example, the manganese concentration was up to more than two times higher in plant components from trees irrigated with effluent than in the same parts from trees without irrigation. However, only a little manganese (0.4 g/m^3) was applied in the effluent. Macagni & Baker (1992) indicated that soybean manganese concentration increased with manganese application but was not affected when lime was also applied. Maher & Thomson (1991) reported that tomato plant manganese content was closely correlated with the concentration of exchangeable manganese in the soil but not with the level of easily reducible or total manganese. Wells & Whitton (1970) found manganese in ryegrass was lower when irrigated with meatworks effluent, but the soil pH was above 6 in their study. Foliar manganese showed some negative correlation with soil pH in a New Zealand country-wide survey on *E. regnans*, *E. delegatensis* and *E. saligna* (Knight & Nicholas 1996). The higher manganese levels in the plant components irrigated with effluent in the present study, therefore, were possibly a result of the soil pH reduction following effluent irrigation.

Feigin et al. (1991) suggested that the range of manganese in plant tissue is 0.015-0.15 mg/g and phytotoxic levels in plant foliage range between 0.4-2 mg/g dry matter. However, more biomass was produced in the trees irrigated with effluent (Lowe 1994) though with higher manganese content in all tree components than the trees without effluent.

Bargali et al. (1992b) found that the concentration of nutrients among different tree components increased in the order: leaves > twigs > branches > bole (wood + bark). In the current study, however, some nutrients were more concentrated in certain tree components than in others, e.g. nitrogen and magnesium in leaves, phosphorus in twigs, and calcium in bark. Ericsson (1994) indicated that plantations managed for short rotations are the most nutrient-demanding, and cause the greatest loss of nutrients from the site at harvest. Therefore, which tree components should be removed from or kept on the site when harvesting must be determined according to the purpose of the system. For short rotation forests not linked with effluent land treatment, tree parts with high nutrient concentration, such as leaves and young branches, should be kept on the site for sustainable land use. However, all the biomass and especially the parts with high nutrient concentrations should be harvested and removed from the site in land treatment systems to give sustainable land use where nutrient removal is one of the main objectives. Eucalypts can be harvested all year around to guarantee maximum nutrient removal for they are evergreen tree.

3.3.3 Litter accumulation in plantations

Much more litter was found on the forest floor under the plantation irrigated with effluent in terms of both depths of layer above the soil surface and the oven dry weight per hectare, particularly in the decaying layer (Table 3.4). The fresh litter layer on the forest floor under the plantation without irrigation was deeper because it was dry and loose rather than being higher dry matter present.

A large quantity of nutrients were present on the forest floor under the plantations. This was especially the case for the plantation irrigated with effluent, which had about four times more nitrogen, phosphorus and potassium, three times the magnesium and manganese and double the calcium and ash than in the plantation without irrigation.

Table 3.4 Litter and nutrient accumulation on the forest floor under eucalypt short rotation forest without irrigation and irrigated with effluent.

Site*	Layer	Litter**		Nutrient Content mg/g *** (Total kg/ha)						
		Depth (mm)	Weight (OD t/ha)	N	P	K	Ca	Mg	Mn	Ash
TN	Leaf	20	2.9	12 (34) c	0.8 (2) c	2.0 (6) c	16.5 (48) a	1.8 (5) b	1.0 (3)bc	70 (20) d
	Branch		1.1	11 (12) c	0.9 (1) c	2.7 (3) b	14.5 (16) b	1.5 (2)bc	0.6 (1) c	79 (9)cd
	Decaying	06	10.7	17(187) b	1.8(19) b	2.8 (30) b	15.8(169)ab	2.1(22) a	1.3(14) b	308(330) a
	Total	26 b	14.7 b	(233)	(22)	(39)	(233)	(29)	(18)	(359)
TI	Leaf	10	3.2	15 (48) c	1.1 (3)bc	2.4 (8)bc	11.3 (36) c	1.6 (5)bc	3.1(10) a	84 (27) c
	Branch		2.3	15 (33) c	1.1 (2) c	2.2 (5) c	14.0 (32) b	1.3 (3) c	1.1 (3) b	91 (21) c
	Decaying	35	33.3	27(888) a	2.7(89) a	3.9(123) a	7.4(246) d	2.2(73) a	1.1(36) b	169(593) b
	Total	45 a	38.8 a	(969)	(95)	(143)	(314)	(81)	(49)	(611)

*Site: TN = plantation without irrigation; TI = plantation irrigated with effluent;
Means with the same letters in same column are not significantly different by Duncan grouping (**n = 10; ***n = 5; $P < 0.05$);
OD = oven-dry.

Trees absorb nutrients from the soil to support their growth. At the same time they return nutrients to the soil through litter fall. Litter, including leaves, branches, bark and other tree components, eventually decomposes and releases nutrients back to the soil. This plays a major role in the transfer of energy and nutrients in woodland ecosystems. Hence, productivity of ecosystems is often indicated by the rates of litter-fall accumulation and its decomposition (Toky & Singh 1993).

In both plantations without irrigation and irrigated with effluent, the concentrations of nitrogen, phosphorus, potassium, and magnesium in the fresh leaves were higher than in the litter leaves, but they had lower calcium and ash content (Tables 3.2 - 3.3). Manganese content in the fresh litter leaves was two times more than in the living leaves in the plantation irrigated with effluent, but there was little difference in the plantation without irrigation. These changes may be caused by translocation before abscission, and leaching before and after litterfall (Toky & Ramakrishnan 1983a). Therefore, the leaves should be harvested before their abscission and removed from the site if removal of nutrients (especially K) is one of the main objectives.

Over a 6 year period, litter had accumulated to 14.7 oven-dry (OD) t/ha on the forest floor under the plantation without irrigation. This was comparable with 17.0 OD t/ha in a 4 year old stand planted at 14933 trees/ha and 21.6 OD t/ha in a 8 year old stand planted at 1486 trees/ha of *E. tereticornis* (Toky & Singh 1993). O'Connell & Grove (1996) indicated that the build-up of litter is rapid following fire and can reach 23 - 30 OD t/ha within 8 years in *E. diversicolor* forests. They proposed that the predicted equilibrium mass of the forest floor (annual litterfall equals decomposition) is approximately 40 OD t/ha. Equilibrium masses of 44 and 47.5 OD t/ha were measured in the forest floor under *E. regnans* forests (Feller 1978; Feller 1980). Conversely, no litter accumulation could be found under an 11 year old *E. regnans* plantation with relatively low tree density (800 trees/ha) (Guo 1993). In the present study, 2.6 times more litter by weight (38.8 OD t/ha) accumulated in the forest floor under the plantation irrigated with effluent than without irrigation. As pH reduction down to pH 3.0 had very little effect on the leaf litter decomposition (Neuvonen & Suomela 1990; Dursun et al. 1993), the lower soil pH under trees irrigated with effluent would have had only a limited effect on the greater litter accumulation.

The amount of litter accumulation is dependent on the litter input from trees and the output by decomposition. According to Bray & Gorham (1964), annual forest litter production in the world varies from 1.0 OD t/ha/y in the arctic-alpine regions to 10.9 OD t/ha/y in equatorial regions. In natural *E. regnans* forests, Ashton (1975) found the annual litter fall was high by world standards (7.66 OD t/ha/y). Toky & Singh (1993) recorded an annual litter fall of 7.2 and 9.1 OD t/ha/y in 4 and 8 year old stands of *E. tereticornis*, respectively. Negi & Sharma (1996) reported litterfall as high as 16.8 OD t/ha/y under 20 year-old *E. camaldulensis* planted on fertile soil. Overall, eucalypts return large amounts of litter due to their fast growth. In the current study, the greater litter accumulation under the plantation irrigated with effluent could have been partly caused by the faster growth of trees since more biomass was produced in the same plantation irrigated with effluent than the one without irrigation (Lowe 1994).

Litter output, the decomposition, can be influenced by environmental factors, such as moisture, temperature, light and biota. Toky & Singh (1993) reported only 29% weight loss from the eucalypt litter in one year and compared it with 87% loss in a moist site. O'Connell (1987) found the most rapid weight loss from eucalypt leaf litter occurred during the first wet season. Baker et al. (1990) reported sewage effluent irrigation increased weight loss from *Pinus radiata* needle litter. The trend was different in the present study since much more litter accumulated in the plantation irrigated with effluent than in the plantation without irrigation. Effluent irrigation may even retard litter decomposition. The relatively high tree density of the plantation plus sufficient moisture from the effluent could be responsible for the higher litter accumulation. Therefore, the greater litter accumulation in the plantation irrigated with effluent could have been caused either by the fast tree growth or by the environmental change resulting from the effluent irrigation, or both.

The return of forest litter is an important process in forest ecosystems. It replenishes soil organic matter, gradually releases nutrients to the soil and creates a wide variety of niches for fauna and micro-organisms. This in turn helps to improve the tree root environment and the uptake of nutrients for successful growth. Forest litter can absorb water like a giant sponge. This water is then slowly released to the groundwater by percolating through soil to streams, creeks and rivers without dislodging soil particles, therefore helping to maintain water purity.

Under a forest effluent land treatment system, the litter has potential to absorb and filter a portion of nutrients from the effluent. Fauna and micro-organisms, inhabiting in and absorbing energy from the litter, may help to consume and/or remove some potentially dangerous trace elements, disease pathogens, and nutrients from the effluent by chemical and biochemical processes. Miller (1973) concluded that soil fungi become the dominant numerical group of soil micro-organisms in litter layer (A_0) and A_1 horizons of acidic forest profiles. The microbial population is concentrated primarily in the top 150 mm of the organic matter rich region of the soil, but decreases rapidly with depth. Relatively slow soil infiltration rates and the litter accumulation on the soil surface could slow the effluent movement in the soil profile, which would give the trees more time to consume the water and the nutrients from the effluent, and reduce the potential for leaching losses of nitrogen. At the same time, the litter layer would protect the top soil from erosion and reduce the chance of direct effluent runoff from soil surface. The litter mat constitutes a physical barrier for seeds, seedlings, and shoots because it may impede or retard seeds reaching the soil, and inhibit the emergence of seedlings or sprouts (Facelli & Pickett 1991). The mat may also reduce the weed competition to early coppice growth soon after trees are harvested in coppice short rotation forests.

Some nutrients can not only be removed from the systems by harvesting, and but also by other ways, such as nitrogen volatilisation. Loehr et al. (1979b) indicated that biodenitrification is the conversion by micro-organisms of nitrate into gaseous forms of nitrogen. This is beneficial because nitrate may be readily leached from the soil to the groundwater. Land application systems must bring nitrate and organic carbon together in order to encourage biodenitrification. Wild (1993) reviewed denitrification and concluded that denitrification requires the presence of nitrate, metabolizable carbon compounds and the almost complete absence of oxygen at the site. The soil does not need to be devoid of oxygen because denitrification will occur at micro-sites that are anaerobic.

In pasture irrigated with meatworks effluent, denitrification and ammonia volatilisation are negligible being only 2.5 - 4% of the applied annual nitrogen (Russell et al. 1988; Russell et al. 1991). However, in plantation irrigated with meatworks effluent, denitrification losses averaged about 27% of the applied annual nitrogen (Russell et al. 1991). The litter layer on the soil surface and organic matter in the top soil under plantations may play a special role for it can provide sufficient organic carbon, the effluent irrigation can reduce soil oxygen level intermittently and nitrate can be formed by nitrification from other nitrogen forms. Therefore, denitrification in forest land treatment systems may relieve groundwater contamination problems by reducing nitrate leaching.

The litter layer stores large amount of nutrients. In the current study, much greater quantities of nutrients were stored in the plantation irrigated with effluent than in the plantation without irrigation (Table 3.4). If the plantation is managed to remove nutrient in the effluent land treatment systems, the litter accumulated in the forest floor should be also removed from the site. Otherwise nutrients stored in this layer could be suddenly released a short time after some major environmental change, for instance, tree harvesting.

Hillis (1990) stated that some of the increasing plantation areas of fast growing trees are being established for their social value. This is dependent on the interactions between environmental improvement (erosion control, shelter, *etc*.), growth rate, and the total value of the products (firewood, cash crops, *etc*.). He suggested that eucalypts and other fast growing young trees remove more carbon dioxide from the atmosphere each year than a mature forest. Litter accumulated on the soil surface, and organic matter in the soil are also carbon sinks. In the long term, production of energy forests to substitute for fossil fuels may be more effective by carbon dioxide cycling than by carbon storage in either forests or forest products as these will eventually saturate with time.

A full nutrient budget of the two systems (pasture and plantation) without irrigation and irrigated with effluent could not be estimated. Such an exercise would have required measurements of nutrient input from effluent irrigation, the plant uptake of nutrients from the soil, an assessment of the nutrient return via litter falling, nutrient removal during harvesting, the role of the litter layer (a special phenomenon in forest ecosystems) and the factors influencing litter decomposition in the land treatment systems. Further research should be done on these aspects, especially on nutrient cycling in short rotation forests (the main objectives of the next few chapters). This would provide useful data for successful management of short rotation forests linked with land treatment systems.

3.4 CONCLUSIONS

Effluent irrigation is beneficial to crop growth due to the addition of soil nutrients and water. There is good potential to use short rotation forests in well designed and managed effluent land treatment systems. Some resulting characteristics, such as relatively slower soil infiltration rates, litter layer accumulation on the soil surface and increased organic matter in the top soil, could be advantageous to nutrient stripping. Nutrients can be removed from the site by harvesting all the above ground biomass, as well as the litter accumulated on the forest floor. Components from the trees irrigated with effluent may be profitable for their energy conversion as they have less ash content.

4. LITTER PRODUCTION AND DECOMPOSITION IN EUCALYPT SHORT ROTATION FORESTS

4.1 INTRODUCTION

Trees in forests absorb nutrients from the soil to support their growth. At the same time some part of the nutrient uptake is returned to the forest floor via litter fall. They will be released to the soil via litter decomposition. The litter accumulating on the forest floor provides energy, nutrients and a living environment to the soil fauna and micro-organisms. Litter, therefore, plays a major role in the transfer of energy and nutrients within a woodland ecosystem and is also a key component of forests as carbon sinks.

Short rotation forests have potential as a renewable source of energy and could reduce the energy demands currently met by fossil fuels. However, frequent harvesting of the trees can remove large quantities of nutrients, such as nitrogen and phosphorus, from the soil, especially when harvesting all the above ground biomass including leaves which is usually the case for short rotation forest systems.

The rate of cycling of nutrients through the decomposer subsystem is an important regulator of ecosystem productivity (Swift et al. 1979). In highly-productive plantation forestry, it becomes important to effectively manage soil development, nutrient cycling and manipulation of litter decomposition productivity (Adams & Attiwill 1986). Therefore, the amount of litter fall and nutrient return via the fall, the litter decomposition and nutrient release via the decomposition, and their seasonal variations need to be clearly understood in order to manage nutrient balances for long-term sustainable land use when growing short rotation forests.

Litter fall and nutrient return in the forest system have been studied and reviewed by many authors (Bray & Gorham 1964; Ashton 1975; Attiwill et al. 1978; Hart 1995). Other studies dealt specifically with short rotation forests (George 1982; George & Varghese 1990b; Toky & Singh 1993). Adams & Attiwill (1986) indicated that the slow rate of decomposition of eucalypt forest litter, resulting in the storage of significant amounts of nutrients in the soil, has been recognised as a feature of this genus. Bargali et al. (1993) indicated that decomposition processes play an important role in soil fertility in terms of nutrient cycling and formation of soil organic matter. Among the factors that control rates of litter decomposition in forests, the influences of climate (temperature, humidity and moisture) and litter quality (e.g. lignin-to-N, C-to-N, the availability of N and P) have been well documented (Nagy & Macauley 1982; Taylor et al. 1991; Attiwill & Adams 1993; Prescott 1996).

However, little information has been published about the tree density effect on eucalypt litter production and nutrient return via litter fall, litter decomposition and nutrient release via litter decomposition.

The objectives of this study were to investigate:

1. litter production and nutrient return via the litter fall under different tree planting densities;
2. litter decomposition and nutrient release via the litter decomposition between various leaf litter types under different tree planting densities;
3. seasonal variations of litter fall and litter decomposition over a period of one year.

4.2 METHODS

4.2.1 Study site

Two trials were established at Massey University, Palmerston North, New Zealand (latitude 40°23′S, longitude 175°37′E) where the 10-year average annual rainfall is 995 mm, the mean annual soil temperature (100 mm) is 13°C. Monthly distributions of rainfall and soil temperature are shown in Figure 4.1. Temperatures during the period of study from July 1994 till June 1995 were close to the average, but rainfall was slightly above average.

The soils are recent belonging to the Rangitikei soils series made up of well to excessively drained and gravely soils. The soil profiles are weakly developed, and variable in both depth and texture. Before the trees were planted, soil pH was 5.5 - 6.2, Olsen phosphorus 6 - 17 mg/g, SO_4 2.8 - 8.5 mg/g, exchangeable potassium 0.09 - 1.37 mg/g, exchangeable calcium 4.0 - 8.2 mg/g, exchangeable magnesium 1.14 - 1.65 mg/g, exchangeable sodium < 0.1 - 0.3 mg/g, and a cation exchange capacity 14 - 16 meq/100 g air dry weight.

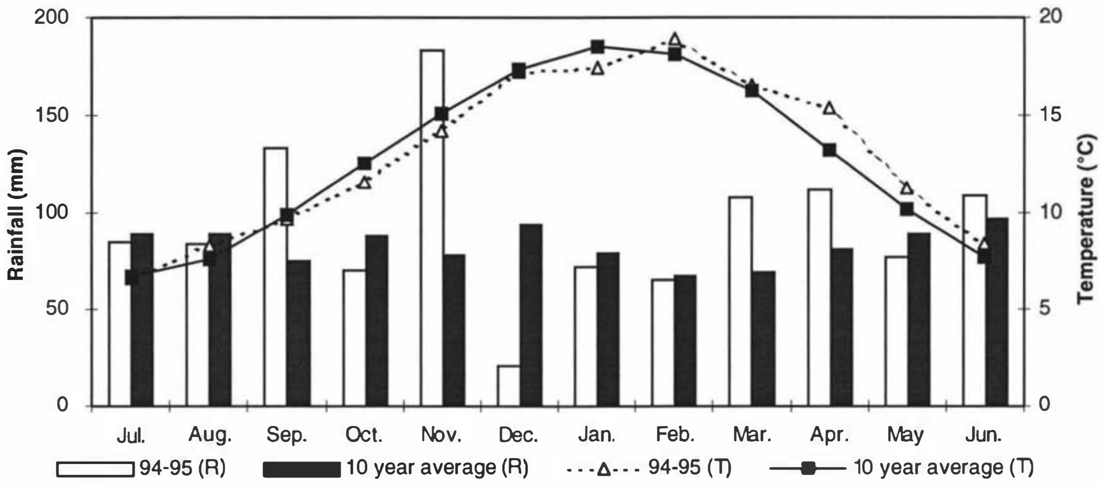

Figure 4.1 Monthly rainfall (R) and average soil temperature (T) at 100 mm depth for the study site at Massey University, Palmerston North, New Zealand.

Two radial trials designed after Nelder (1962) with plant densities ranging from 2000 to 20, 000 trees/ha were monitored. One trial of *Eucalyptus brookerana* A. M. Gray (BR) had been established in November 1991 and the other of *E. saligna* Smith (SA) in November 1987. The latter had been harvested twice previously (November 1990 and 1993) and the third rotation coppice regrowth was 7 months old when litter monitoring began. The BR trial was ready for its first harvest at 4 years old on completion of the monitoring period.

4.2.2 Experimental design and materials

Two experiments were conducted to evaluate:

i) the amounts of litter fall and nutrient return from young eucalypt trees grown as short rotation forests; and

ii) the rates of litter decomposition and nutrient release on the forest floor under the short rotation forests.

4.2.2.1 Experiment one: litter fall and nutrient return

A factorial experimental design was used to monitor litter fall with two factors: month (twelve months from June 1994 to June 1995) and plant density. Three densities were selected within those represented in the BR trial: 2340, 4130, and 9803 trees/ha with three replicates of each; and five in the SA trial: 2000, 3060, 5710, 10,750, and 20,000 with two replicates of each. To catch the litter, the tray method (Newbould 1967) was used. Since the current study was on short rotation forests, trays were put directly on to the forest floor under the trees as Swift et al. (1979) suggested for dwarf shrubs. Litter trays used were 440 × 350 × 170 mm in BR and 540 × 400 × 160 mm in SA, both with 2 mm mesh to permit drainage of rain water but without any litter loss. Litter was collected from the trays monthly after Toky & Ramakrishnan (1983a).

4.2.2.2 Experiment two: litter decomposition and nutrient release

A second factorial experimental design with repeated measurements was used to monitor litter decomposition. Two factors were evaluated: tree density (2340, 4130, 9803 trees/ha in the BR trial) and litter type (*E. brookerana* leaf litter, and two types of *E. botryoides* leaf litter, one from trees irrigated with meatworks effluent, and the other from trees without irrigation). The nylon mesh bag technique (Bocock & Gilbert 1957) was used to monitor litter decomposition. Nylon bags (100 × 150 mm) with 1 mm mesh were used in the current study after Gallardo & Merino (1993) as they considered the mesh was small enough to prevent major losses of the smallest leaves, yet large enough to permit aerobic microbial activity and free entry of small soil animals.

In April 1994, *E. botryoides* fresh litter leaves were collected from forest floor under two six year old stands, one irrigated with meatworks effluent and one without irrigation at Oringi (see section 3.2.1 for more details about the site and trees). *E. brookerana* fresh litter leaves were taken under the BR trial at same time. Two grams of the sample of air-dried leaf material were weighed out (to the nearest 0.01 g) and placed in each litter bag. The filled litter bags were transported and stored in plastic bags in order to minimize any error through spillage (Wieder & Lang 1982). In June 1994, the litter bags were anchored on the forest floor using three replicates of four bags each to allow 3 monthly collection in the 12 month period. Overall, 108 litter bags were used. Five extra bags from each of the three litter types were retained in the laboratory to determine the initial moisture content (80°C) and chemical composition.

4.2.3 Laboratory analysis

After each litter collection from the trays in experiment one, the litter was divided into two components, leaf and non-leaf (consisting of branch and bark). No flowers and fruits were obtained in the litter since the trees were too young. The litter of each component was weighed out after overnight (8 - 24 hours) oven drying at 80°C. The oven-dried samples of litter from under the two medium plant densities (4130 trees/ha in BR, 5710 trees/ha in SA) were analysed to assess nutrient concentration change during the 12 month period. The all year samples from the other six populations were bulked individually before chemical analysis.

After each 3 monthly bag collection in experiment two, the litter from the litter bags was brushed and made free of weed leaves, seeds and roots, tree roots, fauna and other foreign materials by hand. After oven-drying and weighing, the litter was sealed in plastic bags for subsequent chemical analysis.

All samples for chemical analysis were ground to pass through 1 mm sieves. Nitrogen and phosphorus were analysed using a Technicon Auto Analyser following Kjeldahl digestion (details see section 3.2.3).

Litter dry weight loss and nutrient release were calculated as follows:

$$L\ (\%) = 100^*(W_0 - W_t) / W_0$$

and

$$R\ (\%) = 100^*(W_0C_0 - W_tC_t) / W_0C_0$$

where L is litter dry weight loss; R is nutrient release; W_0 is the initial litter dry weight; W_t is the dry weight of the remaining litter in litter bag when it was collected; C_0 is the nutrient concentration (mg/g) in the initial litter; C_t is the nutrient concentration (mg/g) in the remaining litter.

4.2.4 Statistical analysis

The data were analyzed to show seasonal effects on the amount of litter fall and nutrient return, litter decomposition and nutrient release under various population densities using the SAS GLM procedure (SAS Institute 1990).

The litter decomposition was modelled exponentially (Olson 1963):

$$W_t = W_o e^{-kt}$$

where W_o is the initial leaf litter dry weight, W_t the dry weight at time t, and *k* the annual instantaneous decay constant.

4.3 RESULTS AND DISCUSSION

4.3.1 Experiment one: litter fall and nutrient return

4.3.1.1 Weight of litter fall

The average dry weights of litter caught in the trays under the various tree populations are shown in Figure 4.2. There was no significant difference in weight between the plant densities 4130 and 9803 trees/ha in the BR trial, but both were significantly higher than the lowest density of 2340 trees/ha which had not reached canopy closure at that stage.

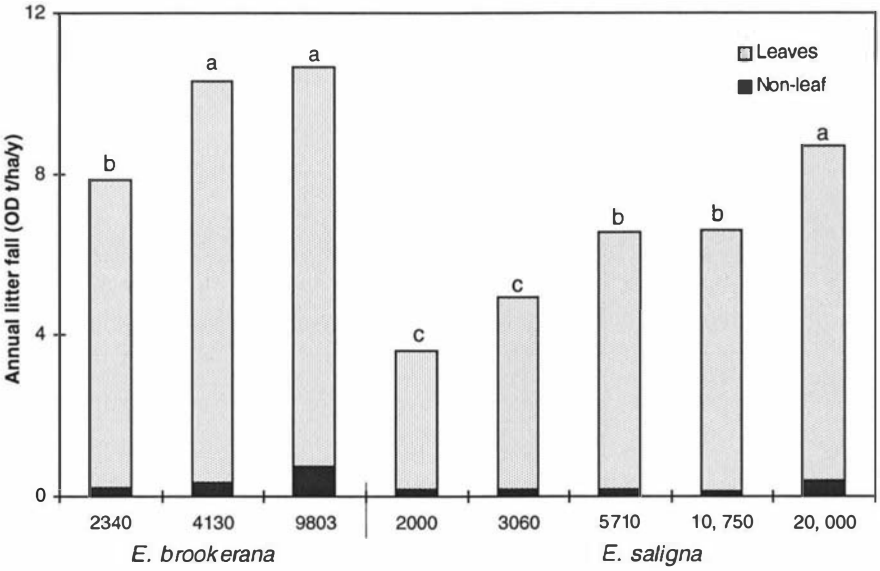

Figure 4.2 Annual litter fall in the two eucalypt population trials (trees/ha; the same letter in each species indicates no significant difference by Duncan grouping, $P < 0.05$).

The greatest litter fall in the SA trial was also found under the highest plant density and it decreased with lower densities (Figure 4.2). Litter fall had already started when the monitoring began in June 1994 (7 months after the second coppice harvest), especially from the trees at the higher densities (10,750 and 20,000 trees/ha). This was earlier than expected as the plant regrowth was only 1 to 2 m tall at that time.

Jensen (1974) pointed out that the age of the trees is important to litterfall only in very young stands, the amount of litter increases with increasing age until the canopy becomes closed, and then the annual litter fall tends to remain fairly constant over a long period of time. However, canopy closure is not only related to stand age, but is also closely related with tree density. Its effects on litter fall will also decline soon after the tree canopy closes in the forests.

The canopy closed relatively quickly in the coppiced populations due to the multi-stem characteristics of the coppiced trees and their fast regrowth after harvest. These were the main reasons for the litter fall starting sooner than expected.

The annual cumulative litter fall ranged between 7.9 to 10.6 OD t/ha/y under the 4-year-old *E. brookerana* plantation whereas it ranged from 3.6 to 8.7 OD t/ha/y under the newly coppiced *E. saligna* trees.

Bray & Gorham (1964) gave a comprehensive account of the litter production in the indigenous forests of the world. Equatorial forests produced the maximum amount of annual total litter (10.9 OD t/ha/y) followed by warm temperate forests (5.5 OD t/ha/y), cool temperate (3.5 OD t/ha/y) and arctic alpine (1.0 OD t/ha/y). Litter fall quantities in the current study were similar to those of equatorial forests and higher than those of the warm temperate forests even under some densities of the newly coppiced stands.

Attiwill & Adams (1993) reviewed that up to 10 OD t/ha litter deposited annually on the forest floor in the more highly productive forests. Litter fall in *Eucalyptus* natural and plantation forests was listed in Table 4.1. The highest amounts of litter fall (8 to 10 OD t/ha/y) in the present study were greater than those from eucalypt natural forests, but comparable with some of results from fast growing plantations, especially when grown under high plant densities.

Leaves fall from rapidly growing crowns more quickly than from slow growing ones if general conditions are equal (Jacobs 1955). The faster the tree grows, the more litter it produces (Penfold & Willis 1961). Litterfall is greatest on moist, warm, fertile and highly-productive sites and least on dry, cold, infertile and poorly-productive sites (Negi & Sharma 1996). The high values may have been related to the fast growth rates and also to self-shading in high density stands which promoted litter fall (Toky & Singh 1993). Recent results showed *E. brookerana* to be one of the highest yielding species for biomass production in the study area (Sims et al. 1998). Therefore, the relatively high litter fall measured in the current study should be due to the fast growing young trees having strong competition between each other and rapid self-shading at the higher densities.

Table 4.1 The annual litter fall, the percentage of leaf component in the litter, and the annual nitrogen (N) and phosphorus (P) return in *Eucalyptus* forests grown under varying management systems (-: not available).

Species	Origin	Age (year)	Density (trees/ha)	Annual litter fall (OD t/ha/y)	Leaves in the total litter (%)	N return (kg/ha/y)	P return (kg/ha/y)	References
Eucalyptus hybrid	Planted	5	1100 - 1200	3.4	76	30	1.6	George (1982)
E. saligna	Planted	2	2000	3.6	95	31	2.2	the present study
Eucalyptus hybrid	Planted	7	1100 - 1200	3.8	66	32	1.9	George (1982)
E. obliqua	Natural	80-90	650	3.9	67	24	0.9	Baker (1983)
E. obliqua	Natural	45 - 60	704 - 976	3.6 - 5.5	54	-	1.0	Attiwill et al. (1978)
E. saligna	Planted	2	3060	4.9	96	49	3.8	the present study
E. obliqua	Natural	70-80	380	5.2	51	30	1.5	Baker (1983)
E. sieberi	Natural	60	1190	5.4	50	21	1.1	Baker (1983)
E. regnans	Planted	4	1400	5.6	88	46	3.3	Frederick et al. (1985b)
E. diversicolor	Natural	5	4000	5.7	71	36	1.5	O'Connell & Grove (1993)
E. globulus	Planted	40	1400	5.8	77	21	1.2	Lisanework & Michelsen (1994)
Eucalyptus hybrid	Planted	10	1100 - 1200	6.2	75	59	3.9	George (1982)
E. saligna	Planted	2	5710	6.5	97	65	4.5	the present study
E. regnans	Natural	23	1025	6.6	52	44	1.3	Ashton (1975)
E. saligna	Planted	2	10750	6.6	98	71	4.6	the present study
E. regnans	Planted	19	560	6.9	38	46	2.0	Baker (1983)
E. regnans	Planted	13	1250	7.0	67	43	2.0	Frederick et al. (1985b)
E. regnans	Planted	7	1575	7.1	69	51	3.3	Frederick et al. (1985b)
E. tereticornis	Planted	4	14,933	7.2	62	-	-	Toky & Singh (1993)
E. regnans	Natural	52	211	7.7	51	-	-	Ashton (1975)
E. regnans	Natural	220	46	7.8	52	58	1.9	Ashton (1975)
E. brookerana	Planted	4	2340	7.9	97	85	4.6	the present study
E. regnans	Planted	10	1400	8.1	70	57	3.8	Frederick et al. (1985b)
E. globulus	Planted	10	1575	8.5	40	58	4.6	George & Varghese (1990b)
E. saligna	Planted	2	20000	8.7	95	84	5.1	the present study
E. tereticornis	Planted	8	1486	9.1	58	-	-	Toky & Singh (1993)
E. brookerana	Planted	4	4130	10.3	97	121	7.0	the present study
E. regnans	Planted	17	1680	10.6	54	66	4.5	Frederick et al. (1985b)
E. brookerana	Planted	4	9803	10.7	93	141	8.2	the present study
E. camaldulensis	Planted	20	-	16.8	-	188	18.0	Negi & Sharma (1996)

4.3.1.2 Components of litter

Leaves were the main contributor (above 90%) of the total litter fall under all densities of both BR and SA trials (Figure 4.2). As the tree density increased in the BR trial, the non-leaf litter components increased from 0.20 to 0.74 OD t/ha or 2.6% to 7.0% of total litter fall.

O'Connell (1987) stated leaves are usually the main contributor to the annual litter fall. On average, the percentage of non-leaf material in forest litter is 30% for angiosperms and 29% for gymnosperms (Williams & Gray 1974). The percentage of leaf components in total litter fall in *Eucalyptus* natural and plantation forests was listed in Table 4.1. Most of them were higher than 50%.

The proportion of leaf in the litter could be mainly affected by tree age and density. Although earlier canopy closure under the higher densities increased the non-leaf litter input, leaves remained the main component of the litter in short rotation forests. In longer rotation forests, it is possible that the non-leaf litter component will rise gradually as the tree age increases.

4.3.1.3 Nutrient return

In the current study, nitrogen return ranged from 85 to 141 kg/ha/y in the BR trial, and from 31 to 84 kg/ha/y in the SA trial. Phosphorus return ranged from 4.6 to 8.2 kg/ha/y and 2.2 to 5.1 kg/ha/y, respectively (Figure 4.3). In most densities, more than 95% of annual nitrogen and phosphorus return in the litter fall were through the leaf component.

The annual nitrogen and phosphorus return through litterfall in *Eucalyptus* natural and plantation forests were listed in Table 4.1. In all of the studies listed, most of nitrogen and phosphorus were returned to the forest floor via the leaf litter.

Comparing with other studies listed in Table 4.1, the amounts of the annual nitrogen and phosphorus return in the present study were relatively higher, especially under the higher density, which was resulted from both the high total litter fall and the high leaf component in that litter. However, they were still lower than the amounts reported by Negi and Sharma (1996).

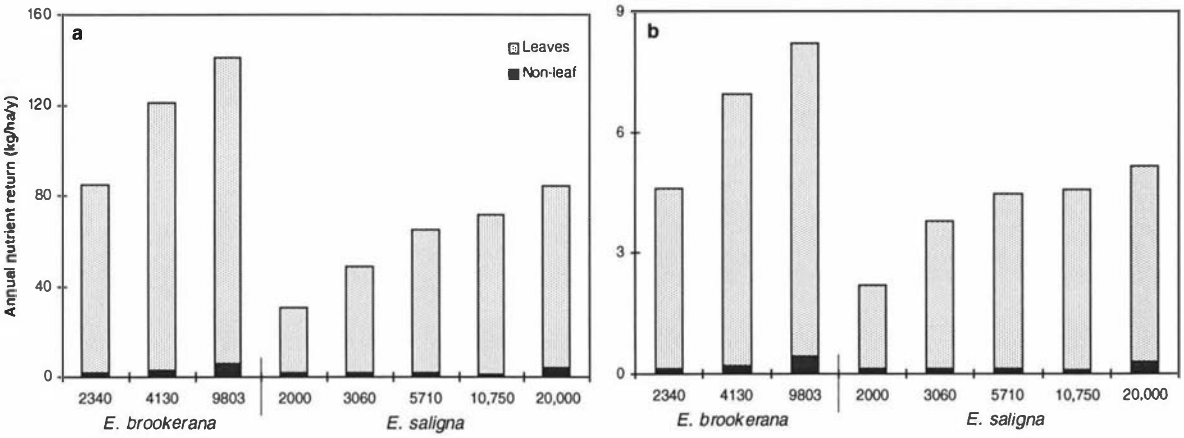

Figure 4.3 Annual nutrient return via litter fall in the two eucalypt population trials (trees/ha): (a) nitrogen and (b) phosphorus.

4.3.1.4 Seasonal variations

Litter fall occurred all year around, but the monthly litter fall significantly changed with season (Figures 4.4 - 4.5). The highest fall occurred during summer time from December to March, and this contributed from 70 to 83% of the total in all densities for both trials. During this period, the mean temperature was above 16°C with a peak in February of 18.9°C, the hottest month in the year and one of the driest (Figure 4.1).

Addicott (1982) concluded that following a period of hot weather, many trees abscise a portion of their leaves and such abscission is characteristic of species of *Eucalyptus*, *Citrus*, and other subtropical broad-leaved evergreens. Summer litter fall peaks were widely reported both in *Eucalyptus* natural forests (Bray & Gorham 1964; Ashton 1975; Attiwill et al. 1978; Birk 1979; Lamb 1985; Hart 1995; Specht 1996) and plantation forests (George & Varghese 1990b; Toky & Singh 1993). Even for *Eucalyptus* planted in effluent land treatment systems where water was not a limiting factor, litter fall still peaked in summer (Myers et al. 1994, and section 5.3.4). Therefore, litter fall appears to be affected more by ambient temperature than by soil moisture as was also concluded by Attiwill et al. (1978).

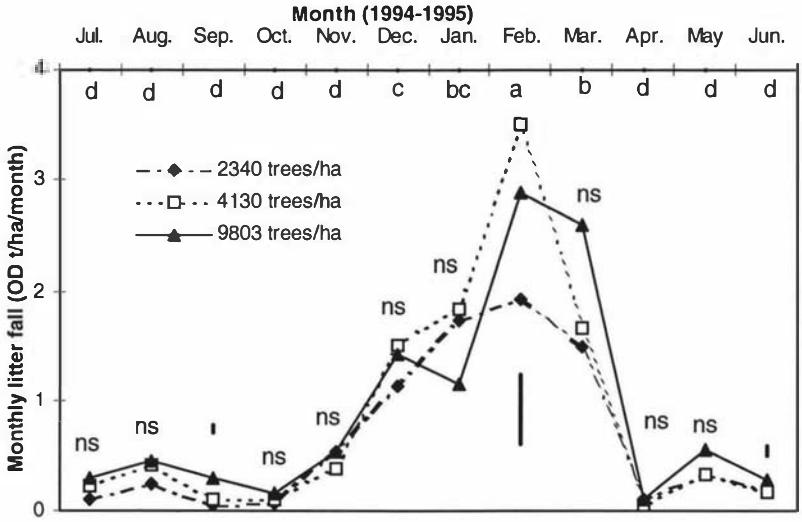

Figure 4.4 Monthly litter fall from three population densities in *E. brookerana* population trial (n = 3; vertical bars indicate $LSD_{0.05}$; ns = not significant between densities in the month; the months with the same letter were not significantly different by Duncan grouping, $P < 0.05$).

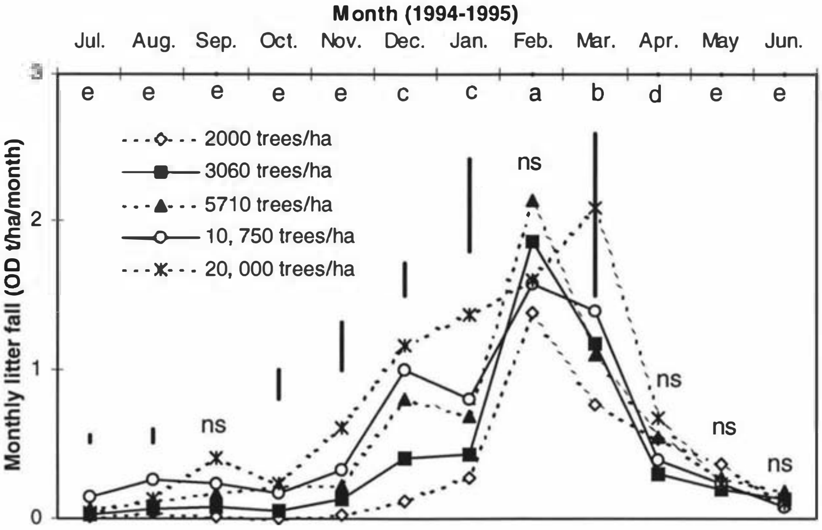

Figure 4.5 Monthly litter fall from five population densities in *E. saligna* population trial (n = 2; vertical bars indicate $LSD_{0.05}$; ns = not significant between densities in the month; the months with the same letter were not significantly different by Duncan grouping, $P < 0.05$).

Baker (1983) found that the concentrations of nitrogen and phosphorus in fallen leaves varied markedly between seasons but were consistently lowest at times of peak fall. In the current study, lowest N and P concentrations were also found when peak litter fall occurred during the summer time (Figure 4.6). However, the nutrient return was not only affected by the nutrient concentration in the litter, but also by the amount of total litter fall. Between December and March while the nutrient concentrations were lower, more than 70% of the annual nitrogen and phosphorus return occurred in the BR medium density of 4130 trees/ha, and more than 80% in the SA medium density of 5710 trees/ha (Figure 4.7).

The time of harvest can result in large differences in the amount of nutrients removed from the site (Wang et al. 1991). To manage the nutrient in the forest systems, the time to harvest all above ground biomass in the short rotation forests of deciduous trees, such as *Populus* and *Salix*, should be either before the leaf fall occurs in autumn to remove the maximum nutrients from the site, e.g. in an effluent land treatment system, or after the fall to remove as few nutrients as possible from the site. It is less easy to determine the optimum harvesting times for evergreen trees, e.g. eucalypts in the current study, as the litter falls consistently throughout the year. Since more nutrients are concentrated in the leaves than in the other tree components, the time of harvesting the above ground biomass should be determined by the purpose for growing the plantation. Harvesting should be carried out after peak leaf fall in the summer to minimise depletion of nutrients from the site, or before summer to remove as many nutrients as possible, as in an effluent land treatment system. This would ensure a more sustainable land use.

The annual litter production should be added to the yield of harvested biomass to obtain the total annual biomass production levels (Toky & Ramakrishnan 1983a). The high litter production found in the eucalypt short rotation forests could theoretically be removed from the site and used for energy conversion, compost production or other uses as long as the nutrient removal would be remedied from fertilizer application, or from solid or liquid waste application. The best time to collect the litter from the forest floor would be after the peak fall occurring in late summer.

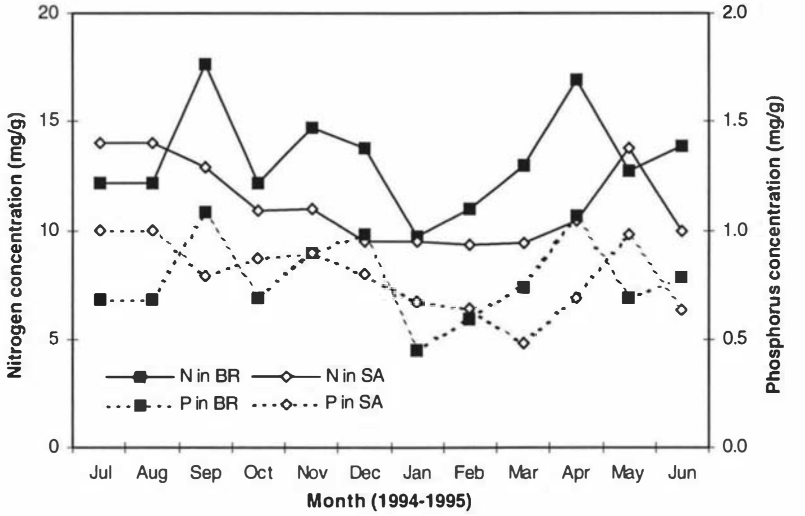

Figure 4.6 Nitrogen and phosphorus concentrations in litter leaves under the medium population densities of the two eucalypt population trials (4130 trees/ha in BR, 5710 trees/ha in SA).

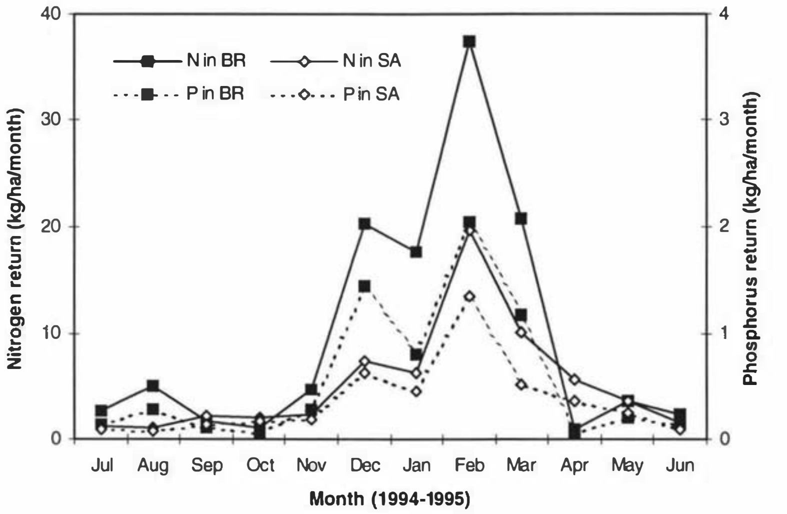

Figure 4.7 Monthly nitrogen and phosphorus return via litter fall under the medium population densities of the two eucalypt population trials (4130 trees/ha in BR, 5710 trees/ha in SA).

4.3.2 Experiment two: litter decomposition and nutrient release

4.3.2.1 Litter decomposition

In the litter decomposition study, the instantaneous decay constant (*k*) is commonly used to compare litter decomposition rates between species or between various environments. The higher the *k* value, the faster the litter decomposition. The *k* values of different litter types under various tree densities in the current study were listed in Table 4.2. The values of k_R estimated from the regression equations were markedly biased by the data from summer time, hence smaller than *k* calculated from data at the end of the year.

Table 4.2 Annual instantaneous decay constants (*k*) for the decomposition rates of three leaf litter types of two eucalypt species.

Litter type	Tree density (stems/ha)	k (year^{-1})	k_R	r^2
E. brookerana	2340	0.94 a	0.77	0.73
	4130	0.80 a	0.67	0.76
	9803	0.76 ab	0.61	0.71
E. botryoides-C	2340	0.35 bc	0.30	0.87
	4130	0.24 c	0.22	0.89
	9803	0.29 c	0.26	0.94
E. botryoides-E	2340	0.36 bc	0.31	0.96
	4130	0.34 bc	0.28	0.67
	9803	0.37 bc	0.29	0.93

C = from trees without irrigation; E = from trees irrigated with meatworks effluent.
The constant *k* was calculated from decomposition data at end of the year (n = 3; means with the same letter in the column are not significantly different by Duncan grouping, $P < 0.05$).
The constant k_R was calculated from the slope of the regression of ln (proportion of dry weight remaining) against time.

Tree density had little effect on the rates of litter decomposition for there was no significant difference between the decay constants (*k*) of each litter type under the three densities monitored (Table 4.2). However, leaf litter from the various sources gave the different decomposition rates (Figure 4.8). In the first nine months, the leaf litter decomposed relatively slowly, especially during summer when virtually no weight change was measured during those three months (Figure 4.8). The decomposition rates increased in autumn, being particularly evident in *E. brookerana* litter. The temperature and moisture in the season may be more suitable for the microbes to consume the litter. Overall, the autumn was the season for most rapid leaf litter decomposition in the current study.

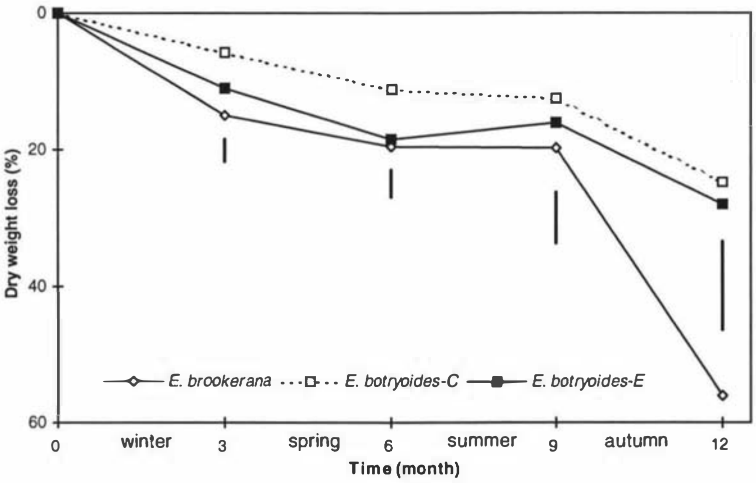

Figure 4.8 Dry weight loss (%) from the bagged leaf litter over the 12 month period (C = litter from trees without irrigation; E = from trees irrigated with meatworks effluent; n = 9; vertical bars indicate $LSD_{0.05}$).

After one year, more than half of the original leaf litter weight was lost from *E. brookerana* leaf litter. Less than one third of dry weight was lost from the *E. botryoides* leaf litter both from trees without irrigation and irrigated with effluent. The above results were comparable to Ericsson et al. (1992). They reported decomposition and mineralization of eucalypt leaves proceeds remarkably fast, 30 to 50% weight loss during the first year despite the sclerophyll nature while the soil moisture content is favourable for microbial activity.

The *k* value was reported for the eucalypt leaf litter decomposition in some studies, such as, 0.47 for *E. dives*, 0.53 for *E. pauciflora* and 0.68 for *E. delegatensis* (Woods & Raison 1983), 0.39 and 0.59 for *E. obliqua* (Baker & Attiwill 1985), 0.54 for *E. diversicolor* (O'Connell 1987). In the current study, the *k* value for *E. botryoides* was lower ($k < 0.4$) than above results whereas that for *E. brookerana* was higher ($k > 0.7$) (Table 4.2). *E. botryoides* leaf litter from trees irrigated with meatworks effluent decomposed faster than from trees without irrigation only significantly for the first 6 months of the period monitored (Figure 4.8).

Litter decomposition can be controlled by the internal physicochemical properties of the substrate and by the external factors of the environment under which decay takes place (Williams & Gray 1974; Gillon et al. 1994). Therefore, consideration of environmental factors must include those which may be regarded as "external" to the decomposition process (e.g. soil moisture, temperature) together with "internal" influences such as the chemical composition of the leaves.

Tree density is an external factor which can cause environmental change on the forest floor, such as light penetration, moisture and temperature. These in turn can affect the activity of soil fauna and micro-organisms. However, the density change appeared to have little effect on litter weight loss in the present study even though the trees in the lowest density had not reached canopy closure at that stage.

Adams & Attiwill (1986) indicated the slow rate of decomposition of *Eucalyptus* forest litter has been recognised as a feature of this genus. However, Briones & Ineson (1996) did not confirm this reputation of *Eucalyptus* as a recalcitrant litter for the decomposition of the eucalyptus paralleled that of the birch litter in terms of mass loss. In the present study, a significant difference was found between the two species, and even between various sources of one species during the first few months. The variation of leaf litter decomposition should be caused by the internal factors, the characteristics of litter itself. These include nutrient concentration, lignin content and the ratios of lignin with nutrients in the litter which are affected by species, and by the environment of the growing trees. As there are over 500 species of *Eucalyptus* (Brooker & Kleinig 1990; Boland et al. 1992), a lot of them are suitable for biomass production, and the variation of litter characteristics does exist between the species, the planting species could be selected according to the need of nutrient cycling. The slow decomposition rate or nutrient cycling can be sped up by selecting the species with quickly decomposed leaf litter.

4.3.2.2 Nutrient release from leaf litter

Nitrogen and phosphorus are usually the major nutrients needed for plantation forests. Only their loss from the leaf litter was monitored in the current study.

Nitrogen

Tree density had little effect on nitrogen loss from the leaf litter during decomposition for there was no significant difference between the nitrogen loss from the bagged litter under the three densities. The nitrogen retention in the litter actually increased in the first nine months instead of any loss (Figure 4.9). At the end of the year, nitrogen release rates from the bagged litter were *E. brookerana* > *E. botryoides-E* > *E. botryoides-C*. More nitrogen was still found in the bagged litter than the initial amount in *E. botryoides* leaf litter from trees without irrigation. Nitrogen was released from *E. brookerana* litter particularly rapidly in the autumn, dropping from 140% to 65% of the nitrogen initial amount, which closely related to litter dry weight loss (Figure 4.8).

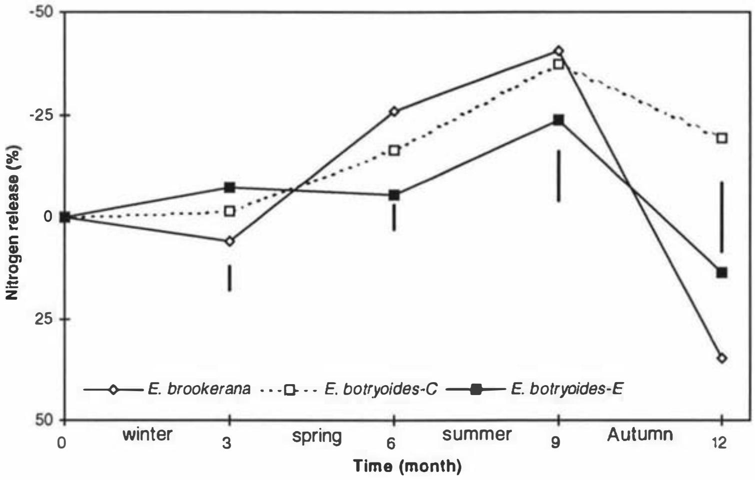

Figure 4.9 Nitrogen release (%) from the bagged leaf litter over the 12 month period (C = litter from trees without irrigation; E = litter from trees irrigated with meatworks effluent; n = 9; vertical bars indicate $LSD_{0.05}$).

Phosphorus

Even though tree density had no evident effects on litter weight loss and nitrogen release rates, it did have a significant influence on the phosphorus release rates from the leaf litter (Figure 4.10). The higher the tree density, the lower the phosphorus release rate.

During the first nine months, phosphorus was accumulated in most of the bagged litter, especially under the highest tree density (9803 trees/ha). After one year exposure in the forest floor under the highest density, phosphorus was released only slightly from *E. brookerana* leaf litter while *E. botryoides* leaf litter still accumulated more phosphorus than the initial amount. Under the lower densities, phosphorus was released other than accumulated in all three litter types at the end of the year. Overall, phosphorus was released faster from *E. brookerana* leaf litter than from *E. botryoides* leaf litter, but there was little difference between the two litter types within the latter species.

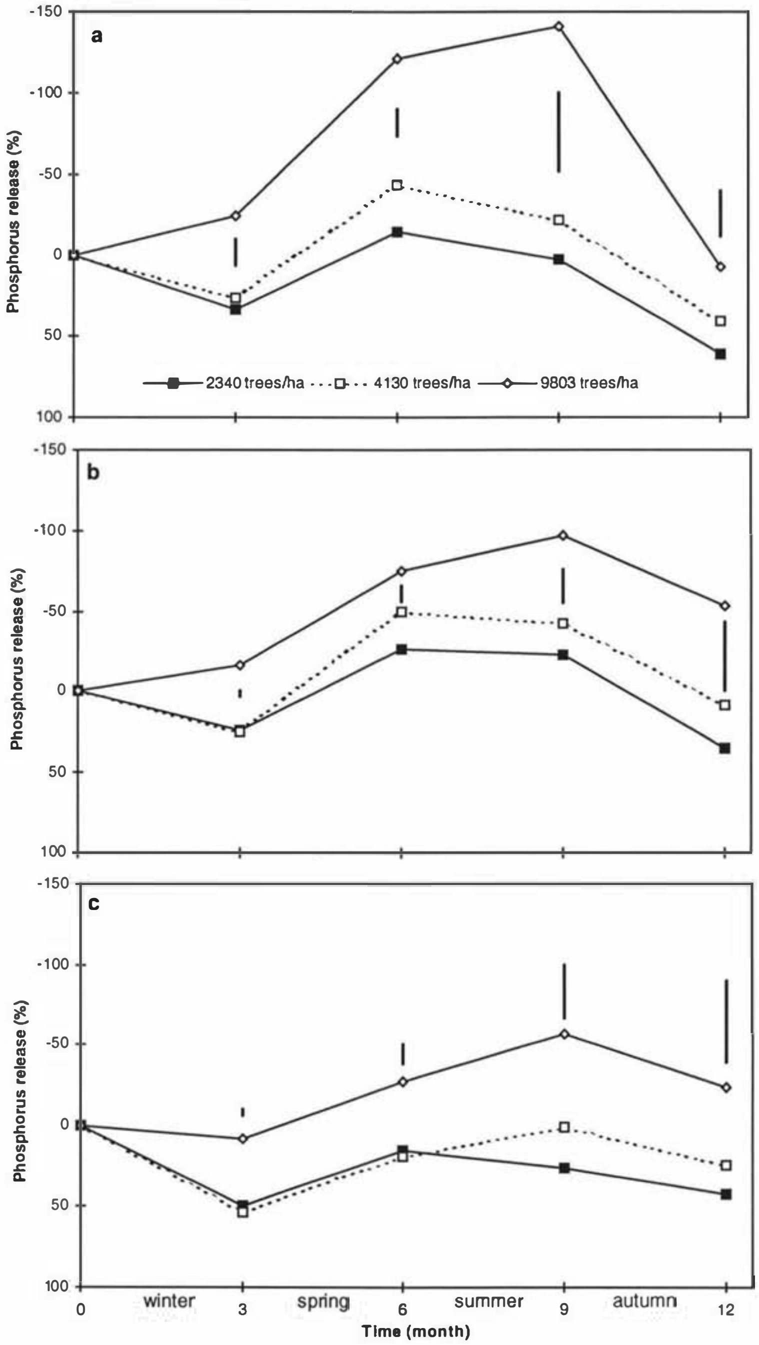

Figure 4.10 Phosphorus release (%) from the bagged leaf litter under three tree densities over the 12 month period: (a) *E. brookerana* litter, (b) *E. botryoides* litter from trees without irrigation, and (c) *E. botryoides* litter from trees irrigated with meatworks effluent (n = 3; vertical bars indicate $LSD_{0.05}$).

Will et al. (1983) reported that the tree density had little or no effect on *Pinus radiata* litter decomposition rate or loss of nutrient. The results in the present study also showed similar trends in litter decomposition and nitrogen loss, but the density did have an effect on phosphorus loss, the higher the density, the slower the phosphorus release, and the more the phosphorus retention.

An increase in nitrogen and phosphorus retention in the litter is frequently reported and the increases can be attributed partly to microbial immobilization and hence redistribution of nutrients between the litter layer (Baker & Attiwill 1985). The nutrients can be imported into the litter layer from other sources, such as rainfall, throughfall, stemflow, frass from herbivores or translocation in fungal hyphae from surface soil and lower strata of the litter layer (O'Connell & Grove 1996). If the litter was removed from forest floor to deplete nitrogen and phosphorus from the site, such as short rotation forests linked with effluent land treatment, the litter could be collected as soon as maximum nitrogen and phosphorus retention was reached. If litter was removed from the site for other use, such as energy conversion, but not for nutrient removal, the litter should be collected soon after summer according to litter fall and decomposition.

4.4 CONCLUSIONS

The higher the tree density in eucalypt short rotation forests, the greater the weight of annual litter fall and the higher nutrient return. Variations between the densities declined with times as the canopy closed. Summer was the main season for litter fall, and nutrient return in the year. Leaves were the main component of the litter fall. The density had little influence on litter decomposition and nitrogen release from litter, but had significant effects on phosphorus release. The higher the density, the slower the phosphorus release. The nitrogen and phosphorus retention in the litter had risen at first, especially phosphorus under the higher density. The litter from different sources had various decomposition and nutrient release rates. Autumn was the main season for litter decomposition and nutrient release. To ensure a more sustainable energy production and land use, short rotation forests should be managed rationally based on the fluctuation of litter fall and decomposition, and nutrient cycling in the system. The management includes: species selection, thinning, tree harvesting, litter collecting, and the time for tree harvesting and litter collecting.

5. THE EFFECTS OF LAND USE CHANGE AND EFFLUENT IRRIGATION ON SOIL PROPERTIES, BIOMASS PRODUCTION, AND NUTRIENT CYCLING

5.1 INTRODUCTION

Effluent irrigation can change soil properties, e.g. soil infiltration rate, hydraulic conductivity, bulk density, porosity, soil pH and nutrient content (Waly et al. 1987; Russell et al. 1988; Cook & Thorne 1990; Mathan 1994; Tipler et al. 1996). The results of the current study as described in section 3.3.1 showed that both tree planting into pasture and effluent irrigation influenced soil properties. These changes are of considerable significance to the search for sustainable land uses, and therefore the processes should be clearly understood.

Estimation of biomass growth potential is essential for determining the status and flux of biological materials in an ecosystem and for understanding the dynamics of the ecosystem (Anderson 1970). Biomass production is closely related to the end products from the system and the nutrient management.

Litter is a major pathway for the transfer of energy and nutrients from above-ground components of forest ecosystems to the soil surface (Bray & Gorham 1964). Nutrient return through litter fall is important in order to manage nutrient balance in a plantation forest for sustainable land use. However in a land treatment system, the nutrient return is usually thought to be a disadvantage for reducing effect of nutrient stripping.

The effects of tree planting into pasture, effluent irrigation and the effects of different eucalypt species on soil properties during the first rotation of 3 year coppice short rotation forests are described in this chapter. Waly et al. (1987) found that total and soluble nitrogen, as well as available phosphorus, increased with prolonged application of sewage effluent and that the highest accumulation was in the upper layers of the soil. Therefore, the present study mainly concentrated on changes in the top soil (0 - 75 mm) over the 3 year period.

Also described in this chapter is the biomass production and nutrient uptake (nitrogen, phosphorus, potassium, calcium, magnesium and manganese) for the different species in the stands without irrigation or irrigated with effluent during the first 3 year rotation. In the forest at harvest the root biomass is usually left on the site. Therefore, the above ground biomass is what is normally implied by the term "biomass". In the broader sense this includes biomass accumulation in the trees plus the litter fall. Hence in this chapter:

i) "biomass accumulation" is defined as above ground biomass in the standing trees;

ii) "total biomass production" is defined as biomass accumulation plus the litter fall during the 3 years;

iii) "nutrient accumulation" is the amount of nutrients accumulated in the standing trees; and

iv) "total nutrient uptake" is nutrient accumulation in the standing trees plus the nutrients returned to the soil via litter fall during the 3 years.

Litter fall and nutrient return via litter fall in the stands during the entire rotation are also described. This includes differences in litter fall and nutrient return between species and their responses to effluent irrigation, monthly distribution of litter fall and nutrient return in each year, and the relationships between biomass production and litter fall, and between nutrient uptake and nutrient return via litter fall.

The overall objective of this part of the study was to determine the soil changes, biomass production and the rate of nutrient cycling during the first rotation of coppiced short rotation forests of various eucalypt species without irrigation and irrigated with effluent. The current study provides a basis for examining the flow of nutrients within short rotation forest ecosystems, and provides information for effective and rational management.

5.2 METHODS

5.2.1 Site, species and experimental design

The study site was at the Richmond Meat Processors & Packers Ltd. processing plant at Oringi, which is adjacent to the Manawatu River, located near Dannevirke, New Zealand. Monthly distributions of rainfall and temperature for 1994-1996 and ten year average are shown in Figure 5.1. Before trees were planted, the site was occupied by pasture which had been irrigated with effluent for 12 years (see section 3.2.1 for more details about the site).

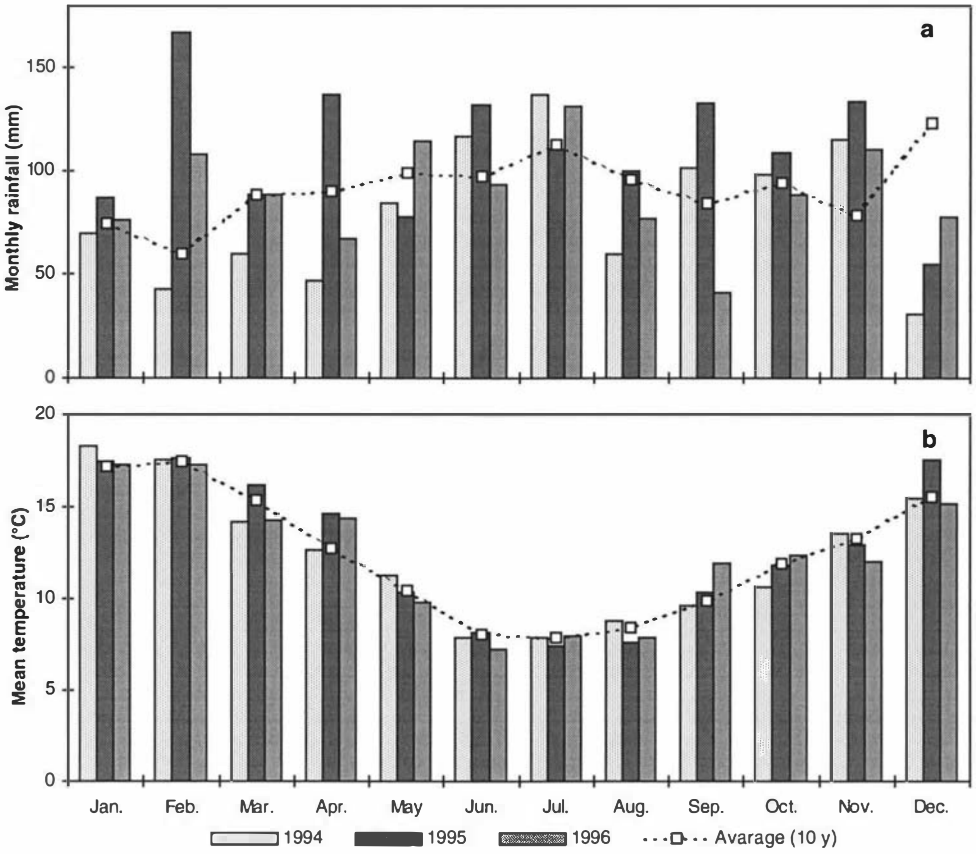

Figure 5.1 Monthly rainfall (a) and mean temperature (b) for Dannevirke, New Zealand (1994-1996 and 10 year average).

A split block experimental design was used with repeated measurements and three blocks. In each block, there were three sub-blocks of eucalypt species, *Eucalyptus botryoides* (B), *E. globulus* (G), and *E. ovata* (O). Each sub-block was split into two plots for the two treatments, without irrigation (N) and irrigated with effluent (I). Each of the 18 plots was 10 m × 10 m with a 10 m buffer zone. Next to each plot, a same treatment plot was established for tree sampling when the trees were 1 and 2 years old.

Tree seedlings were planted in December 1993 at a density of 4167 stems/ha (1 m spaces × 2.4 m rows), giving 40 trees per plot. Effluent from the meatworks anaerobic pond was irrigated onto the plots at 20 mm/week using flood irrigation (see Table 3.1 for details about effluent characteristics). The rotation length between coppice harvests was 3 years. The current study was conducted during the first rotation.

5.2.2 Measurements and sampling

Soil analyses were undertaken before tree planting (see section 3.3.1). Repeat measurements and sampling of both soil and tree biomass were taken in December 1994, 1995, and 1996 when trees were 1, 2 and 3 years old. The litter was collected monthly and soil infiltration rates were measured in February 1995, 1996, and 1997.

5.2.2.1 Soil measurement and sampling

Infiltration rates were measured using double ring infiltrometers with two concentric cylinders of 205 and 510 mm diameter (Anon. 1982). Soil infiltration rates were measured only under the *E. globulus* stands during late summer using three replicates for each plot to compare without irrigation and irrigated with effluent.

Soil bulk densities were determined by the core method (Blake & Hartge 1986) with two soil cores sampled between 0 and 75 mm depth in each plot. Ten soil samples (0 - 75 mm) were collected by corers in each plot for chemical analysis. Five core samples were mixed thoroughly into one giving two soil samples per plot.

5.2.2.2 Tree measurement and sampling

Tree diameters and heights were measured when trees were 1, 2 and 3 years old. The mean tree method was used for destructive sampling as the tree of mean basal area seems to be the best for biomass estimation in even-aged stands of a single species (Carron 1968; Cromer et al. 1976; Parde 1980). The mean trees were selected according to the mean height and the mean diameter calculated from the mean basal area in each plot, but account was also taken of the crown width. Tree stem diameters were measured at ground level in 1 year old stands, but at breast height for 2 and 3 year old stands.

Whenever multi-stems occurred, the tree diameter was calculated as follows:

$$D = \sqrt{\sum_{1}^{n} D_i^2}$$

where D is the tree diameter, n is the number of stems, D_i is the diameter of each stem.

The mean tree determined was selected and harvested in the same treatment plot next to each plot when the trees were 1 and 2 years old. The mean tree for the final sampling was selected and harvested within each plot when the trees were 3 years old. The whole tree above ground was harvested and stored in a cool room before processing.

5.2.2.3 Litter collection

To catch the litter, the tray method was used (Newbould 1967). Since this was a study of short rotation plantations, trays were put directly on to the forest floor under the plantation as Swift et al. (1979) suggested for dwarf shrubs. Litter trays used were 440 × 350 × 170 mm with 2 mm mesh to permit drainage of rain water but without allowing any physical litter loss. Litter was collected from the trays monthly as recommended by Toky & Ramakrishnan (1983a).

Two litter trays were put on the forest floor on each plot from May 1994 onwards when litter fall was first observed.

5.2.3 Laboratory analyses

The soil cores sampled to assess bulk density were oven dried at 105°C. Other soil samples taken for chemical analysis were separated into two parts: i) fresh soil was used to measure available nitrogen (ammonium and nitrate); ii) air-dried soil at approximately 20°C was passed through a 2 mm sieve, then stored in sealed polystyrene containers until required for chemical analysis.

The sample trees were divided into five components: leaves, branches (< 6.4 mm diameter), branches (6.5 - 25.4 mm diameter), bark and wood from stem and branches larger than 25.4 mm (Young & Carpenter 1976). New (soft) shoots with young leaves not fully open and dead parts were treated as special groups. The usual description of the size of the photosynthetic system is the leaf area index: the area of leaves carried above a unit area of ground (Newbould 1967). Leaf area index was estimated from leaf biomass using a weight/leaf area conversion factor determined from a sub-sample for the leaves. The leaf area was measured by a LI-Cor LI-3100 leaf area meter (Lambda Instruments Co, Lincoln, NE, USA).

After each litter collection from the trays, the litter was divided into two components, leaf and non-leaf (consisting of branch and bark). No flowers or fruits were present in the litter since the trees were too young.

Samples of tree leaf and litter were oven dried at 80°C overnight for weighing, but samples of wood, branch and bark were dried for more than three days. Then, the samples were ground to pass through a 1 mm sieve for further analyses of nitrogen, phosphorus, potassium, calcium, magnesium, and manganese.

Fresh soil samples were analysed for ammonium and nitrate using a Technicon Auto Analyser following KCl extraction. Total nitrogen and total phosphorus for soil and tree components were analysed using a Technicon Auto Analyser following Kjeldahl digestion. Potassium, magnesium, calcium and manganese for tree components were analyzed using an Atomic Absorption Spectroscopy (GBC 904 AA) following nitric acid digest for cation analysis. All the above methods were recommended by the Fertilizer and Lime Research Centre, Massey University (see section 3.2.3 for details).

The air-dried soil samples were analysed for organic matter through ignition at 500°C for one hour. Soil pH was measured using a soil to water ratio of 1:2.5 according to Nicholson (1984).

Total oven dry (OD) biomass in each plot was obtained from the basal area of the trees in the plots and the sample trees as follows (Madgwick 1976; Frederick et al. 1985a, 1985b):

$$W_P = A_P \frac{\sum W_T}{\sum A_T}$$

where W_P is the plot biomass (OD t/ha), A_P is the plot basal area (m^2/ha), W_T is the sample tree biomass (OD t), and A_T is the sample tree basal area (m^2).

The nutrient accumulation in the above ground biomass was assessed by determining: i) the proportion of above-ground components, e.g. leaves, branches, bark, and wood in the harvested biomass (biomass distribution); ii) the total biomass produced or harvested per unit area and iii) the concentrations of nutrients in these components of the biomass (Wise & Pitman 1981). The distribution of nutrients (kg/ha) in each plot was calculated by multiplying the nutrient percentage in the different tree components by their respective biomass yields (Negi & Sharma 1984). Nutrients accumulated in every tree component in the plots were estimated as follow:

$$N_C = 1000 C_N W_C$$

> where N_C is the nutrient accumulation (kg/ha) for each tree component in the stands, C_N is the nutrient concentration (%) of the tree component, W_C is the total biomass of the tree component (t/ha).

Total nutrient accumulation by the trees was estimated from the tissue nutrient concentration and biomass production:

$$N_p = \sum_{1}^{n} N_i$$

> where N_P is plot nutrient accumulation (kg/ha), N_i is the nutrient accumulation in each tree component in each plot (kg/ha), n is the number of tree components

5.2.4 Statistical analysis

All data from the split block design experiment were analysed using the SAS GLM procedure (SAS Institute 1990). The model of a 2-factorial combination was used for analysing the data of soil, biomass accumulation, nutrient accumulation, litter fall, and nutrient return via litter fall. Soil infiltration rate data were analysed using a 1-factorial model.

5.3 RESULTS

5.3.1 Soil properties

5.3.1.1 Soil bulk density

The bulk density was consistently lower under trees irrigated with effluent than under trees without irrigation during the whole rotation (Figure 5.2a). Soil bulk densities were lowest in *E. globulus* stands and highest in *E. botryoides* stands when trees were 2 years old, but otherwise there was no significant difference between the three species.

The soil bulk density was 0.96 g/cm^3 before the trees were planted (Table 3.2). After the first 3 year rotation, there was little change on soils without irrigation. However, the soil bulk densities were reduced where effluent was applied, especially under *E. ovata* stands at the end of the 3 year period (Figure 5.2a).

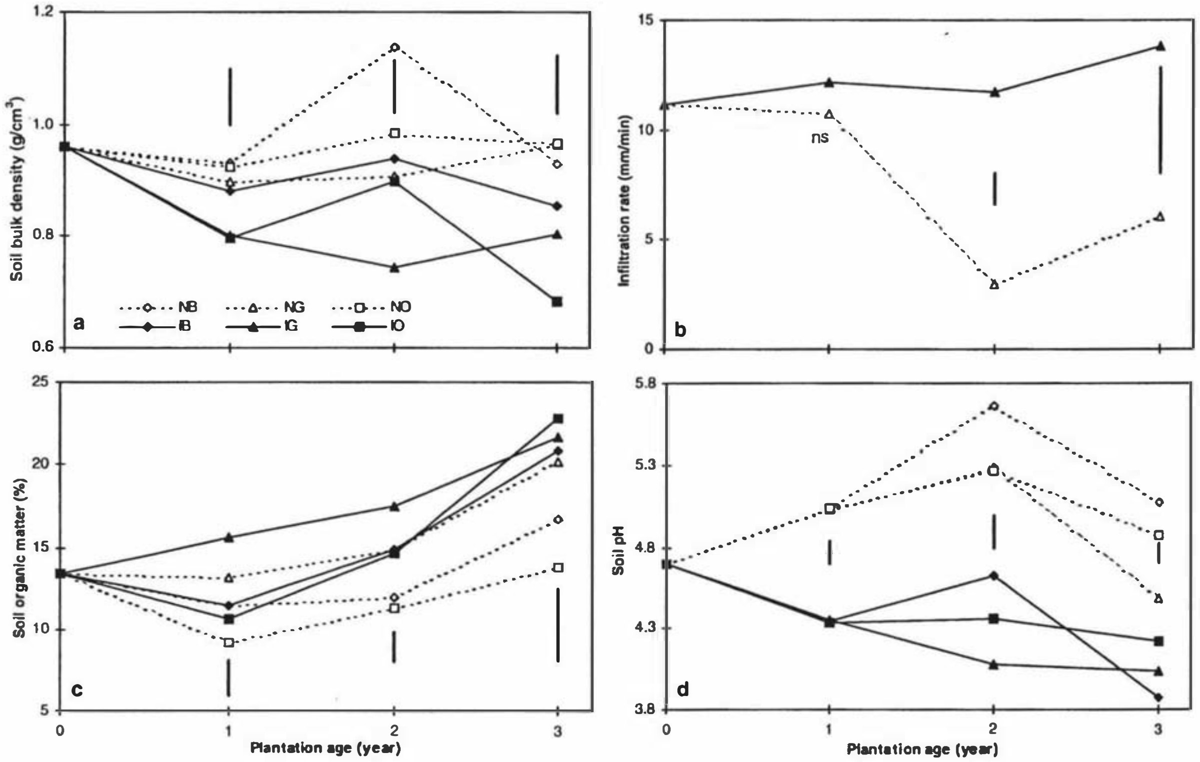

Figure 5.2 Soil changes in eucalypt plantations over the 3 year period for: (a) bulk density, (b) infiltration rate, (c) organic matter, and (d) pH (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; n = 6, but 9 for the infiltration rate; Vertical bars indicate the LSD$_{0.05}$; ns = not significant).

5.3.1.2 Soil infiltration rate

The soil infiltration rates in pasture were 11.2 mm/min before trees were planted (Table 3.2). Under *E. globulus* stands, there was no significant difference in infiltration rates between stands without irrigation and irrigated with effluent after 1 year (Figure 5.2b). Then, the rates decreased rapidly in the soil without irrigation. Overall, the soil infiltration rate was reduced by tree planting into pasture, but there was little change for the combination of tree planting and effluent irrigation.

5.3.1.3 Soil organic matter

Before trees were planted, the soil organic matter under pasture was 13.4% (Table 3.2). Tree planting increased soil organic matter with time, and effluent irrigation tended to enhance the increase (Figure 5.2c). More organic matter was found in soil under *E. globulus* stands than under other species stands after 1 year. Then, the difference between species decreased with tree age while the difference between stands without irrigation and irrigated with effluent increased.

5.3.1.4 Soil pH

Soil pH was 4.7 under pasture before trees were planted (Table 3.2). Tree planting increased the soil pH initially, but by year 3 reduced it to the value before trees were planted (Figure 5.2d). When effluent was applied to the trees, the pH was reduced significantly.

By year 2, the highest soil pH value was found under *E. botryoides* stands whether without irrigation or irrigated with effluent. Soil pH was higher under *E. ovata* than under *E. globulus* when irrigated with effluent. By year 3, the highest pH value was found under *E. botryoides* without irrigation and the lowest pH was under *E. botryoides* irrigated with effluent.

5.3.1.5 Soil nutrients

Total Kjeldahl Nitrogen

Soil nitrogen was 6.5 mg/g under pasture before trees were planted. After 3 years, the soil total nitrogen was slightly reduced following tree planting and there was no significant difference between species in the stands without irrigation (Figure 5.3a). Effluent irrigation increased the total nitrogen, especially under *E. globulus* and *E. ovata.*

Available Nitrogen

Soil available nitrogen was 40.8 ppm under pasture before trees were planted (Table 3.2). Tree planting had little effect on soil available nitrogen (Figure 5.3b). A slightly lower concentration was found in the soil under *E. botryoides*, but only in the first year. Effluent irrigation significantly increased the concentration in the soil under all species.

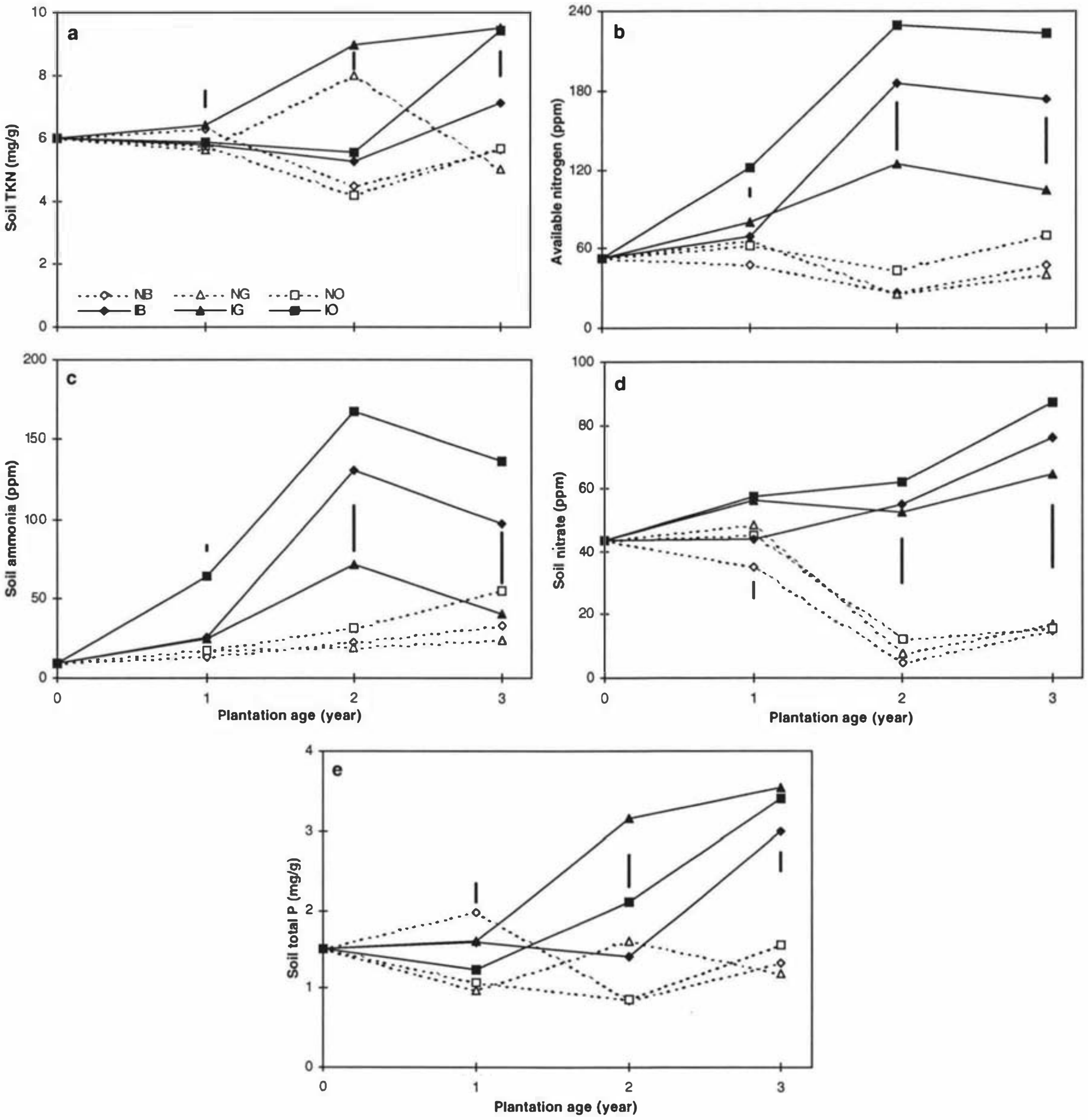

Figure 5.3 Soil nutrient changes in eucalypt plantations over the 3 year period for: (a) total Kjeldahl nitrogen, (b) available nitrogen, (c) ammonium, (d) nitrate, and (e) total phosphorus (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; n = 6; Vertical bars indicate the $LSD_{0.05}$).

Ammonium

Ammonium is the less prone to leaching than nitrate. Its pattern following tree planting and effluent irrigation was similar to that for soil available nitrogen (Figure 5.3c). Soil ammonium nitrogen was only 8.8 ppm under pasture before trees were planted (Table 3.2). The tree planting increased it marginally during the 3 year rotation. Effluent irrigation significantly increased its concentration in the soil under all species, especially under *E. ovata* trees although some reduction had occurred by the third year.

Nitrate

Nitrate was 32.0 ppm under pasture and quickly reduced after trees were planted, though some recovery was found by the end of the 3 year period (Figure 5.3d). Effluent irrigation increased the soil nitrate levels.

Total phosphorus

The soil total phosphorus concentration was 1.5 mg/g under pasture before trees were planted (Table 3.2). Tree planting had little effect on phosphorus concentration during the 3 year period (Figure 5.3e). However, when combined with effluent irrigation, soil total phosphorus was about twice the value of that under pasture.

5.3.1.6 Correlation between the factors

Among the all soil factors measured, there was only one highly significant correlation, a positive correlation between soil infiltration rate and the nitrate concentration in the soil (Figure 5.4). As infiltration rate increased, nitrate concentration increased too. However, the original soil under pasture without any effluent irrigation (PN in section 3.3.1.1) had low nitrate concentration at the highest infiltration rate. This could be a result of the high nitrate leaching under such high infiltration rate, or there being less nitrogen in the soil initially for it was the only soil without effluent irrigation history in the current study.

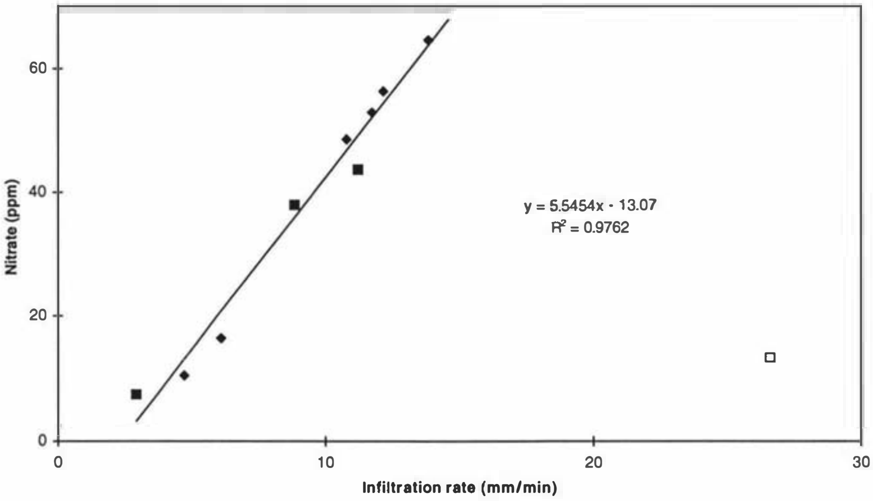

Figure 5.4 Correlation between soil infiltration rate and nitrate concentrations (◆ the data reported in this chapter; ▪ the data from section 3.3.1.1; □ soil under pasture without effluent irrigation from section 3.3.1.1).

5.3.2. Tree performance, and biomass and nutrient accumulation

5.3.2.1 Tree performance

Tree diameter

In the first year, effluent irrigation only increased tree stem diameter at ground level (DG) in *E. globulus* and had no effects on the other two species (Figure 5.5a). By year 2 and year 3, it increased the diameter at breast height (DBH) in all three species, except *E. globulus* at the end of the 3 year period.

E. globulus irrigated with effluent had the highest DG in the first year, and *E. botryoides* the lowest. Then, the DBH was larger in *E. globulus* and *E. botryoides* irrigated with effluent in the second year. At the end of the rotation, *E. ovata* irrigated with effluent caught up to *E. globulus.* The lowest DBH was found in both *E. botryoides* and *E. ovata* without irrigation.

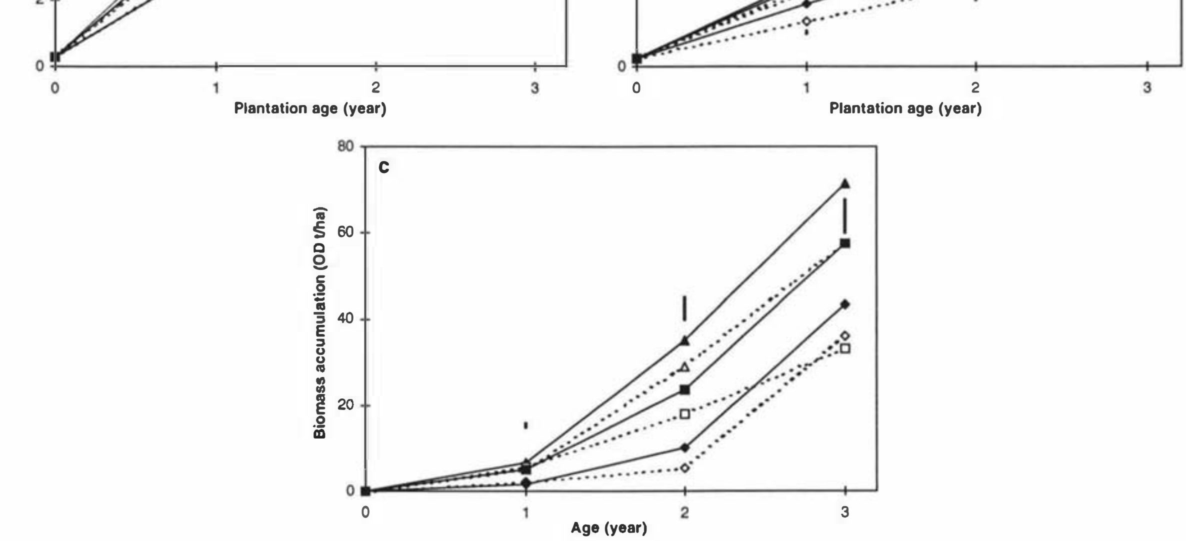

Figure 5.5 Tree performance and biomass accumulation in eucalypt plantations: (a) diameter (at ground level when 1 year old and at breast height when > 2 years old), (b) height, and (c) biomass accumulation (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; n = 120, but 3 for biomass; Vertical bars indicate the $LSD_{0.05}$).

Tree height

E. globulus was the tallest species, and *E. botryoides* was the shortest during the 3 year period (Figure 5.5b). Effluent irrigation tended to increase height throughout the 3 year period for *E. botryoides* and for *E. ovata* by year 3. However, *E. globulus* trees without irrigation were taller than the trees irrigated with effluent at the end of the 3 year period.

5.3.2.2 Biomass

There were significant differences in above ground biomass accumulation between the three species, *E. globulus* being the highest yielding whether without irrigation or irrigated with effluent (Figure 5.5c). Effluent irrigation significantly increased the biomass accumulation in all three species after 2 and 3 years, especially *E. ovata.* Relatively little biomass was accumulated in the first year.

The distribution of biomass in various tree components was also affected by effluent irrigation (Figure 5.6). Less leaf biomass was found in the trees irrigated with effluent than in the trees without irrigation, but there were more branches. More wood was found in the trees irrigated with effluent than in the trees without irrigation, except for *E. globulus.* Overall, about half of the biomass was wood except in *E. botryoides* without irrigation (28%).

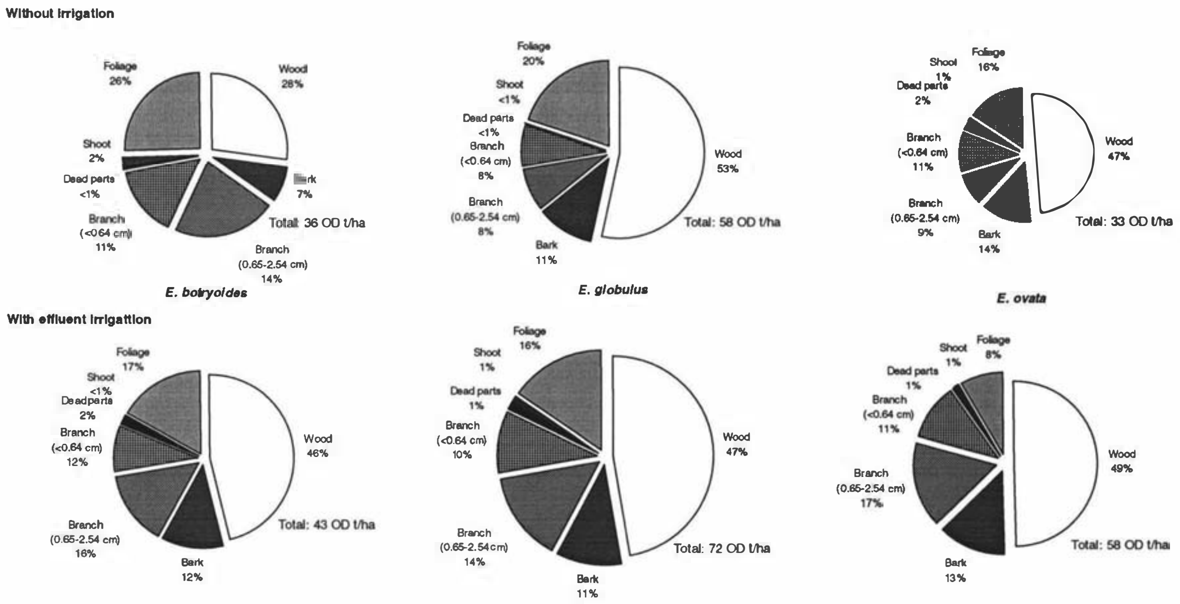

Figure 5.6 The distribution of harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total biomass accumulation).

5.3.2.3 Nutrient

Nitrogen

There were significant differences in nitrogen accumulation between the three species, the trend being similar to biomass accumulation (Figure 5.7a). Less nitrogen was accumulated in *E. botryoides* in the first 2 years, but by year 3 this species had accumulated about 400 kg/ha and caught up with *E. globulus* without irrigation and *E. ovata* irrigated with effluent. At the end of the 3 year period, *E. globulus* irrigated with effluent accumulated the greatest amount of nitrogen, and *E. ovata* without irrigation the least.

Nitrogen distribution in tree components was affected by effluent irrigation (Figure 5.8). Less nitrogen was found in the leaf portion of trees irrigated with effluent than those without irrigation, and more was found in branches and wood. Overall, less than one quarter of total nitrogen was accumulated in the wood for all three species.

Phosphorus

There were also significant differences in tree phosphorus accumulation between the three species (Figure 5.7b). Less phosphorus was accumulated in *E. botryoides* in the first 2 years. Then, the accumulation of phosphorus in this species reached about 40 kg/ha in the third year and caught up with *E. globulus* without irrigation and *E. ovata* irrigated with effluent.

At the end of the rotation, *E. globulus* trees irrigated with effluent accumulated the greatest amount of phosphorus, and *E. ovata* without irrigation accumulated the least. Little net phosphorus accumulation occurred in *E. ovata* without irrigation during the third year.

Phosphorus distribution in various tree parts was also affected by effluent irrigation (Figure 5.9). Less phosphorus was in leaf portion of the trees irrigated with effluent than in the leaf of the trees without irrigation, but more was found in branches. More phosphorus was found in the wood of trees irrigated with effluent than in the trees without irrigation, but less in *E. globulus*.

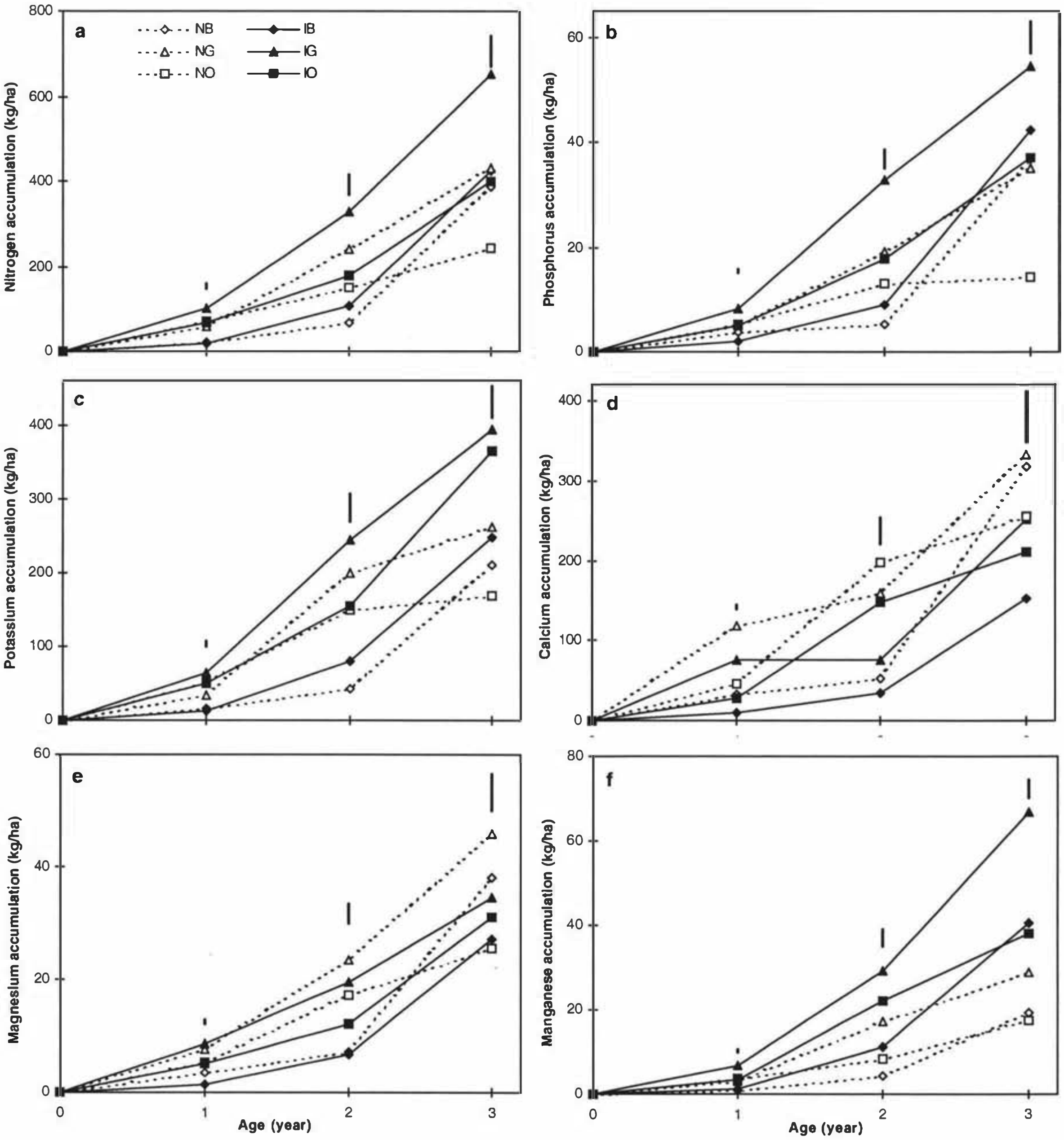

Figure 5.7 Nutrient accumulation in eucalypt plantations over the 3 year period: (a) nitrogen, (b) phosphorus, (c) potassium, (d) calcium, (e) magnesium, and (f) manganese (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; Vertical bars indicate $LSD_{0.05}$; n = 3).

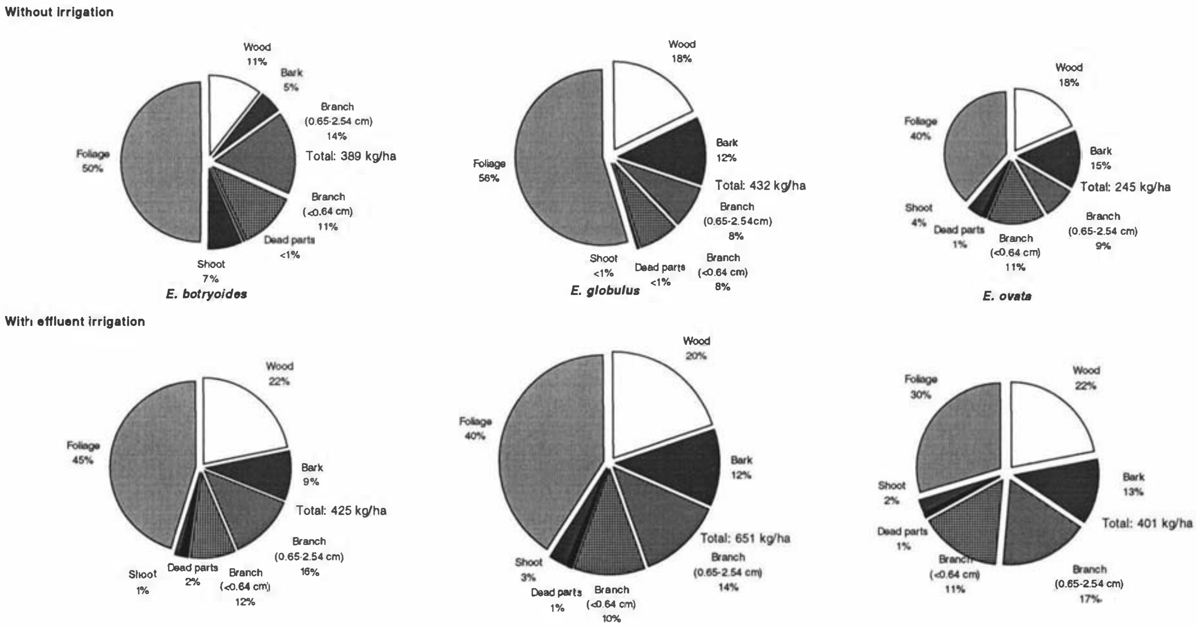

Figure 5.8 Nitrogen distribution in the harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total nitrogen accumulation).

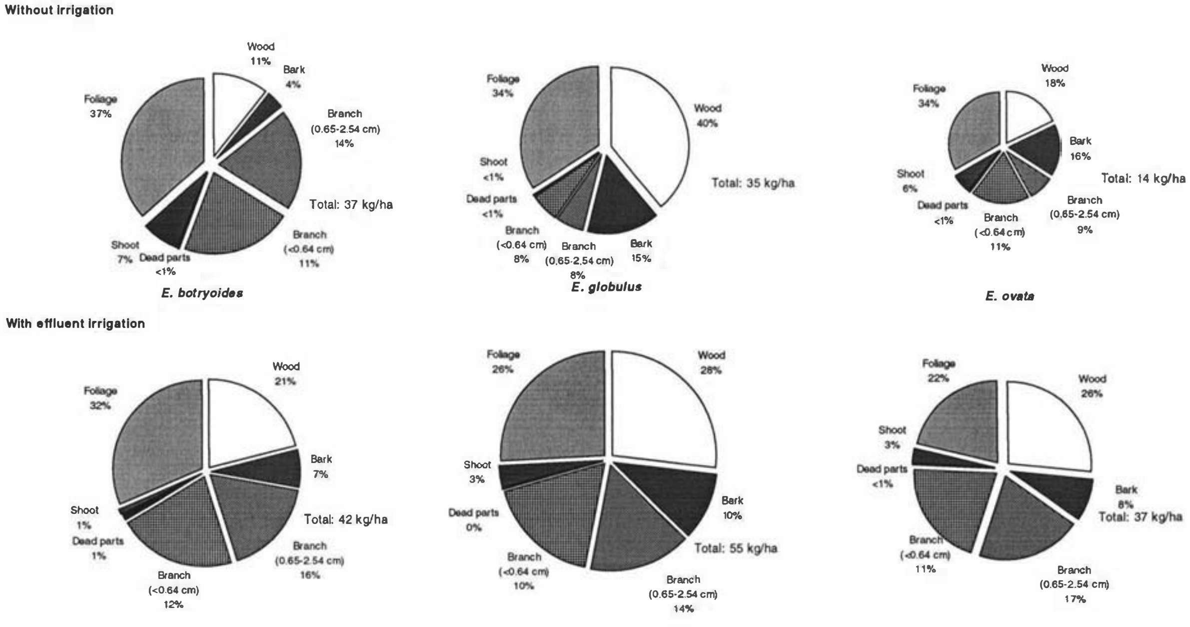

Figure 5.9 Phosphorus distribution in the harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total phosphorus accumulation).

Potassium

There were also significant differences in tree potassium accumulation between the three species (Figure 5.7c). Effluent irrigation only enhanced potassium accumulation in *E. globulus* at first, then in *E. botryoides* in the second year. By year 3, effluent irrigation significantly enhanced potassium accumulation in all three species. During the third year, no net potassium accumulation occurred in *E. ovata* without irrigation, but a significant amount was accumulated in *E. ovata* irrigated with effluent which caught up with *E. globulus* irrigated with effluent.

Less potassium was found in the leaf portion of the trees irrigated with effluent than in the leaf of the trees without irrigation, but more was found in branches (Figure 5.10). More potassium was found in the wood of the trees irrigated with effluent than in the trees without irrigation, except for *E. globulus.*

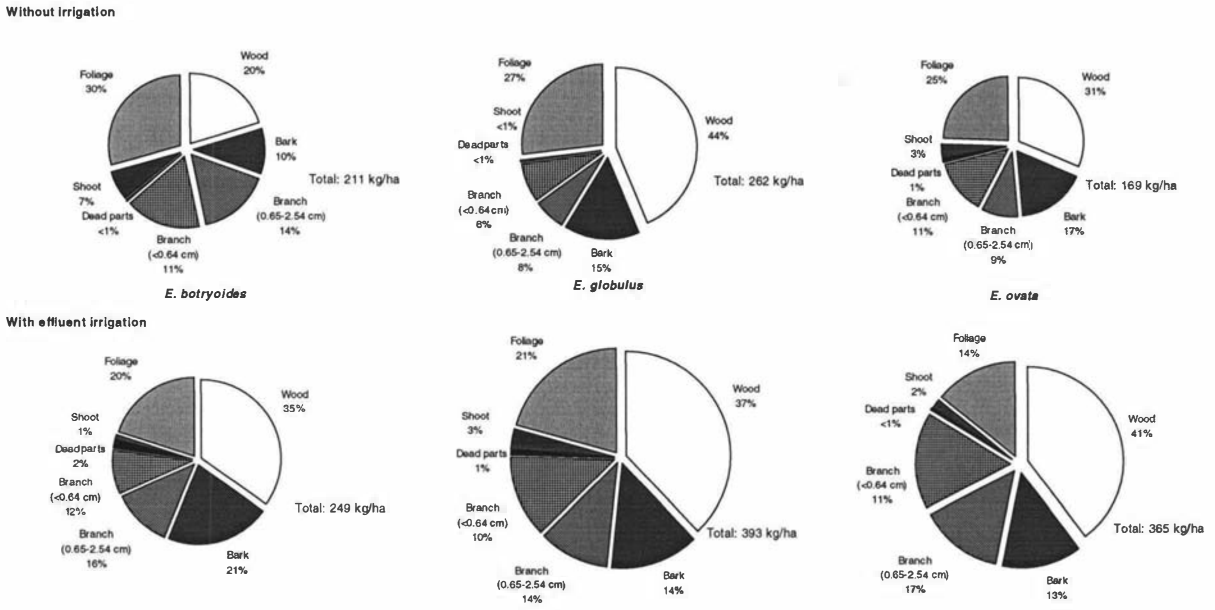

Figure 5.10 Potassium distribution in the harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total potassium accumulation).

Calcium

There were significant differences in tree calcium accumulation between the three species and effluent irrigation retarded calcium accumulation in all three species although it increased the biomass accumulation during the whole 3 year period (Figure 5.7d). Calcium accumulation in *E. ovata* without irrigation rose sharply in the second year. A similar rise also occurred in *E. botryoides* in the third year and its final accumulation was similar to *E. globulus* without irrigation, the greatest quantity accumulated over the 3 year period.

Less calcium was found in the leaf portion of the trees irrigated with effluent than in the leaf portion of the trees without irrigation, but more was found in the branches (Figure 5.11). Approximately double the calcium was stored in wood of the trees irrigated with effluent than in the trees without irrigation, except for *E. globulus*. In *E. ovata*, about half of the total calcium was found in the bark.

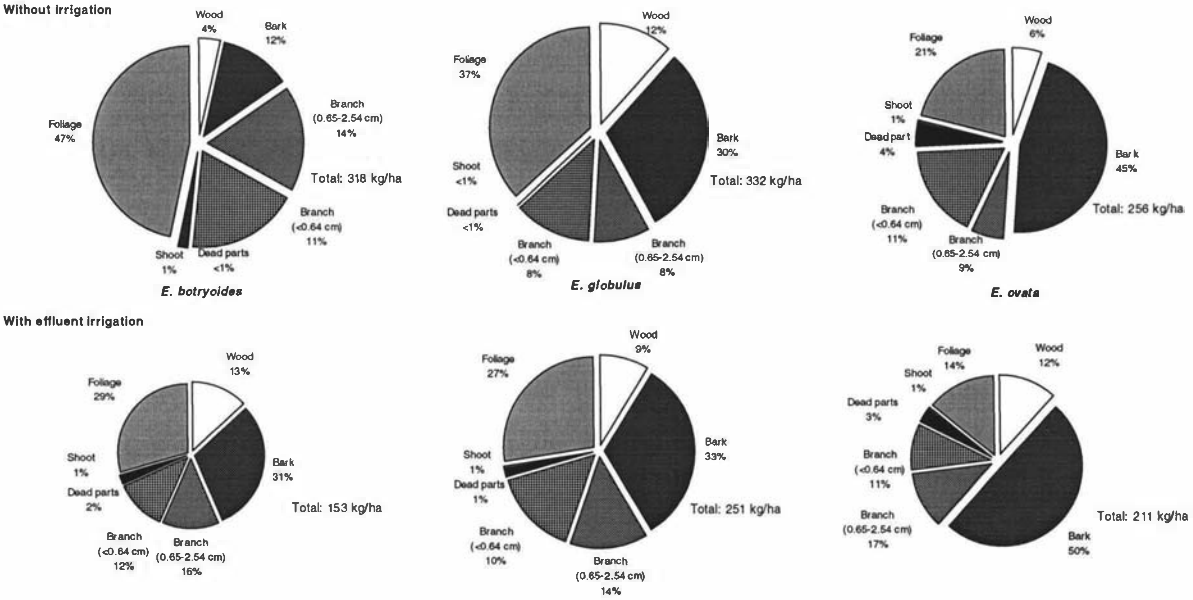

Figure 5.11 Calcium distribution in the harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total calcium accumulation).

Magnesium

The response of magnesium accumulation to effluent irrigation varied between the three species (Figure 5.7e). In the first year, effluent irrigation retarded magnesium accumulation in *E. botryoides*, had no effects in *E. ovata*, and enhanced it slightly in *E. globulus*. By year 2, effluent irrigation retarded magnesium accumulation in *E. globulus* and *E. ovata*, but had no effects in *E. botryoides*. At the end of the 3 year period, the irrigation significantly retarded the magnesium accumulation in *E. globulus* and *E. botryoides*, but not in *E. ovata* due to less biomass accumulation in the stands without irrigation.

Less magnesium was found in the leaf portion of the trees irrigated with effluent than in the leaf portion of the trees without irrigation, but more was found in the branches (Figure 5.12). Bark contained more than one quarter of the total magnesium, except for *E. botryoides* without irrigation where there was only 13%.

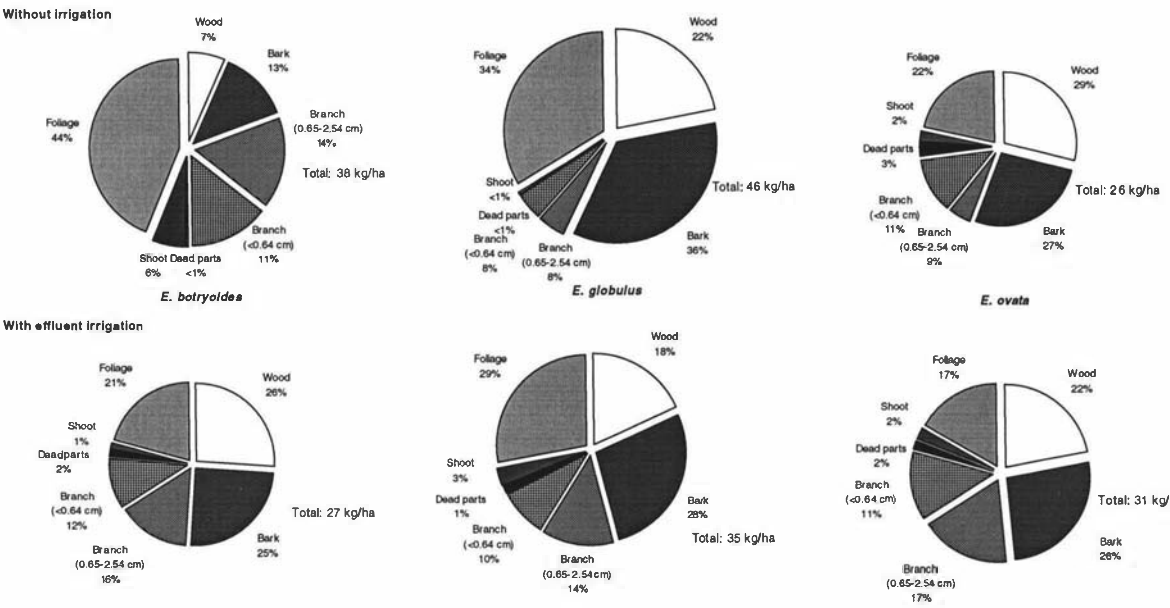

Figure 5.12 Magnesium distribution in the harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total magnesium accumulation).

Manganese

There were significant differences in tree potassium accumulation between the three species and effluent irrigation significantly enhanced manganese accumulation in all three species (Figure 5.6f). At the end of the 3 year period, *E. globulus* had accumulated more manganese than the other two species for both without irrigation and irrigated with effluent. There was no difference between *E. botryoides* and *E. ovata.*

Approximately half of the total manganese was stored in the leaf portion of the trees without irrigation (Figure 5.13). Less than 15% was found in the wood in all species without irrigation and irrigated with effluent.

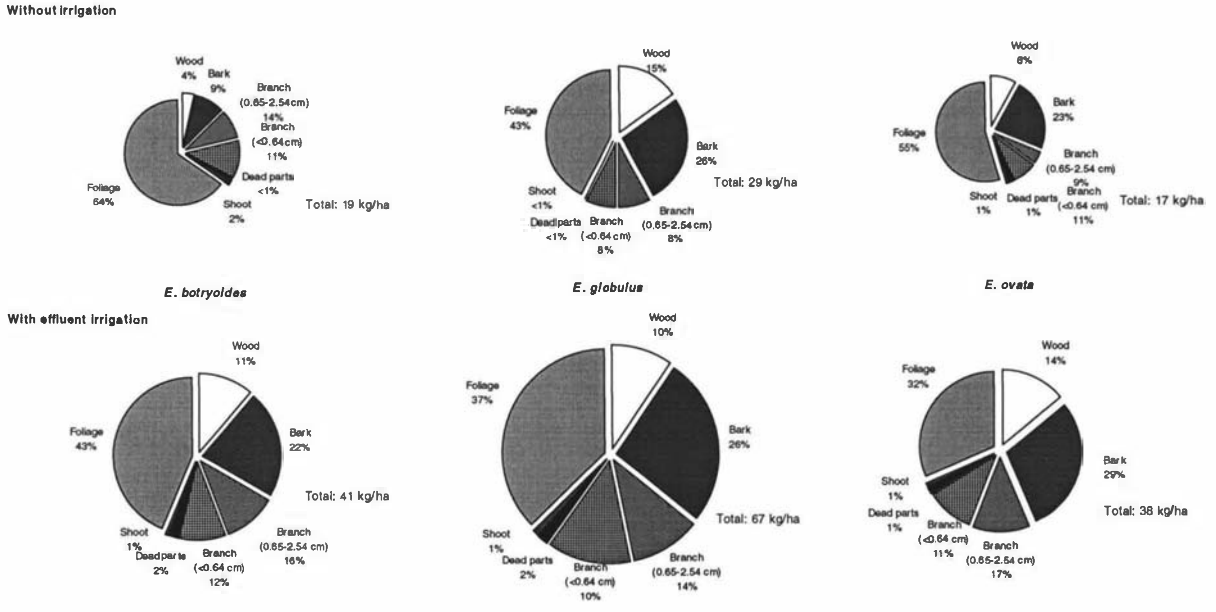

Figure 5.13 Manganese distribution in the harvestable above ground biomass at the end of the 3 year period (area of each chart depicts total manganese accumulation).

5.3.3 Tree foliage

5.3.3.1 Leaf area index (LAI)

There were significant differences in LAI between the three species and effluent irrigation reduced the LAI in all three species during the 3 year period (Table 5.1). LAI increased with time, but some reduction occurred at the end of the 3 year period.

Table 5.1 Leaf area index (LAI) in eucalypt plantations over the 3 year period.

	E. botryoides		*E. globulus*		*E. ovata*		
Age (year)	N	I	N	I	N	I	$LSD_{0.05}$
1	0.38	0.15	1.33	1.41	1.81	1.31	0.21
2	0.79	0.88	8.12	5.54	3.28	2.20	0.52
3	10.55	3.87	5.42	5.27	3.00	2.50	0.51
$LSD_{0.05}$	0.22	0.42	0.77	1.13	0.88	0.45	-

unit: m^2/m^2; N = without irrigation; I = irrigated with effluent.

5.3.3.2 Nutrient concentration changes

Leaves are usually the shortest living tree components in the above ground biomass. Nutrient concentrations change during the life of a leaf. Nutrient retranslocation before leaf senescing is important to manage nutrient balance in forests. “Young leaves” in the current study were defined as those not open when the trees were harvested. “Mature leaves” were those fully open with full size on the harvested trees. “Litter leaves” were those collected from the litter trays on the forest floor.

The three main nutrients, nitrogen, phosphorus and potassium, showed similar trends during the leaf life cycle (Figure 5.14a, b, and c). All the three nutrients were more concentrated in young leaves. As leaves grew, their concentrations reduced, which continued until leaf fall. The main reduction of phosphorus concentration was from young leaf to mature leaf. Nitrogen reduction mainly occurred before leaf fall, which was defined as retranslocation. The potassium concentration consistently reduced as leaves grew.

Calcium concentration tended to increase as leaves grew (Figure 5.14d). Some reduction occurred before leaf fall though this was only significant in *E. botryoides* without irrigation.

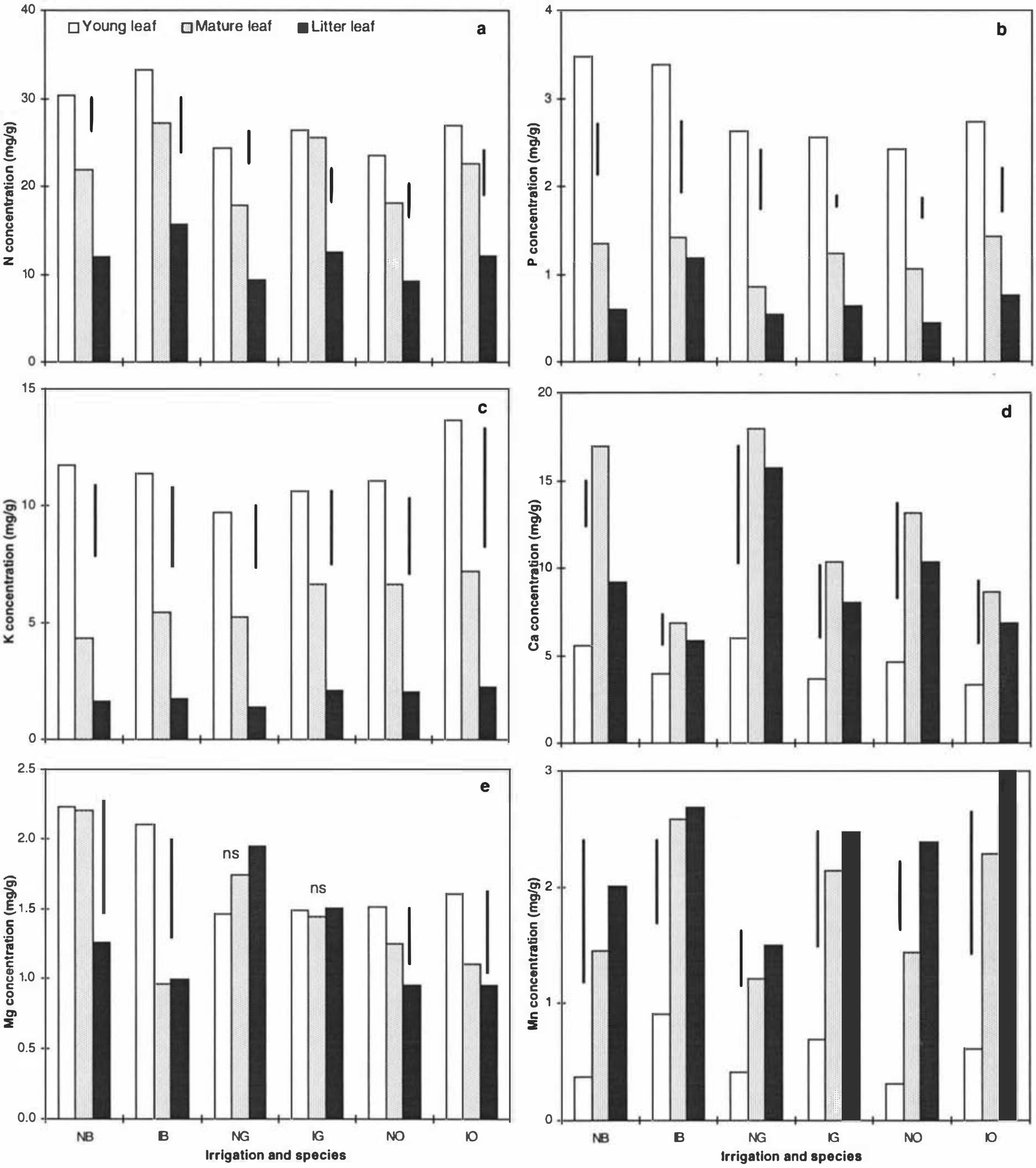

Figure 5.14 Nutrient concentrations in young leaves, mature leaves and litter leaves in eucalypt plantations: (a) nitrogen, (b) phosphorus, (c) potassium, (d) calcium, (e) magnesium, and (f) manganese (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; vertical bars indicate $LSD_{0.05}$; ns = not significant; n = 3).

The change of magnesium concentration during leaf life cycle varied between species and between trees without irrigation and irrigated with effluent (Figure 5.14e). In *E. botryoides*, magnesium concentration reduced before leaf fall in the trees without effluent, but from young to mature in the trees irrigated with effluent. Magnesium concentration had no change in *E. globulus* leaves. In *E. ovata*, magnesium concentration consistently reduced as leaves grew, but the only significant difference was between young leaves and litter leaves.

More manganese was accumulated in the leaves as leaves grew. Further increases occurred before leaf fall, though this was only significant in *E. ovata* without irrigation (Figure 5.14f).

5.3.4 Litter fall and nutrient return

5.3.4.1 Litter fall

Litter had started falling before the trees reached 1 year old. The mass of litter fall increased with tree age (Figure 5.15). *E. globulus* had the highest litter production of the three species whether without irrigation or irrigated with effluent during the 3 year period. The annual litter fall reached 13.4 OD t/ha under 3 year old *E. globulus* stands irrigated with effluent. Effluent irrigation enhanced litter fall but was only significant in *E. globulus* during the second year and in *E. ovata* during the third year.

The non-leaf components contributed less than 5% of the total litter. The average of all stands monitored was only 3%. There were no differences between species and between without irrigation and irrigated with effluent. The contribution increased as the trees grew, but this increase was only significant in *E. globulus* stands where the contribution rose from 1.0% to 3.1% after the 3 years.

5.3.4.2 Nutrient return via litter fall

E. globulus returned the highest amount of all six nutrients via litter fall during the 3 year period (Figure 5.16). Effluent irrigation enhanced the return of nitrogen, phosphorus, potassium and manganese, but had no effect on calcium and magnesium return. The return increased with tree growth. There was less change in the return of nitrogen and phosphorus either in *E. botryoides* or *E. ovata* without irrigation in the third year.

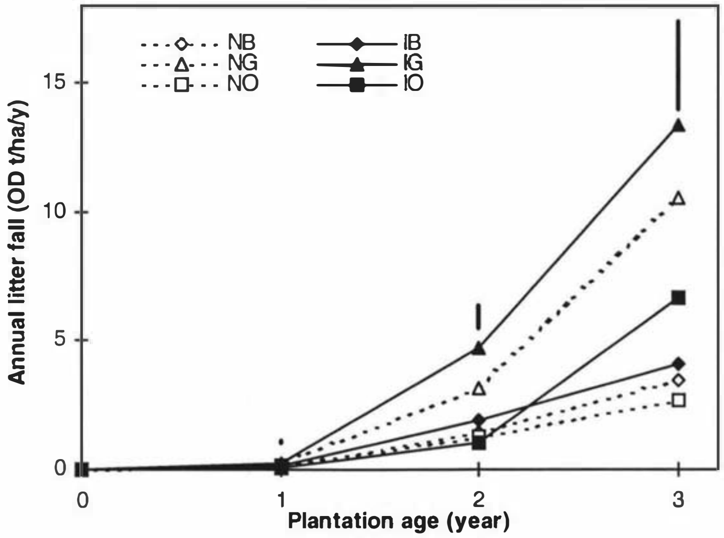

Figure 5.15 Total annual litter fall in eucalypt plantations over the 3 year period (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; vertical bars indicate $LSD_{0.05}$; n = 3).

The non-leaf litter components contributed less than 5% of the total nutrient return. The average in all stands monitored was under 3% (nitrogen 1.6%, phosphorus 2.5%, potassium 3.0%, calcium 2.4%, magnesium 2.4% and manganese 1%). There were no differences between the three species, and between without irrigation and irrigated with effluent. The contribution of the non-leaf litter increased slightly as trees grew.

5.3.4.3 Monthly litter fall, nitrogen return and phosphorus return

Up to 1 year old, only a little amount of litter was produced as trees had not fully occupied the site. Therefore, no monthly analysis was done on the litter fall and nutrient return during the first year. The monthly distribution of litter fall, and nitrogen and phosphorus returns were analysed for years 2 and 3.

Litter fall

Litter fell all year round in all stands, peaking in summer time in both years, particularly in December and January (Figure 5.17). There was no difference between the monthly litter fall under *E. globulus* without irrigation in the third year. Species and effluent irrigation had no effects on litter fall during the peak fall period from December and January except in December 1995.

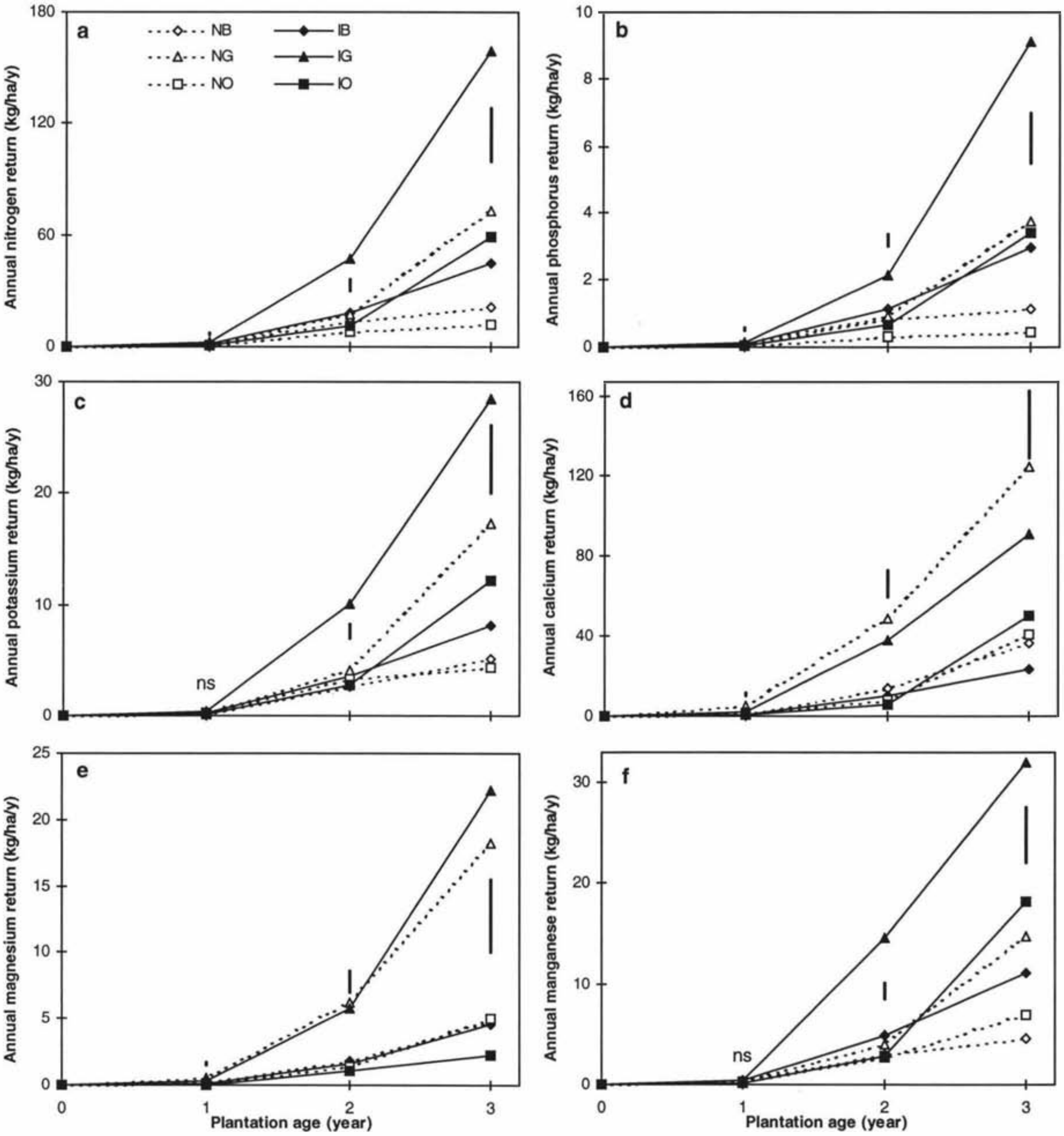

Figure 5.16 Annual nutrient return via litter fall in eucalypt plantations over the 3 year period: (a) nitrogen, (b) phosphorus, (c) potassium, (d) calcium, (e) magnesium, and (f) manganese (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; vertical bars indicate $LSD_{0.05}$; ns = not significant; n = 3).

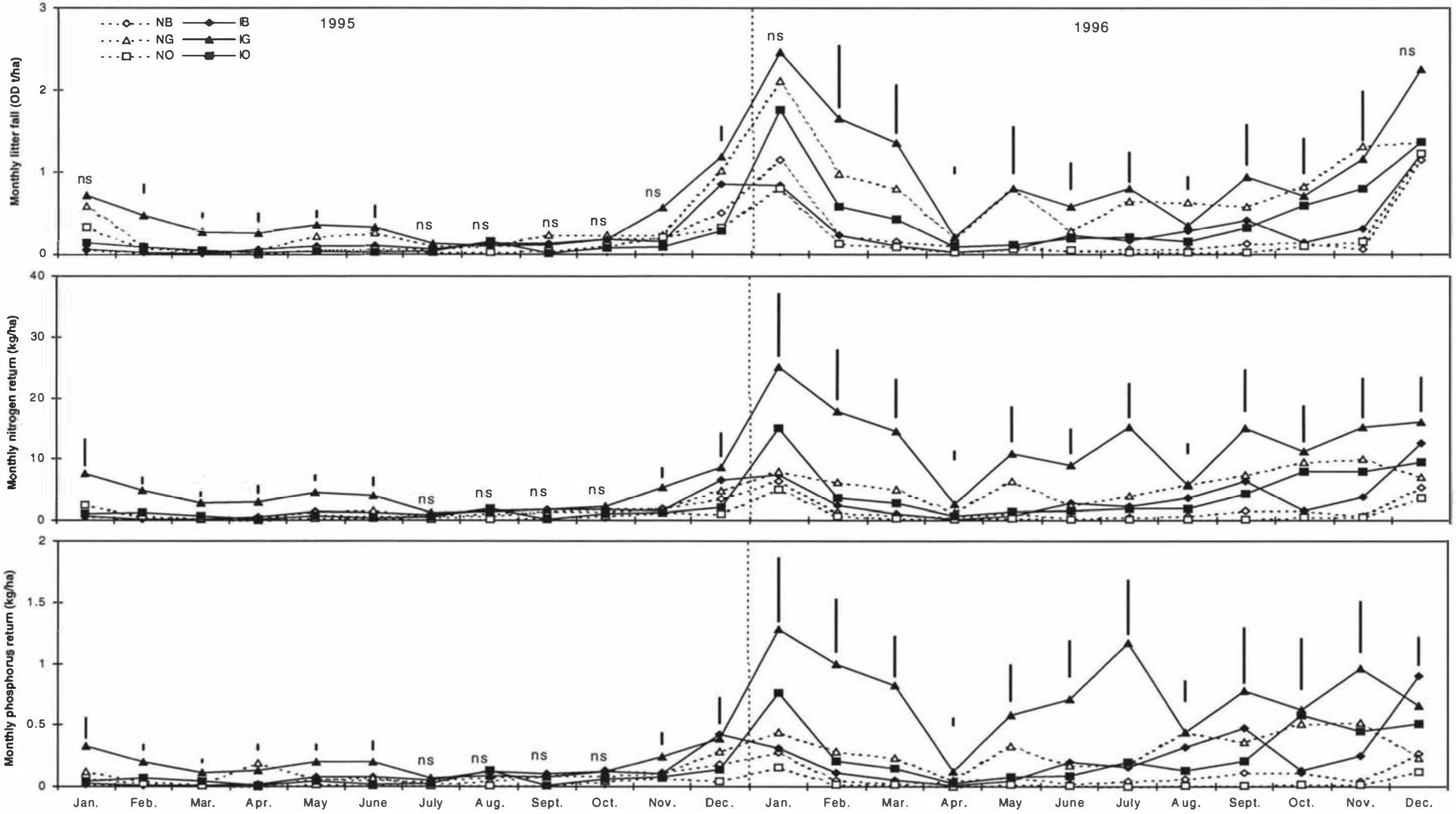

Figure 5.17 Monthly litter fall (top), nitrogen return (middle), and phosphorus return (bottom) via litter fall over 2 year period (1995-1996) in eucalypt plantations (N = without irrigation; I = irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*; vertical bars indicate $LSD_{0.05}$; ns = not significant; n = 3).

As the fastest growing species, litter fall in *E. globulus* stands was consistently higher than in the other two species during the rest of year, especially in the stands irrigated with effluent. There were hardly any differences between *E. botryoides* and *E. ovata.* Effluent irrigation tended to increase litter fall, but this was only significant from February to May 1995 and in June and September 1996.

Nitrogen return

Nitrogen return via litter fall occurred all year around (Figure 5.17). Monthly nitrogen returns varied during the 2 years, but were not significant in *E. ovata* stands irrigated with effluent in 1995 and in *E. globulus* without irrigation in 1996. Nitrogen return peaked in summer time, especially in December and January.

From July to October 1995, nitrogen return was independent of species and effluent irrigation. In the other months, it was higher in *E. globulus* than in the other two species. *E. botryoides* and *E. ovata* were similar in most months. Effluent irrigation increased the nitrogen return in the other months, but this increase was not significant in January 1995, and April, May and October 1996.

Phosphorus return

The monthly pattern of phosphorus return via litter fall was similar to nitrogen (Figure 5.17). There was no difference in monthly phosphorus return under *E. ovata* irrigated with effluent in 1995 and under *E. globulus* without irrigation in 1996. Phosphorus return also peaked in summer time.

From July to October 1995, species and effluent irrigation had no effects on phosphorus return. In the other months, phosphorus return was higher in *E. globulus* than in other two species. *E. botryoides* and *E. ovata* were similar in most months. Effluent irrigation increased phosphorus return in the other months, but this was not significant in January 1995, or April and May 1996.

5.3.5 Total biomass production and total nutrient uptake

Total biomass production in the first 3 year rotation included both biomass accumulation and litter fall. Similarly, total nutrient uptake was defined as nutrient accumulation plus nutrient return via litter fall.

E. globulus had the highest biomass production of the three species (Table 5.2). Ninety OD t/ha of total above ground biomass were produced in its stand irrigated with effluent. Effluent irrigation increased the total biomass production in *E. globulus* and *E. ovata*, but was not significant in *E. botryoides*. The response to effluent irrigation was significantly higher for *E. ovata*, with 80% more biomass produced.

Table 5.2 Total biomass production and total nutrient uptake during the 3 year period in eucalypt plantations.

	E. botryoides		*E. globulus*		*E. ovata*		
	N	I	N	I	N	I	$LSD_{0.05}$
Biomass (oven-dry t/ha)	42.0	49.3	71.6	89.8	36.1	65.3	9.5
Nitrogen (kg/ha)	424.8	490.1	524.3	859.0	265.5	471.2	45.5
Phosphorus (kg/ha)	38.8	46.6	39.8	65.9	15.2	41.7	3.4
Potassium (kg/ha)	218.4	260.5	283.8	432.3	176.9	380.2	30.6
Calcium (kg/ha)	369.1	186.5	511.3	382.6	306.3	367.8	37.2
Magnesium (kg/ha)	44.8	33.8	70.9	62.9	29.5	37.3	4.8
Manganese (kg/ha)	27.1	56.9	47.8	113.6	27.5	59.5	5.6

N = without irrigation; I = irrigated with effluent.

The fastest growing *E. globulus* took up the greatest amount of nitrogen in the 3 years (Table 5.2). Effluent irrigation enhanced nitrogen uptake by 15%, 64% and 77% for *E. botryoides*, *E. globulus* and *E. ovata*, respectively.

Effluent irrigation also enhanced phosphorus uptake by 20%, 66% and 174% for *E. botryoides*, *E. globulus*, and *E. ovata*, respectively (Table 5.2). In the stands without irrigation, *E. globulus* and *E. botryoides* took up more phosphorus than *E. ovata*. In the stands irrigated with effluent, the highest uptake occurred in *E. globulus* and was lowest in *E. ovata*.

Effluent irrigation enhanced potassium uptake too, by 19%, 52% and 115% for *E. botryoides*, *E. globulus*, and *E. ovata*, respectively (Table 5.2). *E. globulus* took up most potassium either when without irrigation or irrigated with effluent.

Effluent irrigation reduced the calcium uptake in *E. botryoides* and *E. globulus* by 50% and 25%, respectively, but increased it by 20% in *E. ovata* (Table 5.2). In the stands irrigated with effluent, *E. globulus* and *E. ovata* took up more calcium than *E. botryoides*. In the stands without irrigation, *E. globulus* took up more calcium than the other two species.

In a manner similar to calcium uptake, effluent irrigation reduced magnesium uptake in *E. botryoides* and *E. globulus* by 25% and 11% respectively, but increased it by 26% in *E. ovata* (Table 5.2). *E. globulus* took up more magnesium than the other two species either when without irrigation or irrigated with effluent. *E. botryoides* took up more than *E. ovata* only in the stands without irrigation.

Effluent irrigation doubled manganese uptake in all species (Table 5.2). *E. globulus* took up the most manganese either without irrigation or irrigated with effluent. There was no difference between the other two species.

5.3.5.1 Correlation of biomass production and litter fall

Although species and effluent irrigation had some effects on tree biomass production and litter fall, the quantity of litter fall depended mostly on how much biomass was produced. On the other hand, annual litter fall was determined more by the previous year's annual biomass production than by the current annual biomass production (Figure 5.18a). The higher the previous year's annual biomass production, the greater the amount of litter fall in the current year. The total litter fall in the stands depended on the total biomass production (Figure 5.18b). The more the total biomass produced, the more the litter fall.

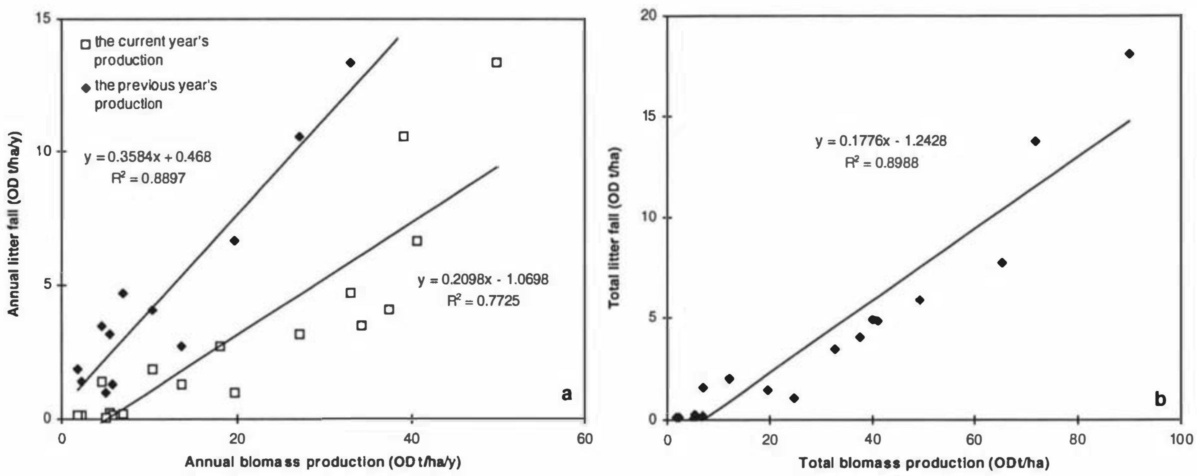

Figure 5.18 The correlation between biomass production and litter fall in eucalypt plantations: (a) annual production and annual fall, and (b) total production and total fall.

5.3.5.2 Correlation of nutrient uptake and return

In a manner similar to the amount of litter fall, the quantity of nutrients returned via litter fall also depended on the nutrient uptake by trees. This varied between different nutrients. Annual nutrient return via litter fall was determined more by the previous year's annual nutrient uptake than by the current annual nutrient uptake for nitrogen, phosphorus and calcium (Figures 5.19a, 5.20a). The higher the previous year's annual uptake, the greater the amount of nutrient return via litter fall in the current year.

In contrast, annual nutrient return via litter fall was determined more by the current annual nutrient uptake than by the previous year's annual nutrient uptake in potassium, magnesium and manganese. The higher the current annual uptake by trees, the greater the amount of their return via litter fall in the same year.

The total uptake of each nutrient by trees also influenced the total return of the nutrient via litter fall in the stands (Figures 5.19b, 5.20b). The more the nutrient uptake, the more the nutrient return via litter fall in the stands.

The highest correlations between uptake and return were found for manganese (Figure 5.20). More than half of its annual uptake was returned through litter fall in the same year. A similar trend was also found in its total uptake and total return during the 3 year period.

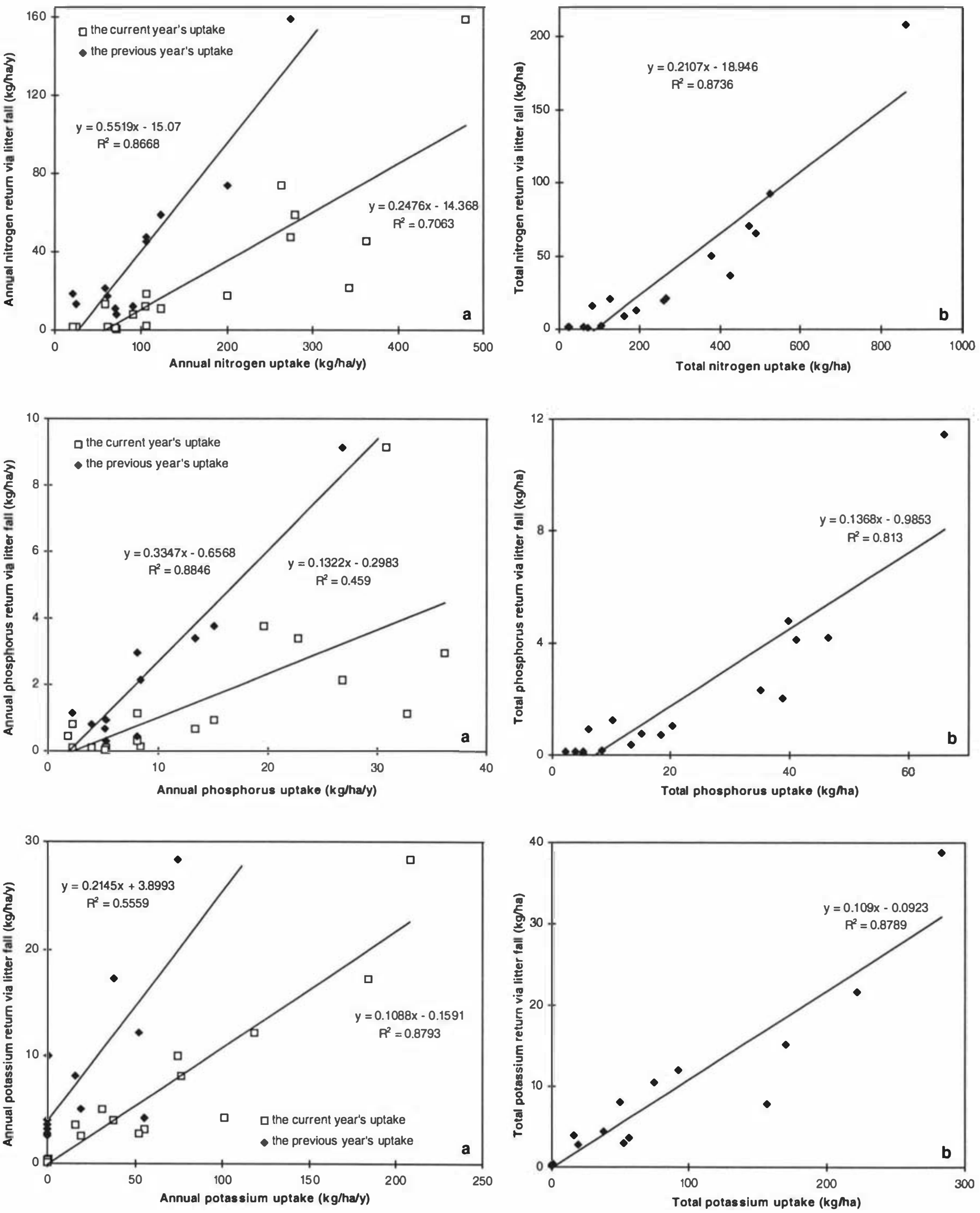

Figure 5.19 The correlation of nutrient uptake and its return via litter fall in eucalypt plantations (part 1) -- nitrogen (top), phosphorus (middle), and potassium (bottom): (a) annual uptake and annual return, and (b) total uptake and total return.

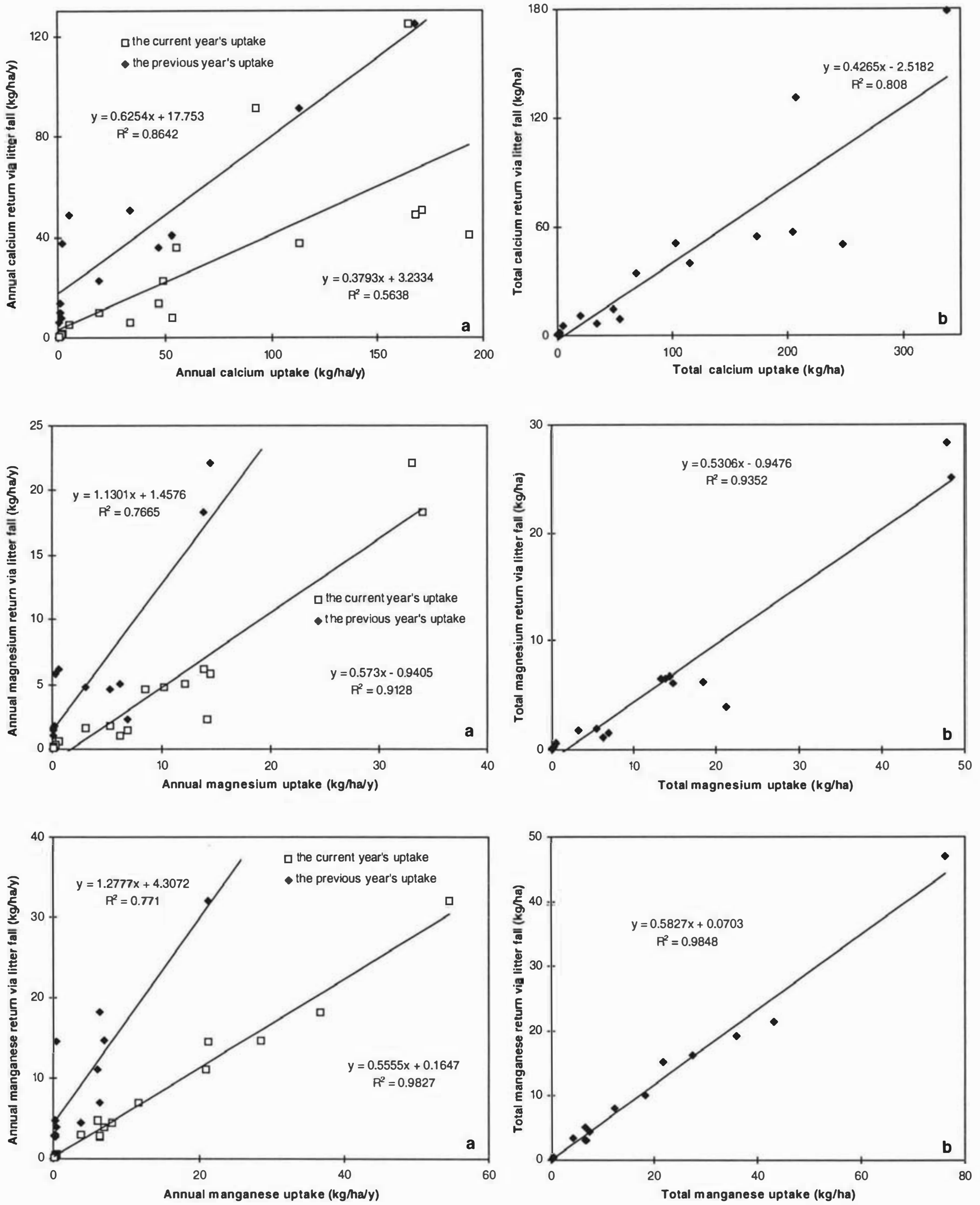

Figure 5.20 The correlation of nitrogen uptake and its return via litter fall in eucalypt plantations (part 2) -- calcium (top), magnesium (middle), and manganese (bottom): (a) annual uptake and annual return, and (b) total uptake and total return.

5.4 DISCUSSION

5.4.1 Soil properties

5.4.1.1 Soil bulk density

In the current study, site preparation and tree planting disturbed the soil structure and at first increased soil bulk density under all 3 species of trees without irrigation (data not shown). Then, bulk density decreased slightly after 1 year (Figure 5.2). At the end of the rotation, the bulk densities were similar to the originals under pasture before tree planting. However, Pereira et al. (1996) found that modification of physical properties of soils under *E. globulus* plantations compared with soils under a native oak species (*Quercus suber*) was mostly related to an increase in compaction.

Across the three species, the soil bulk density was consistently lower in soil irrigated with effluent than in soil without irrigation during the rotation. This could be caused by the fauna or micro-organism activity responding to effluent irrigation directly rather than due to faster tree growth.

Other studies have also shown that meatworks effluent irrigation (Tipler et al. 1996) and sewage irrigation (Mathan 1994) reduced soil bulk density. However, the irrigation effects may last only for a few years in forest plantations as there was no difference between soil bulk densities under six year old trees either without irrigation or irrigated with effluent (Table 3.2). Litter fall contributing to the soil organic matter under the stands without irrigation would play a special role in that.

5.4.1.2 Soil infiltration rate

Cook & Thorne (1990) found that infiltration rate dropped by 50% from 7200 mm/day to 3550 mm/day after 3 years of effluent application. In the current study, the soil infiltration rate was significantly reduced by *E. globulus* tree planting into pasture, but there was little change for the combination of tree planting and effluent irrigation (Figure 5.2). Sodium input via effluent irrigation had not resulted in increased soil bulk density or further soil infiltration reduction. Similar results were also found under the six year old *E. botryoides* (Figure 3.2).

Soil permeability influences the length of time liquid wastes remain in the soil, and hence potential loading rates. If permeability is high, liquid wastes or soluble components are not adequately treated, especially during periods of high rainfall, and groundwater may be contaminated. On the other hand, if permeability is too low, permissible application rates would be too low to be practical, or anaerobic conditions would be induced (Witty & Flach 1977).

Suitable soil infiltration rates ensure effluent passes through the soil profile and provide time for plant roots and micro-organisms to consume the nutrients in it. This avoids both run-off from effluent ponding and crusting on the soil surface, and groundwater contamination, which are the major problems in land treatment.

5.4.1.3 Soil organic matter

Effluent irrigation raised the soil organic matter content significantly (Figure 5.2). However, the irrigation may have little direct effect on organic matter content and only for a very short time. Sufficient nutrients and water in effluent encouraged trees to grow fast (Figure 5.5). The faster the tree grows, the more the litter fall (Figure 5.18). Litter on the forest floor contributed organic matter through litter decomposition other than that directly from effluent. For example, high soil organic matter was found under *E. globulus* stands without irrigation.

The quantity of organic matter in soils is usually small, averaging about 2 to 10 % (Ferguson 1976). Tipler et al. (1996) reported that ten year meatworks effluent irrigation raised soil organic matter content by 40% (from 4.9 to 6.75%) under pasture. The organic matter contents measured in the current study were much higher than the above figures with the highest being 23% at the end of the 3 year period. The organic matter was increased by 56 - 70% in the stands irrigated with effluent.

Ferguson (1976) indicated that organic matter has typical cation exchange capacity of about 200 me/100g. It has many reactive sites that have the ability to fix both anions and cations in exchangeable forms, and it forms many relatively stable complexes. It has a tremendous capacity to absorb water. Therefore, all these changes following soil organic matter increase would affect tree growth and the sustainable use of the land, particularly in a land treatment system.

Polglase et al. (1992) found that the increasing amount of organic matter with stand age was associated with a decrease in soil bulk density. Therefore, as soon as litter plays its role in the contribution to soil organic matter, the difference on soil bulk density between without irrigation and irrigated with effluent would decline (section 3.3.1).

5.4.1.4 Soil acidity

A side effect of the application of sewage effluents to soil is the production of acid in the nitrification reactions (Gilmour et al. 1977). Russell et al. (1988) suggested that irrigation with meatworks effluent on to pasture decreased the soil pH, which may be due to the higher ammonium ion concentration of this effluent displacing cations from the soil and the oxidation of ammonia to nitrate. However, Wells & Whitton (1970) reported that irrigation of pasture with meatworks effluents for 15 years raised the pH from 6.2 to 6.5 in Lismore silt loam, but lowered it from 6.4 to 6.2 in Selwyn sandy loam.

Waly et al. (1987) found that the pH value of the surface layer decreased gradually in soil treated with sewage water, but this tendency was less pronounced in the deeper layers. This fall could be attributed to the production of CO_2 and organic acids by soil micro-organisms. Falkiner & Smith (1997) reported that soil pH increased under a plantation of two tree species (*Pinus radiata* and *E. grandis*) when irrigated with secondary-treated sewage effluent for two and four irrigation seasons. In *E. camaldulensis* fuelwood plantation irrigated with sewage effluent in Australia, the soil pH increased, but the infiltration rate decreased (Stewart et al. 1986). Under both pasture and forest plantation, the soil pH response to effluent irrigation has varied between studies.

At the end of the 3 year period in the current study, no soil pH change was found under trees without irrigation, but it was significantly decreased where effluent had been applied (Figure 5.2) despite the pH of the effluent being 6.8 (Table 3.1). This may contribute to production of acid in the nitrification reactions (Gilmour et al. 1977) thereby lowering the soil pH. However, soil pH will decrease even without irrigation as litter decomposition will also contribute to the production of acid. The products of decomposition such as carbon dioxide from decomposer organisms and organic acids from litter materials, will tend to increase the acidity of water percolating through the litter (Feller 1978). This is likely to be the main reason for a soil pH decrease following eucalypt tree planting into grassland (Herbert 1996). On the other hand, tree planting of different species also effects the soil pH. For example, in 8 year old plantations, Frederick et al. (1985a) found the pH of the mineral soil at depth 0 - 200 mm was lowest (5.2) under *E. regnans*, highest (6.0) under *P. radiata* and medium (5.5) under *Acacia dealbata*.

Furthermore, the sources of soil organic nitrogen in a forest land treatment system can be both from effluent irrigation and from litter decomposition. Nitrification of organic nitrogen will reduce the soil pH value which could be harmful to a lot of crops in the long-term. *Salix* roots do not grow at low pH in the soil, inhibiting root growth at pH values below 5 (Ericsson & Lindsjo 1981, cited in Elowson & Rytter 1986). Acidity must be reduced to favour growth and penetration of roots. However, some species are less sensitive to soil pH reduction. For example, grey alder (*Alnus incana*) was not sensitive to pH values below 5 in a peat soil (Elowson & Rytter 1986).

Soil pH in natural and plantation eucalypt forests is usually low and 4 - 5 is common (section 3.3.1.4). Even though the soil pH in the current study was reduced by effluent irrigation to as low as 3.9 under *E. botryoides* trees irrigated with effluent, they still grew much better than the trees without irrigation. This confirms that the planting of eucalypts in effluent land treatment systems is a good choice. On the other hand, the low pH may also be related to the summer season of soil sampling as soil pH was reduced while the temperature was high (section 7.3.1.1).

5.4.1.5 Soil nutrients

As soon as effluent N reaches the soil, it becomes part of the soil nitrogen cycle (Feigin et al. 1991). Abd Elnaim et al. (1987) reported that with irrigation of sewage water for 70 years, the soils have improved due to changes in the soil texture from sandy to loamy-sand, increase of soil organic matter and clay minerals, giving increased cation exchange capacity and improved structure. Wells & Whitton (1970) found that irrigation of pasture with organic-rich effluents from meatworks for 15 years raised nitrogen levels and increased base saturation of the topsoils.

Bargali et al. (1992b) found that the total quantity of nutrients in the soil decreased from 7166 kg N/ha, 301 kg P/ha, and 5330 kg K/ha in a 2-year-old plantation to 7092 kg N/ha, 227 kg P/ha and 4401 kg K/ha in an 8-year-old plantation. This reduction should be caused by tree consumption. Waly et al. (1987) reported that total and soluble nitrogen, as well as available phosphorus, increased with prolonged application of sewage water and maximum accumulation occurred in the upper layers of the soil. Surface irrigation of pasture with meatworks-fellmongery wastes increased the nutrient status of the soil to the point where most of the applied nutrients, with the exception of phosphorus, were lost in drainage water and eventually reach the saturated zone (Keeley & Quin 1979).

Effluent irrigation raised all soil nutrients monitored in the current study in only 3 years, but there was little change or even some reduction (e.g. nitrate level) found in the stands without irrigation (Figure 5.3). In the stands irrigated with effluent, there were some differences in soil nutrients between species. For example, lower available nitrogen in the soil under *E. globulus* trees. This could be caused by the higher nutrient demand for this faster growing tree. However, there was hardly any difference in soil nutrients between species in the stands without irrigation despite differences in yield.

In New Zealand, the main fertiliser elements are phosphorus and nitrogen, and new exotic plantings are fertilised annually (Ballard 1978). Nitrogen and phosphorus can significantly influence eucalypt growth (Messica 1990). Bennett et al. (1996) reported that *E. globulus* growth increased in response to all fertilizer additions, leading to the greatest mean volumes at the highest combined rates of N and P. Hence, the increase in the quantities of these nutrients, especially the available fractions of the nutrients, played a key role in more biomass produced (Table 5.2).

In *P. radiata* plantations irrigated with streamwater and domestic effluent, Schipper et al. (1996) found that changes in the soil properties receiving effluent were attributed to nutrient input rather than from additional water loading. The changes in the soils receiving effluent at the end of the 3 year period in the current study should also be attributed to the nutrient input from the huge litter fall (Figure 5.15).

Nitrate leaches from the soil to the groundwater. Therefore, leaching may occur in the soil under trees irrigated with effluent where the higher nitrate concentration was found (Figure 5.3). Bio-denitrification is the conversion by micro-organisms of nitrate into gaseous forms of nitrogen. Loehr et al. (1979b) suggested that land application systems must bring nitrate and organic carbon together in order to encourage biodenitrification.

Wild (1993) concluded that denitrification requires the presence of nitrate, metabolizable carbon compounds and the almost complete absence of oxygen at the site. Nitrate is formed by nitrification or might be added in fertilizer or from effluent irrigation in the land treatment system. Soil organic matter, plant roots and litter above the soil surface provide metabolizable carbon compounds. The concentration of oxygen is reduced to a sufficiently low level when the soil air is displaced by water, such as after heavy rainfall or irrigation. The soil does not need to be devoid of oxygen because denitrification will occur at micro-sites that are anaerobic, for example within water-saturated aggregates or where an energy-rich substrate causes oxygen depletion, even though the soil as a whole contains oxygen.

Schipper et al. (1996) found that the rate of denitrification doubled under effluent irrigation compared with under stream water irrigation or no irrigation. Koops et al. (1996) found that denitrification losses of nitrogen in the soil of grassland on peat soils totalled up to 70 kg N /ha/y.

Higher nitrate concentrations were found in the stands irrigated with effluent. Therefore, the nitrate was more likely to be leached to the ground water. However, the litter provides plenty of organic carbon, and the effluent irrigation can reduce soil oxygen levels intermittently. Denitrification may be another main nitrogen output from a forest effluent land treatment system, which could be an advantage for consuming nitrogen originating from the effluent. Further studies should be done to test this hypothesis.

There was a positive relationship between soil infiltration rate and soil nitrate concentration (Figure 5.4). The faster infiltration rate may give faster air and water exchange in the soil profile, which could enhance the nitrification process. However, the nitrogen supply may limit the nitrification in the original soil even though it had the highest infiltration rate.

5.4.2 Biomass production and nutrient uptake

5.4.2.1 Biomass production

Effluent application increased both the total biomass accumulation and the total biomass production by about 17%, 25% and 80% among the three species, *E. botryoides*, *E. globulus* and *E. ovata*, respectively (Table 5.2). The response of *E. ovata* to effluent was significantly higher than that of the other two species. *E. globulus* showed the best growth performance in the three studied species, either without irrigation or irrigated with effluent. In its stands irrigated with effluent, 90 OD t/ha of above ground biomass were produced in the 3 year period (Table 5.2), and 72 OD t/ha of above ground biomass were accumulated in the standing trees at the end of the 3 year period (Figure 5.5).

Neenan & Steinbeck (1979) concluded that differences in biomass yields and ecological tolerances are likely to be more important in species selection than variation in their heating values. Therefore, the species selection should be mainly based on the biomass yield and ecological tolerances at an individual site or for special management considerations, e.g. high nutrient and water availability from effluent at the site in the current study.

Species selection significantly influenced the success of the short rotation forests. Boardman et al. (1996) pointed out that *E. globulus* is the preferred species for short-rotation pulpwood, it also is highly productive, and retains high levels of foliar N and P. In the current study, *E. globulus* also produced the highest levels of biomass and retained the greatest quantities of all six nutrients in the three species studied (Figures 5.5, 5.7). Therefore, *E. globulus* is highly recommended as a suitable species for 2 or 3 year rotation forests both without irrigation or irrigated with effluent at the study area. The other two species may be suitable in longer rotations since their current annual increment (CAI) rose sharply in the third year (Figure 5.5) and might well catch up to *E. globulus* by year 4 or 5. *E. ovata* should be only used when linked with effluent irrigation because of its poor performance in the stands without irrigation. In addition, disease (*Ophelionus euclaypli*) was only found on *E. botryoides* leaves, which could be one of the reasons for the species' poor performance.

The highest biomass production and nutrient uptake in *E. globulus* stands was matched by its denser junior foliage. Hillis (1990) indicated that early investment in leaf area, and thus maximum light interception by the *Symphomyrtus* subgenus leads to a more rapid increase in canopy photosynthesis than with the *Monocalyptus* subgenus. Even within the *Symphomyrtus* subgenus, the species with dense junior foliage (e.g. *E. globulus*) should be selected, for the initial high biomass in short rotation forests, rather than *E. botryoides* and *E. ovata.* Fertilization and irrigation should be essential for sustainable high production if not linked with effluent land treatment.

Eucalypt biomass production has been studied both for timber and energy production. Sachs et al. (1980) indicated that *Eucalyptus spp.* are prime candidates for woody biomass plantations because of their rapid growth rate, and biomass accumulation, being as much as 40 OD t/ha/y on a wide range of sites. The growth rate was highly related to species (including cultivars, clones), climate, and management (e.g. fertilization, irrigation, rotation length, site preparation, *etc*.).

Cromer et al. (1976) found that the total above ground biomass of *E. globulus* (2196 stems/ha) ranged from 1 OD t/ha without fertilizer to 8.6 OD t/ha following the heaviest application rate (nitrogen 202 kg/ha, phosphorus 90 kg/ha) at age 2, and 6.3 OD t/ha to 30.3 OD t/ha at age 4. Wise & Pitman (1981) reported that above ground biomass produced for six *Eucalyptus* species grown in rotations of ten years ranged from 110 to 162 OD t/ha (mean annual increment - MAI: 11.0 to 16.2 OD t/ha/y). George & Varghese (1990a) found only 77 OD t/ha (MAI: 7.7 OD t/ha/y) at the same age of *E. globulus* plantation.

High MAI's have been reported from very high density short rotation plantations of 20000, 30000 and 40000 trees/ha giving 16.0, 21.2, 18.8 OD t/ha/y respectively for *E. globulus* and 19.6, 20.1, 22.2 OD t/ha respectively for *E. camaldulensis* after 2 years (Pereira et al. 1996). Another study of *E. camaldulensis* gave 25.6 OD t/ha/y at first of the 2 year rotation harvest, 24.2 OD t/ha/y at the second, and 35.2 OD t/ha/y at the third at densities of 10000 to 20000 plants/ha (Dalianis et al. 1996). Ericsson (1994) estimated that MAI of above-ground-biomass ranged from 6.2 to 22.3 OD t/ha and CAI from 10 to 27.7 OD t/ha in managed stands (irrigated and treated with liquid fertiliser).

In the present study, the MAI ranged from 10.7 to 23.9 OD t/ha/y, and the CAI from 13.0 to 35.4 OD t/ha/y. The highest total above-ground-biomass accumulation was 72 OD t/ha after the 3 year growth of *E. globulus* stands irrigated with effluent (Figure 5.5). This was comparable with 73 OD t/ha for the same species at the same age, but with irrigation and fertiliser in Australia (Pereira et al. 1994). Toky & Ramakrishnan (1983a) suggested that the annual litter production should be added to the above ground biomass value to give the annual net production. This was defined as the total biomass production in the current study and gave a MAI ranging from 12.0 to 29.9 OD t/ha/y, and a CAI ranging from 18.0 to 49.9 OD t/ha/y.

Even though *E. globulus* trees irrigated with effluent had the greatest biomass production, their diameters and tree heights were lower than in trees without irrigation (Figure 5.5). As a result, less wood was present, but there were more branches in the trees irrigated with effluent (Figure 5.6). Although it made little difference to the biomass production, this should be considered if stem wood is the desired main end product.

In a 10 year old *E. globulus* plantation, 66% of the total above-ground biomass was contributed by wood, then branches, bark, leaves and twigs (George & Varghese 1990a). In the current study, a lower stem wood percentage (28 to 58%) was found in the biomass accumulation at the end of the 3 year period (Figure 5.6). On the other hand, rotation length also influenced the proportion of biomass. If wood was the main product desired from the system, a longer rotation should be used. For example, a 15 year rotation of *E. globulus* plantations can yield 80% of total above ground biomass as wood (Figure 5.21). The shorter the rotation, the more the other tree parts (mainly leaves and branches) contributed to the total above-ground biomass. Less stem wood in the total above ground biomass is a characteristic of a short rotation forest.

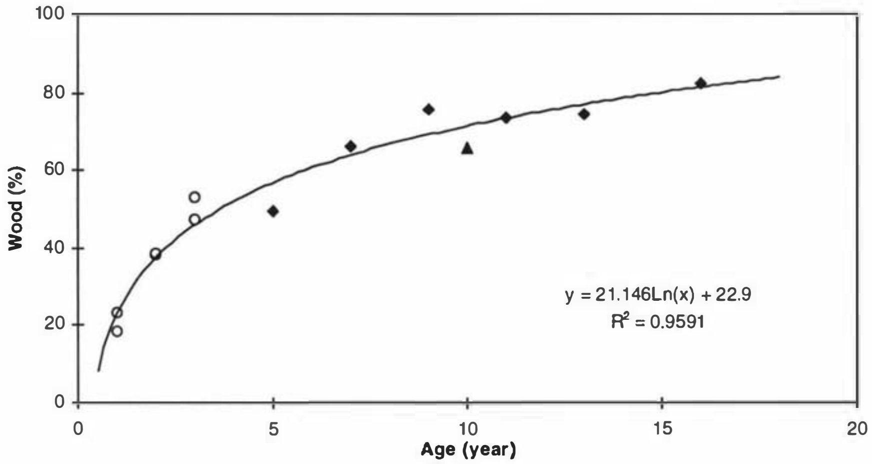

Figure 5.21 The effect of plantation age on the percentage of wood in total above ground biomass in *E. globulus* plantations (◆ = data from Negi & Sharma (1984); ▲ = data from George & Varghese (1990a); o = data from the current study).

Even though Dalianis et al. (1996) reported the stem percentages increased from first to third rotation following coppicing, other tree parts would still contribute a lot to the harvestable biomass, especially if irrigated with effluent. Therefore, the whole above ground biomass must be consumed in a suitable way after the biomass is harvested and removed from the site in short rotation forests.

In *Eucalyptus*, the reported heating values of branches (18.4 to 19.5 MJ/kg) are similar to those of the stem wood (18.8 to 19.5 MJ/kg) (Madgwick et al. 1981; Frederick et al. 1985a; Dalianis et al. 1996). However for leaves there are conflicting results: Dalianis et al. (1996) reported 16.0 MJ/kg whereas other studies (Madgwick et al. 1981; Frederick et al. 1985a; Senelwa 1997) reported 21.3 to 24.1 MJ/kg. Even if calculated using the lower values, the heating value of the wood component in the current study was still under half the heating value of the total biomass.

The density of different tree components appeared as the main factor to be considered other than their heating values. A key question is how to utilize the tree parts (even the litter on the forest floor) other than stem wood only after harvesting for energy production. The harvested biomass has been utilised for a fuelwood by shredding all of the stems, leaves and branches and then compacting these into a dense 'fuelbrick' used for energy production (Thomsen 1990). If the biomass was used in this way, the greater branch portion found on the trees irrigated with effluent is of little concern. Fuel briquettes made from branches, leaves, and even the litter on the forest floor, may be practical for energy conversion. While a short rotation forest not linked with waste land treatment, the nutrients removed via harvesting all above ground biomass must be replaced by application of commercial fertilizer for sustainable land use.

5.4.2.2 Nutrient uptake

The total quantity of nutrients stored in vegetation increased with age from 80.5 kg N/ha, 5.3 kg P/ha, and 41.2 kg K/ha in a 2-year-old plantation to 298.2 kg N/ha, 25.4 kg P/ha and 300.8 kg K/ha in an 8-year-old plantation (Bargali et al. 1992b). A similar trend was found in the current study and the total nutrient accumulation in the stands at the end of the 3 year period ranged from: 245 to 651 kg N/ha, 14 to 55 kg P/ha, 169 to 393 kg K/ha, 153 to 352 kg Ca/ha, 26 to 46 kg Mg/ha, 17 to 67 kg Mn/ha (Figures 5.7 - 5.13).

Although the *E. globulus* biomass accumulation under effluent irrigation in the current study was similar to results from Pereira et al. (1994) at the same age in Australia, the nitrogen accumulation in the current study (651 kg N/ha) was much higher than their results (229 kg N/ha). However, nitrogen accumulation from the current study was similar to the 239 to 639 kg N/ha measured for 3 year old *E. botryoides* and *E. ovata* without irrigation and irrigated with effluent from the same source at the same site (Knight & Nicholas 1996).

The mean annual nitrogen accumulation in the current study ranged from 81.7 to 217.0 kg N/ha/y, and the current annual nitrogen accumulation ranged from 92.6 to 320.9 kg N/ha/y. These were higher than Ericsson's (1994) results from managed eucalypt stands (26 to 130 kg N/ha).

The total nutrient uptake includes its accumulation, return via litter fall and some other outputs, such as throughfall, stemflow, consumption by herbivores *etc.* In forest studies, these other outputs are usually ignored even though this will result in an under-estimate of the total uptake. In the current study, the total nutrient uptake only included the accumulation in the standing biomass and the return via litter fall.

Rockwood et al. (1996) reported that in a wastewater bioremediation system, annual nutrient uptake rate by *E. ampligolia*, *E. camaldulensis* and *E. grandis* in 2 years ranged from 15.5 to 65.9 kg N/ha/y, 3.3 to 14.2 kg P/ha/y, 13.4 to 77.6 kg K/ha/y, 18.6 to 112.1 kg Ca/ha/y, 2.9 to 12.1 kg Mg/ha/y. In this present study, the mean annual nutrient uptake ranged from 88.5 to 286.3 kg N/ha/y, 5.1 to 22.0 kg P/ha/y, 16.7 to 94.4 kg K/ha/y, 23.0 to 112.7 kg Ca/ha/y, 4.5 to 16.2 kg Mg/ha/y, and 4.1 to 25.4 kg Mn/ha/y during the 3 year period (Table 5.2). The current annual nutrient uptake in the third year alone ranged from 104.4 to 479.6 kg N/ha/y, 1.8 to 36.2 kg P/ha/y, 31.1 to 208.2 kg K/ha/y, 48.9 to 193.1 kg Ca/ha/y, 8.5 to 34.1 kg Mg/ha/y, and 8.1 to 54.5 kg Mn/ha/y. The higher nutrient uptake in the stands irrigated with effluent was most likely the direct response to nutrient and water supply from the effluent. The high tree density also possibly played a key role in this.

The manganese accumulation was from 38 to 67 kg/ha in the three species irrigated with effluent and around half this in trees without irrigation (Figure 5.13). However, total manganese input to the site via effluent irrigation was only 12 kg/ha in total over 3 years (4 kg/ha/y). Therefore, effluent irrigation somehow increased tree Mn uptake from the soil reserves rather than from the effluent source.

Smith (1990) reported that acid soils high in Mn and organic matter showed an increase in the concentration of water-soluble Mn^{2+}. Haynes & Swift (1985) reported that $CaCl_2$- and HCl-extractable Mn showed broadly similar trends, both increasing markedly as the pH was lowered. The concentration of Mn and plant biomass in highbush blueberry plants (*Vaccinium corymbosum* cv. Blueray) also increased significantly. It could be that these side effects follow the pH reduction. Greater manganese uptake may be caused by lower pH or wetter soil conditions after effluent was applied, which make the manganese more soluble. Conversely, calcium uptake was significantly retarded by effluent irrigation and its accumulation was reduced by 18 to 52% (Figure 5.11).

Bargali et al. (1992a) reported that the total tree biomass increased with age from about 4 OD t/ha in 2-year-old to 121 OD t/ha in 8-year-old *E. tereticornis*. Fast-growing species like *Eucalyptus* will make a greater demand on nutrients in the early phase of growth, and minimize nutrient loss from the system. The harvesting age of *Eucalyptus* might coincide with peak production. Fertilizer should therefore be applied before canopy closure or before peak production is reached (Negi & Sharma 1996).

Nutrient uptake in very young plantations of any species is low because they do not fully occupy the site (Brockway et al. 1982). Less biomass and nutrient accumulation were found in the first year (Figures 5.5, 5.7). Therefore, less effluent should be irrigated during the first year after trees are planted since the nutrient and water consumption is correlated to the growth rate. The young trees in the first year mainly develop their root systems, then, the accumulation of above ground biomass increases greatly in the second and third years. Hence, the first year after tree planting could be considered to be an establishment period and not ready to play the treatment role fully in an effluent land treatment system. However on the trial site, *E. globulus* stands irrigated with effluent were able to accumulate 104 kg N/ha nitrogen in the first year (Figure 5.7).

5.4.2.3 Nutrient consumption by trees

The calculation of the biomass:nutrient content ratio (nutrient use efficiency or dilution) may give more valuable information than the absolute amounts of nutrients present (Negi & Sharma 1996). Nutrient use efficiency (NUE) is an evaluation of nutrient performance in forest systems.

Wang et al. (1991) indicated that the concept of sustainable production generally connotes the absence of longer site degradation, with nutrient depletion being an important component of degradation. Thus, in a short-rotation, high-yield plantation system where nutrients removed in repeated harvests may exceed natural rates of nutrient inputs, nutrient-use efficiency becomes an important concept. The role of tree size in determining nutrient-use efficiency suggests that the use of coppice or 'wood grass' harvest schemes, would be very 'expensive' from a nutrient perspective.

At least for nitrogen, intensively managed temperate forests are not self-sufficient (Bormann & Gordon 1989). Thus, understanding nitrogen removal is critical for sustained-yield management. In theory, the ideal tree should (a) achieve rapid growth, (b) remove few nutrients from the site at each rotation, and (c) be better suited to poor sites where growth may be normally limited by the rate at which nutrients are made available.

As nutrient removal is the main objective in an effluent land treatment system, here the ideal tree should (a) achieve rapid growth, (b) remove nutrients as much as possible from the site at each rotation, and (c) be suited to sites with sufficient nutrient and water availability. Therefore, a new concept should be introduced into the forests linked with effluent land treatment systems: "nutrient-consumption efficiency", being the ratio of the nutrient content:biomass. This is the opposite to the nutrient-use efficiency. Hence, the role of tree size in determining nutrient-consumption efficiency suggests that the use of coppice or 'wood grass' harvest schemes, would be 'cheap' from a nutrient perspective. On the contrary, long rotation forests become more 'expensive' from the perspective of effluent land treatment systems. In other words, short rotation forests are more practical than longer rotation ones in land treatment systems to maximize nutrient depletion.

Eucalyptus plantations realize high use efficiencies for these nutrients (net primary productivity in relation to net nutrient uptake), because of low nutrient concentrations in their tissues (Bargali et al. 1992b). Nutrient use efficiencies of eucalypts growing in relatively infertile soils are much greater than those for other species. Their luxury consumption of nutrients in more fertile soils results in a decrease in nutrient use efficiency (Negi & Sharma 1996).

There are more than 500 species in the genus (Brooker & Kleinig 1990; Boland et al. 1992), and it has been determined that 95 eucalypt species could be suitable for short rotation forests (Eliseo & Mariani 1978). The ideal species for land treatment site will be those with high nutrient concentrations in tissues. In the current study, the ratio of nutrient content to total biomass production varied with species (Table 5.3). *E. botryoides* consumed more nitrogen and phosphorus than other species to produce one tonne of biomass. The highest potassium and calcium consumption occurred in *E. ovata* without irrigation. The highest magnesium was consumed by *E. globulus* without irrigation, but the highest manganese was consumed by *E. globulus* and *E. ovata* irrigated with effluent.

Table 5.3 Specific nutrient consumption efficiency by trees following a 3 year growth period in the eucalypt plantations (kg of nutrient/OD t biomass).

	E. botryoides		*E. globulus*		*E. ovata*	
	N	I	N	I	N	I
Nitrogen	10.1	10.1	7.3	9.6	7.4	7.2
Phosphorus	0.9	1.0	0.6	0.7	0.4	0.6
Potassium	0.7	1.6	2.6	2.3	2.8	1.8
Calcium	1.3	1.0	2.3	1.0	5.4	2.6
Magnesium	0.2	0.2	0.5	0.4	0.4	0.2
Manganese	0.2	0.4	0.4	0.6	0.3	0.6

N = without irrigation; I = irrigated with effluent.

5.4.3 Tree foliage

Leaf biomass

The major effect of improved nutrient and water availability in the soil was to enhance foliage growth which included larger leaves as well as more leaves per plant and thereby increased light interception (Pereira et al. 1989). Usually, the greater the leaf area index and leaf biomass, the more the total biomass production because leaf is the unit for primary production. In the current study, effluent irrigation reduced the leaf proportion of the biomass (Figure 5.6) and the leaf area index (Table 5.1) even though it increased total above ground biomass accumulation (Figure 5.5). This phenomenon was consistent in all three species during the 3 year period although there were some exceptions in the leaf area index. However, the leaf area index was positively related to the current annual biomass increment ($R^2 > 0.7$) if data were divided into two groups, the stands without irrigation and the stands irrigated with effluent.

Cromer et al. (1975) found that there was a substantially greater proportion of leaf in unfertilized plots (46%) than in fertilized plots (33%) by age 2, but little difference (17%) by age 4. The competition between individual trees affected the results and the proportion of wood and dead branches will rise steadily with age at the expense of the leaf component. Hence, there are two possibilities: i) photosynthesis becomes more efficient after effluent application provides sufficient nutrient and water which results in less leaves but more productivity; ii) more leaf biomass, but leaf longevity becomes shorter due to the fast tree growth responding to the sufficient supply of nutrient and water.

The total net leaf biomass production was equal to the leaf biomass on the trees at harvest, but should also include fallen leaves. More litter fall was found in stands irrigated with effluent, which was consistent across all three species (Figure 5.15). Therefore, leaf longevity may have been reduced when faster growth was achieved after effluent was applied. On the other hand, more branch biomass (percentage in total biomass) was also found in the stands irrigated with effluent (Figure 5.6). The more branches should support more leaves, even though some leaves may only live for a short time.

The results from single leaf monitoring showed that a shorter leaf life occurred on trees irrigated with effluent (data not shown). Escudero et al. (1992) indicated that the lower the nutrient status of a species the longer the life-span of its leaves. Contrarily, the higher the nutrient status, the shorter the leaf life-span should be.

Ackerly & Bazzaz (1995) suggested the short leaf longevity in deciduous and evergreen species is generally associated with highly productive environments and rapid plant growth rates. Son & Gower (1992) found a significant positive linear correlation between leaf longevity and current foliage P concentration but not for N. A similar trend existed within genus or even species. However, eucalypts in the current study did not show such a trend.

Ackerly & Bazzaz (1995) found that leaf longevity was reduced whereas leaf initiation rates and leaf numbers increased when high nutrients were available. Escudero et al. (1992) suggested that changes in leaf longevity can be interpreted, at least in part, as a response to differences in nutrient availability. Within species, a luxurious nutrient supply could also reduce leaf longevity, leading to increased litter fall and faster nutrient cycling. That could also be part of the reason for the trend to less leaf biomass, but higher litter fall from trees irrigated with effluent in the current study. Sufficient nutrients and water from the effluent would enhance the leaf biomass production, and at the same time, increase the competition between leaves, shorten the life-span of each individual leaf, and speed up the nutrient cycling via litter fall.

Therefore, leaf longevity could play a very important role for the less leaf biomass in the trees irrigated with effluent. More branches and possibly less stem in the total biomass harvest was therefore expected after sufficient water and nutrient had been supplied from effluent.

Soil acidification enhances the solubility of manganese and causes it to accumulate in plants to concentrations that constitute toxicity (Fernandez 1989). Manganese toxicity is a major factor limiting plant growth in acidic soils (Foy et al. 1978; Sumner et al. 1991). Leaf shedding also results from manganese toxicity for some plant species, e.g. satsuma mandarin, potato and cowpea. Ethylene formation is clearly a secondary effect, but may be responsible for Mn-induced leaf shedding (Horst 1988). Abnormal defoliation was caused by excess manganese in satsuma mandarin trees as the soil was acidified at first and the solubility of Mn was increased for the occurrence of the disorder associated with excess Mn uptake of tops (Aoba 1986).

In the current study, the shorter leaf life and higher litter fall from trees irrigated with effluent may be caused by more Mn and less Ca accumulation in the leaf, or by light competition after canopy closure in such high tree density or some other indirect factors.

A few studies reported that excess Mn in leaves can cause photosynthesis decline in trees (Kitao et al. 1996; Kitao et al. 1997) and also in other plants (Ohki 1985; Nable et al. 1988). In the current study however, irrigated eucalypt species grew very well, even though with less living leaf than the trees without irrigation. The higher biomass in the stands irrigated with effluent gave no evidence of any photosynthesis decline. Hence, eucalypt species may have relatively high manganese tolerance. At the same time, the fast litter fall may also protect them by getting rid of the excess manganese and avoiding any possible toxic accumulation in the tree tissues.

Nutrient accumulation in leaves

For *E. tereticornis* plantations at 2 - 8 years old, Bargali et al. (1992b) found foliage was the largest component of nutrient storage in trees although its contribution decreased with age. The relative contribution to the proportion of nutrients in different above-ground components was generally in the order: foliage > bole (wood + bark) > branch > twig > reproductive parts. Similar results were also found in the current study, but the leaf contribution decreased only marginally with age in the 3 years. At the end of the 3 year rotation, the leaves accumulated 30% to 56% of the nitrogen, 26% to 37% of the phosphorus, 14% to 30% of the potassium, 14% to 47% of the calcium, 17% to 44% of the magnesium and 32% to 64% of the manganese (Figures 5.8 - 5.13).

The shorter the rotation, the more the foliage contributes to the total above-ground biomass. Leaves have a short life. Therefore, their harvesting and removal from the site should be a major consideration for crop production and sustainable land use. To minimize nutrient removal, leaves, branch and even bark should be kept on the site. To strip nutrients in effluent land treatment system, all tree parts, even including the litter accumulated on the forest floor, should be removed from the site. Therefore, it is important to manage foliage in the plantation to help achieve nutrient balance on the site, either without irrigation or irrigated with effluent. In effluent land treatment systems, it is necessary to remove foliage frequently because of high rates of nitrogen accumulation, and the need to prevent excessive nitrogen mineralization from litterfall. Then composting of the foliage may prove to be a lucrative option (Boardman et al. 1996).

Nutrient concentration change

Some nutrient concentrations (calcium and manganese) increased as leaves grew, whilst others (nitrogen, phosphorus and potassium) decreased (Figure 5.14). Furthermore, nutrient concentrations of nitrogen and potassium decreased before leaf fall occurred. These nutrients could be transferred to new growth or stored in other plant parts for further use. This is usually defined as retranslocation in the trees though nutrients may be lost through other outputs, e.g. potassium leaching directly from leaves.

Nutrient withdrawal from senescent leaves to stems and roots is an important mechanism by which plants make more efficient use of a limited resource. Between one and two thirds of the leaf N and P contents can in this way be transported back to woody tissues and stored for use during the coming season (Ericsson et al. 1992). The percentage retranslocation from senescing leaves was lower for N (25.2 - 38.1%) and P (18.1 - 35.6%) than for K (62.5 - 66.3%). The greater proportion of K lost may be partly due to leaching as K is easily leachable (Bargali et al. 1992b).

Retranslocation of nutrients is generally greater on infertile soils than fertile soils (Negi & Sharma 1996). In the current study, nutrient availability had little effect on nutrient retranslocation for there was hardly any difference between without irrigation and irrigated with effluent (Figure 5.14).

The retranslocation that occurs before leaf senescence should be considered in managing plantation forests. To remove calcium or manganese from the site, collecting the leaf litter is recommended. To remove other nutrients, especially potassium, more fresh foliage should be harvested along with the total biomass.

Overall, more nutrients could be removed from a well-managed land treatment system if the trees are harvested as soon as maximum mean annual nutrient accumulation is achieved. The tree should be harvested soon after tree canopy closure for maximum nutrient removal. However, the end product use and most economical return should also be considered.

5.4.4 Litter fall and nutrient return

Litter fall

During the 3 year period, 10% to 20% of the total above ground biomass produced fell from the trees as litter (sections 5.3.4.1 and 5.3.5). Annual litter fall increased with age and reached up to 13.4 OD t/ha (Figure 5.15). Litter started falling even before the trees reached 1 year of age and the total mass of litter fall increased with tree age. Between 65% to 86% of total litter fall and total nutrient return occurred in the third year of the 3 year period.

The production of litter is closely related to the initiation rate and longevity of leaves. The total annual litter fall ranged from 0.8 to 6.5 OD t/ha in 2 to 8 year old plantations (Bargali et al. 1992a). Ashton (1975) reported that the maximum litter fall coincided with the culmination of annual growth increment in *E. regnans* natural forests in Australia. O'Connell & Grove (1993) indicated that variation in litter fall between fertilizer treatments was related to the differences in above ground biomass. Boardman et al. (1996) found that for above ground biomass, the CAI of *E. globulus* irrigated with secondary sewage effluent for ages 3 to 4 and 4 to 5 years was related to the high foliage biomass, being 13.8 and 18.2 OD t/ha, respectively. As leaf life-span of *Eucalyptus* is under 18 months (Jacobs 1955), the current foliage should fall next year. Therefore, the potential of leaf litterfall in next year should be roughly the leaf biomass, or even more because of the shorter leaf life under the sufficient nutrient and water availability.

Knight & Nicholas (1996) indicated that litter fall was sensitive to treatments with nitrogen fertilizer and a heavy application of fertilizer increased the canopy mass and, as a consequence, increased litter fall. O'Connell & Grove (1993) found that the amounts of *E. diversicolor* leaf litter fall were significantly affected by nutrient additions and application of nitrogen fertilizer increasing leaf litter fall by 6%, 11% and 18% for the 3 successive years.

Litter fall is greatest on moist, warm, fertile and highly-productive sites and least on dry, cold, infertile and poorly-productive sites (Negi & Sharma 1996). In the current study, effluent irrigation significantly increased litter fall in all three species as it increased soil moisture and nutrients, and enhanced biomass production.

Annual litter fall ranged from 2.7 to 13.4 OD t/ha during the third year in the current study. These figures were comparable with other studies on eucalypt litter fall (Table 4.1), and were less than the 16.8 OD t/ha/y of litter fall in 20 year-old *E. camaldulensis* planted on fertile soil (Negi & Sharma 1996).

Annual litter fall above 8.0 OD t/ha/y was only found in plantations with high biomass production (Table 4.1). O'Connell & Grove (1996) reported that higher annual litter fall reflected higher productivity of *E. diversicolor* stands. The faster the tree grows, the more litter it produces (Penfold & Willis 1961). Leaves fall from rapidly growing crowns more quickly than from slow growing ones if general conditions are equal (Jacobs 1955). The amount of foliage will be more easily correlated with current growth than with mean growth over the lifetime of a tree or forest and there are some correlations between litterfall and forest production (Bray & Gorham 1964).

In the current study, the total litter fall over the 3 year period depended on the total biomass production: the more the production, the more the litter fall (Figure 5.17). Litter fall cannot be avoided no matter whether desired to keep nutrient balance in the plantations or not desired in order to reduce nutrient removal from the site in an effluent land treatment system.

Litter production was determined more by the previous year's annual biomass production than by the current annual biomass production (Figure 5.18). The higher the previous year's annual biomass production, the greater the amount of litter fall the following year. Leaf longevity could be the key factor in this phenomenon. Other evergreen broadleaf trees may also show a similar trend, but the litter production in evergreen conifer trees may correlate with the annual biomass production from 2 or even 3 years ago.

The contribution of leaf fall declined from 71.6% to 55.2% in 2 and 8 year old plantations (Bargali et al. 1992a). The fall of eucalypt leaves as a proportion of total litter decreased as stand age increased - from 53% of the total at age 5 years to about 30% of the total at ages 80 and 250 years (Polglase & Attiwill 1992). Therefore, tree age influences litter components although tree density also had some effects (section 4.3.1.2). In the current study, leaves contributed over 95% by weight of the total annual litter fall (section 5.3.4.1). This was comparable with other studies of plantations less than 3 years old (Table 4.1).

Litter fell all year around, but the monthly amount of litter fall changed significantly (Figure 5.17). Summer, particularly January and December in each year, was the main season for litter fall and nutrient return in most stands in the current study. Addicott (1982) concluded that following a period of hot weather, many trees abscise a portion of their leaves. Such abscission is characteristic of species of *Eucalyptus*, *Citrus*, and other subtropical broad-leaved evergreens. Summer litter fall peaks were widely reported both in natural and plantation *Eucalyptus* forests (section 4.3.1.4).

In the current study, sufficient soil moisture from effluent irrigation during summer made no distinct difference in all three species studied, and there was little difference between species (Figure 5.17). Therefore, litter fall appears to be affected more by ambient temperature than by soil moisture (Attiwill et al. 1978). Frederick et al. (1985b) found a similar pattern in an 8 year old *E. regnans* plantation.

More total above ground biomass could be removed if harvested before the peak litter fall, unless the litter is also to be collected. Before final tree harvesting, litter could be collected and removed from the site to maximize nutrient removal and the litter possibly used for energy purposes along with the rest of the biomass. The best time for the litter collection is soon after summer in each year.

Nutrient return

The return of nutrients in litterfall, like nutrient uptake, is a function of growth rate, but the decomposition and release of the nutrients from the litter is not necessarily related to growth rate (Miller 1989). Bargali et al. (1992b) reported that the total nutrient returns to the forest floor were: 64.3 - 75.6 kg N/ha/y; 3.4 - 4.3 kg P/ha/y; 27.6 - 27.9 kg K/ha/y in an age series of *E. tereticornis* from 2 to 8 years old.

In the current study, nutrient return increased significantly with tree growth (Figure 5.16). Less than 5% N and P, 3% Ca and Mn, 1.2% Mg, and 0.3% K of the total nutrient return during the 3 year period occurred in the first year. Annual nutrient returns via litter fall to forest floor in the third year were: 11.8 - 158.7 kg N/ha/y, 0.4 - 9.1 kg P/ha/y, 4.3 - 28.3 kg K/ha/y, 23.1 -124.7 kg Ca/ha/y, 2.3 - 22.1 kg Mg/ha/y, and 4.6 - 32.0 kg Mn/ha/y. Even though these results were comparable with some studies on the nutrient returns in eucalypt forests (e.g. N and P in Table 4.1), they were lower than the nutrient return under 20 year-old *E. camaldulensis* planted on a fertile soil, where there were returns of 188 kg N/ha/y, 18 kg P/ha/y, 149 kg K/ha/y, 277 kg Ca/ha/y and 27 kg Mg/ha/y (Negi & Sharma 1996). Higher litter fall and nutrient returns would be expected if the trees were kept on the site for longer than the 3 years in the current study.

High nutrient return via litter fall may be good for a short rotation forest without effluent irrigation because it maintains nutrients in the system. Since nutrient removal is one of the main objectives of an effluent land treatment system, litter should be removed from the site.

Based on his study of poplar irrigated with municipal wastewater in America, Sopper (1980) reported that wastewater irrigation more than tripled the potential biomass production, more than doubled foliar biomass, and also tripled the amounts of nutrients recycled. Effluent irrigation in the current study increased biomass production, the total leaf biomass (including living and litter leaves), and also sped up nutrient cycling. During the 3 year period, the trees took up a total of 266 - 860 kg N/ha, 15 - 66 kg P/ha, 177 - 432 kg K/ha, 187 - 511 kg Ca/ha, 30 - 71 kg Mg/ha and 27 - 114 kg Mn/ha (Table 5.2). However, they returned through the litter fall 8 - 24% of the N, 5 - 17% P, 5 - 14% K, 20 - 63% Ca, 18 - 59% Mg, and 49 - 65% Mn. Effluent irrigation increased N, P, and Mg cycling consistently in the three species. Nutrient return depended on nutrient uptake more than species or effluent irrigation (Figures 5.19 - 5.20).

Like the effect of annual biomass production on annual litter fall, annual nutrient uptake also influenced the annual nutrient return (Figures 5.19 - 5.20). There was a delay period between maximum annual uptake of some nutrients and their maximum annual return. For nitrogen, phosphorus and calcium, the greater the annual uptake in the previous year, the greater their annual return in the following year. An appreciation of this delay between years is important to the management of these nutrients. In land treatment systems, trees should be harvested after the maximum uptake but before maximum nutrient return to give greater removal of these nutrients. Otherwise, trees can be harvested after the annual maximum return for less removal of these nutrients.

Conversely, the greater the potassium, magnesium and manganese annual uptake, the greater their annual return via litter fall in the same year. It may show that these nutrients are more mobile than other nutrients in the trees. The harvesting time in the year is important to these nutrients to achieve either more or less nutrient removal from the site.

At lower soil pH, manganese in their tissue is toxic to many plants. Eucalypt trees showed tolerance to manganese (section 5.4.2.2), but at the same time rapid return through shorter leaf life is another self-protection method. More than half of the manganese uptake was returned via litter fall to avoid toxic accumulation in the tree tissue (Figure 5.20).

More nitrogen and phosphorus return via litter fall occurred in summer time (from December to February) in most stands (Figure 5.17). More nutrients concentrate in the leaves than in other components of the trees. Therefore, the time of year for harvesting whole above ground biomass should be determined by the purpose of the plantation. Since the highest litter fall occurred in summer, eucalypt trees should be harvested after this period to minimize depletion of nutrients from the site. As the nutrient removal is one of the main objectives of an effluent land treatment system, if the litter needs to be removed from the site, the best time to collect it would be after the peak fall period. Alternatively, the total above ground biomass should be harvested before the peak leaf fall in the summer to remove most nutrients before their peak return via litter fall.

For the management of short rotation forests, it should be noted that physiological effects from harvesting at different seasons on tree survival and regrowth where coppicing is undertaken. However from preliminary trials, it appeared the coppiced short rotation eucalypt trees can be harvested all year around with little effects on tree survival and regrowth (Sims et al. 1994).

5.5 CONCLUSIONS

In the current study of 3 year growth of short rotation eucalypt forests, tree planting into pasture influenced the soil properties, including bulk density, pH, organic matter content and nutrient content. Effluent irrigation reduced the soil bulk density and soil pH, but had no effect on soil infiltration rates. It increased soil nutrient concentration and organic matter content. These changes resulting from effluent irrigation increased the total biomass production of the plantation.

It is important that the correct species is selected to achieve maximum biomass production, and in the case of a land treatment system, nutrient uptake. Using eucalypts in a short rotation forest linked with effluent land treatment is a good choice as their growth is not adversely affected by the soil pH reduction following effluent irrigation. In the study area, *E. globulus* showed good potential when grown as an energy short rotation forest, either linked with effluent land treatment or not. To maximize nutrient removal from the site in effluent land treatment system, the whole above ground biomass (including the litter on the forest floor) should be harvested and removed. How to successfully convert all of the biomass harvested into useful energy should be carefully considered while designing the system.

If the system is managed rationally, the short rotation forests linked with effluent irrigation have good potential as a sustainable renewable energy source and also as a sustainable effluent land treatment system to protect the environment from pollution. Based on tree growth ratios, it is suggested that less effluent should be applied in the first year after trees are planted. In a coppice crop, the second and subsequent rotations may not need so long for establishment if fast growth occurs, the crops show good coppice vigour, and they recover quickly from the shock of cutting.

Litter production is correlated with biomass production regardless of species or effluent irrigation. Meatworks effluent irrigation increased biomass production and litter fall. The design and management of a short rotation forest should be based on its main objective and related to nutrient cycling within the system. If the short rotation forest is grown only for energy biomass production, the species, variety, family or clone with fast growth and high nutrient use efficiency should be selected. Only the tree parts with high nutrient use efficiency (e.g. wood) should be removed from the site. Then, less nutrients will need to be added through commercial fertilizer to remedy nutrient loss.

When the short rotation forest is designed to strip nutrients in a land treatment system, the species, variety, family or clone with high growth rates, but having a low nutrient use efficiency should be selected. This is a new challenge to tree breeders. All above ground tree parts, even the litter accumulated on the forest floor, should be harvested and removed from the site. The suitable time to harvest the trees, and collect the litter must be determined in order to maximize or minimize nutrient removal, based on the knowledge of the nutrient cycling in the system. Overall, there is good potential to use eucalypt short rotation forests for energy biomass production linked to land treatment if the overall system is well designed and managed.

On the other hand, a suitable program should be set up to monitor the system for correct management in order to avoid soil degradation and environment pollution whilst optimising crop production, and to maintain the nutrient balance in the system.

6. INTERNAL AND EXTERNAL EFFECTS ON LITTER DECOMPOSITION AND NUTRIENT RELEASE

6.1 INTRODUCTION

A large amount of litter is produced in eucalypt short rotation forests especially when irrigated with effluent (as outlined in chapters 4 and 5). In highly-productive plantation forests it becomes important to effectively manage soil development, nutrient cycling and manipulation of litter decomposition productivity (Adams & Attiwill 1986). The litter fall contributes a nutrient return to the site and hence the forest floor accumulates a large proportion of nutrients in the system, being dependent on the rate of litter decomposition. Bargali et al. (1993) indicated decomposition processes play an important role in soil fertility in terms of nutrient cycling and formation of soil organic matter.

The rate of litter decomposition is controlled by internal factors (the physicochemical properties of the substrate) and external factors (the environment under which decay takes place) (Williams & Gray 1974; Gillon et al. 1994). Therefore, consideration of environmental factors must include those which may be regarded as "external" to the decomposition process (e.g. moisture, temperature and humidity) together with "internal" influences (e.g. lignin-to-N, C-to-N, the availability of N and P) (Jensen 1974; Nagy & Macauley 1982; Woods & Raison 1983; Taylor et al. 1991; Attiwill & Adams 1993; Briones & Ineson 1996; Prescott 1996).

Wood (1974) found *Eucalyptus* leaves decomposed more slowly than leaves of many European broad-leaved tree species. Adams & Attiwill (1986) indicated that the slow rate of decomposition of eucalypt forest litter resulted in the storage of significant amounts of nutrients in the soil, which has been recognised as a feature of this genus. There was 38.8 oven-dry t/ha of litter accumulated on the forest floor under a six year old *E. botryoides* plantation irrigated with effluent in the current study, which may be related to the low decomposition rate (see section 3.3.3). Conversely however, Penfold & Willis (1961) mentioned that the eucalypt litter in Australia decays quite rapidly. No eucalypt litter accumulation could be found under an 11 year old *E. regnans* plantation (Guo 1993). Briones &

Ineson (1996) were unable to confirm the reputation of *Eucalyptus* as having a recalcitrant litter since the decomposition rate of *Eucalyptus* litter paralleled that of birch litter in terms of mass loss over time. Variations between species and environmental factors both significantly influence *Eucalyptus* litter decomposition and nutrient release from the litter (see section 4.3.2).

Staaf (1987) pointed out litter decomposition is regulated mainly by temperature and water regimes; soil fertility may have secondary importance. When climate and site factors such as soil types are constant, decomposition rates are regulated primarily by the chemical composition and physical structure of the litter: features often jointly termed “substrate” (Swift et al. 1979). In a given forest, especially a plantation, the environmental factors relate to the tree population and silvicultural regime, which also influence litter decomposition and nutrient release. Bargali et al. (1993) reported that the most rapid litter weight loss occurred under a 1 year old plantation and decreased with plantation age within their series of 1-8 year *E. tereticornis* plantations. The decomposition rates were significantly correlated with the initial nutrient concentrations of the litter.

Effluent irrigation not only changes soil moisture, but also adds nutrients and organic matter, which influences the litter decomposition rate. Baker et al. (1990) reported that irrigation with effluent significantly increased the rate of loss of organic matter and nutrients from *Pinus radiata* litter needle. Limited information is available about the impact of internal factors (species and litter source), external factors (plantation age, and effluent irrigation) and the interactions of these factors on litter decomposition and nutrient release in eucalypt short rotation forests. Studies often concentrate on leaf litter decomposition because leaves are usually the main contributor to annual litter fall (Frederick et al. 1985b; O'Connell 1987). In the current study, more than 90% of the total litter fall was contributed by leaves in eucalypt short rotation forests under four years old (sections 4.3.1.2 and 5.3.4.1). Therefore, only leaf-litter was studied here. This chapter describes the experiments designed to compare the effects of internal and external factors on the rates of eucalypt leaf litter decomposition and nutrient release.

The objectives were to:

1. test the effects of external factors (plantation age and effluent irrigation) on the eucalypt litter decomposition and nutrient release;

2. examine the effects of internal factors (species and litter source) on the eucalypt litter decomposition and nutrient release;
3. determine the interactions between these above factors; and
4. investigate the effects of the initial litter composition on litter decomposition and nutrient release.

6.2 MATERIALS AND METHODS

6.2.1 Experimental site

The study was conducted at the Richmond Meat Processors & Packers Ltd. processing plant at Oringi, which is adjacent to the Manawatu River, located near Dannevirke, New Zealand. Monthly distributions of rainfall and temperature for a 12 month period from June 1995 to May 1996 and ten year average are shown in Figure 6.1 (For more details about the site see section 3.2.1).

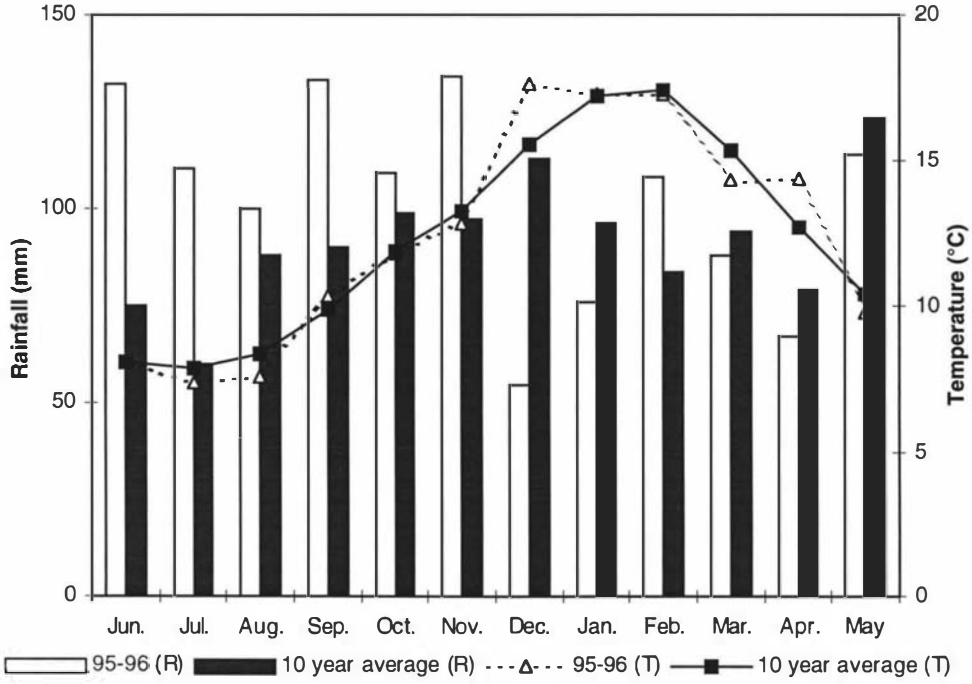

Figure 6.1 Monthly rainfall (R) and mean temperature (T) for Dannevirke, New Zealand (10 year average and the period of June 1995 - May 1996).

The stands used in the current study were 1 to 3 year old *E. globulus* with a tree density of 4167 stems/ha (1 m spaces × 2.4 m rows). Tree seedlings were planted annually in three blocks over a three-year period (November 1992, 1993 and 1994). The rotation length between coppice harvests was planned to be three years, but the current study was carried out before harvest of the first three year rotation. The meatworks effluent from an anaerobic treatment pond was irrigated using flood irrigation at 20 mm/week. Details about the effluent characteristics were given in Table 3.1.

When the experiment started, trees in the 1 year old stands were about 2 m high, and the tree crowns were separate. Trees in the 2 year old stands were about 5 m high, tree crowns touched each other between trees in the row, but not yet between trees across the rows. Trees in the 3 year old stands were about 7 m high and the canopy was fully closed.

6.2.2 Experimental design

A factorial experimental design, with four repeated measurements of litter bags collected after 3, 6, 9, and 12 months from the forest floor, was used to monitor litter decomposition during a 12 month period. Four factors were evaluated (Table 6.1):

i) species: *E. botryoides* (B), *E. globulus* (G), and *E. ovata* (O);
ii) leaf litter source: the litter from trees without irrigation (C), and the litter from trees irrigated with effluent (E);
iii) plantation age: under 1, 2, and 3 years old stands;
iv) irrigation: under *E. globulus* stands without irrigation (N) and irrigated with effluent (I).

6.2.3 Materials

The nylon mesh bag technique (Bocock & Gilbert 1957) was used to monitor litter decomposition. Nylon bags (100 × 150 mm) made of 1 mm mesh material were used in the current study after Gallardo & Merino (1993). They considered the mesh was small enough to prevent major losses of the smallest leaves, yet large enough to permit aerobic microbial activity and free entry of small soil animals.

Table 6.1 Factorial experimental design with four repeated measurements to ascertain the internal and external effects on eucalypt leaf litter decomposition.

	Source	Litter from trees without irrigation (C)			Litter from trees irrigated with effluent (E)		
	Species	*E. botryoides* (B)	*E. globulus* (G)	*E. ovata* (O)	*E. botryoides* (B)	*E. globulus* (G)	*E. ovata* (O)
Irrigation	Age (y)						
Without irrigation (N)	1	CB$^{\&}$N1	CG$^{\&}$N1	CO$^{\&}$N1	EB$^{\&}$N1	EG$^{\&}$N1	EO$^{\&}$N1
	2	CB$^{\&}$N2	CG$^{\&}$N2	CO$^{\&}$N2	EB$^{\&}$N2	EG$^{\&}$N2	EO$^{\&}$N2
	3	CB$^{\&}$N3	CG$^{\&}$N3	CO$^{\&}$N3	EB$^{\&}$N3	EG$^{\&}$N3	EO$^{\&}$N3
With effluent irrigation (I)	1	CB$^{\&}$I1	CG$^{\&}$I1	CO$^{\&}$I1	EB$^{\&}$I1	EG$^{\&}$I1	EO$^{\&}$I1
	2	CB$^{\&}$I2	CG$^{\&}$I2	CO$^{\&}$I2	EB$^{\&}$I2	EG$^{\&}$I2	EO$^{\&}$I2
	3	CB$^{\&}$I3	CG$^{\&}$I3	CO$^{\&}$I3	EB$^{\&}$I3	EG$^{\&}$I3	EO$^{\&}$I3

Letters before $^{\&}$ represent internal factors; letter and number after $^{\&}$ represent external factors.

In April 1995, six types of freshly abscised leaves were collected from the forest floor under 2 year old stands of each of the three species (B, G, O) without irrigation (C) and irrigated with effluent (E). Four grams of air-dried leaf material were weighed to the nearest 0.01 g and placed in a litter bag. Overall, 288 litter bags (3 species × 2 sources × 3 ages × 2 irrigation treatments × 2 replicates × 4 collections) were used in the experiment. All litter bags were stored and transported in plastic bags in order to minimize any error through spillage (Wieder & Lang 1982). Five extra bags from each of the six litter types were retained in the laboratory to determine the initial moisture content and the initial chemical composition of each leaf litter type.

At the end of May 1995, the leaf litter bags were pinned down to the forest floor under 1, 2, and 3 year old *E. globulus* stands without irrigation (N) and irrigated with effluent (I). Two replicates were used. During the next 12 month period, litter bags were collected from the field four times seasonally after 3 months (August 1995), 6 months (November 1995), 9 months (February 1996), and 12 months (May 1996) (Figure 6.2).

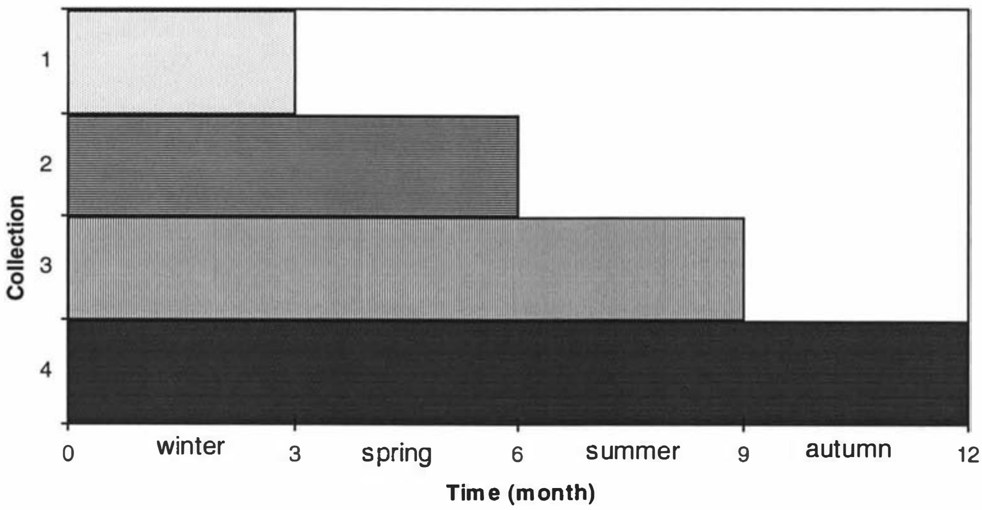

Figure 6.2 The time schedule for collecting litter bags on the forest floor.

6.2.4 Laboratory analysis

Leaf litter samples from the extra retained bags before experiment began were oven-dried at 80°C for overnight (more than 8 hours) to determine the litter initial moisture content. Then, they were ground to pass through 1 mm sieves and sealed in plastic bags for subsequent chemical analysis of leaf litter composition.

Nitrogen and phosphorus in the litter were analysed using a Technicon Auto Analyser following Kjeldahl digestion. Potassium, magnesium, calcium and manganese were analyzed using an Atomic Absorption Spectroscopy (GBC 904 AA) following nitric acid digest for cation analysis. Details about above methods were given in section 3.2.3.

Initial acid detergent fibre (ADF) contents in the litter, including cellulose and lignin, were analysed by a standard fibre determination method (Robertson & Van Soest 1981).

The emissions from the combustion process at 1050°C in a resistance furnace were measured by infrared cell (LECO FP2000 Analyser) to determine the initial carbon content.

The initial chemical composition of the six leaf litter types used for this experiment is shown in Table 6.2.

Table 6.2 Initial chemical composition of the six leaf litter types used for the litter materials (unit: mg/g).

Species	*E. botryoides*		*E. globulus*		*E. ovata*	
Litter source	C	E	C	E	C	E
Nitrogen	12.39	13.47	8.63	13.15	8.23	17.48
Phosphorus	0.84	0.92	0.42	0.79	0.40	1.13
Potassium	1.85	2.23	2.23	2.57	1.92	5.10
Calcium	12.24	8.70	12.78	7.06	10.79	4.87
Magnesium	1.25	0.79	1.71	1.26	0.60	0.86
Manganese	1.48	3.13	2.54	3.48	1.96	1.82
Carbon	462.7	464.6	460.9	469.2	468.6	469.6
Lignin	161.7	189.2	79.6	81.7	197.5	230.4
Cellulose	150.2	157.0	105.0	104.6	174.6	179.4
ADF*	311.9	346.2	184.7	186.3	371.9	409.8

C = litter from trees without irrigation; E = litter from trees irrigated with effluent; *ADF = acid detergent fibre (lignin + cellulose).

After each litter bag collection after 3, 6, 9, or 12 months, the litter remaining inside each litter bag was manually taken out and kept free of weed leaves, seeds and roots, tree roots, fauna and other foreign materials, and brushed if necessary. After overnight (more than 8 hours) oven drying at 80°C, the leaf litter was weighed, and ground to pass through 1 mm sieves then sealed in plastic bags for subsequent chemical analysis.

All litter samples were analysed for nitrogen, and phosphorus, but only selected litter samples from the final 12 month litter bag collection (May 1996), and from bags $CB^{\&}N3$, $CG^{\&}N3$, $CO^{\&}N3$, $EB^{\&}I3$, $EG^{\&}I3$, and $EO^{\&}I3$ (Table 6.1) from the 3 month, 6 month and 9 month bag collections, were analysed for potassium, calcium, magnesium and manganese. The methods for chemical analysis were as described above.

Litter dry weight loss and nutrient release were calculated as follows:

$$L\ (\%) = 100*(W_0 - W_t)\ /\ W_0$$

and

$$R\ (\%) = 100*(W_0C_0 - W_tC_t)\ /\ W_0C_0$$

> where L is litter dry weight loss; R is nutrient release; W_0 is the initial litter dry weight; W_t is the dry weight of the remaining litter in litter bag when it was collected; C_0 is the nutrient concentration (mg/g) in the initial litter; C_t is the nutrient concentration (mg/g) in the remaining litter.

6.2.5 Statistical analysis

All data were analysed using the SAS GLM procedure (SAS Institute 1990). The litter dry weight loss, and nutrient release for nitrogen, phosphorus, potassium, calcium, magnesium, and manganese from the bagged leaf litter were analyzed using the model for a 4-factorial combination with four repeated measurements.

6.3 RESULTS

6.3.1 Litter decomposition

The percentage of dry weight losses of leaf litter samples contained within the litter bags after 3, 6, 9, and 12 month periods are summarised in Table 6.3. Of the four factors tested, the weight loss of leaf litter was significantly affected by species, plantation age, and irrigation after all four periods, but litter source only had an influence after the first three months giving a greater dry weight loss in the litter from trees irrigated with effluent. The only important interaction among factors was that between plantation age and irrigation.

Species

Significant differences in litter decomposition were found between the three studied species (Table 6.3). *E. globulus* leaf litter decomposed fastest and the trend was constant throughout the whole 12 month period. At the end of this period, the average annual dry weight loss from the *E. globulus* litter was more than 80% of the original dry matter, whereas for *E. botryoides* it was 55%, and for *E. ovata* only 41%.

Plantation age and effluent irrigation

Plantation age and effluent irrigation significantly influenced the litter decomposition, and they also interacted with each other (Table 6.3). The leaf litter decomposition was closely related to the age of plantation under which they were placed, but the effluent irrigation interfered with the effects of plantation age (Figure 6.3).

In the stands without irrigation, the litter decomposed slowest under 1 year old stands over the 12 month period, being 46% dry weight loss at the end of the period. The highest dry matter loss (74%) was found under 3 year old stands though there was no difference over first six months between the litter under 2 year old stands and under 3 year old stands.

Effluent irrigation significantly increased litter dry weight loss from 46% to 62% under 1 year old stands at the end of the 12 month period. As the plantation age increased, the influence declined under 2 year old stands giving similar dry weight loss of 66% and 68%. Under 3 year old stands, the irrigation had the opposite effects and reduced the litter dry weight loss from 75% to 42% by the end of the 12 month period.

Table 6.3 Litter dry weight loss (%) after periods of 3, 6, 9, and 12 months under eucalypt stands.

Duration (month)		3	6	9	12	$LSD_{0.05}$
Species	*E. botryoides*	22.0	32.8	40.9	55.1	5.9
	E. globulus	34.2	52.7	64.9	83.7	6.8
	E. ovata	16.0	24.3	31.6	40.6	4.7
	$LSD_{0.05}$	3.3	7.6	8.0	6.5	--
Litter source[@]	C	22.6	34.1	44.4	59.1	4.9
	E	25.5	39.2	47.2	60.5	5.4
	$LSD_{0.05}$	2.7	ns	ns	ns	--
Plantation age	1	19.2	30.7	38.3	53.9	5.3
	2	28.0	43.3	51.5	66.9	5.4
	3	25.0	35.9	47.5	58.5	8.0
	$LSD_{0.05}$	3.3	7.6	8.0	6.5	--
Irrigation[#]	N	25.4	40.4	49.4	63.0	5.0
	I	22.7	32.9	42.1	56.6	5.3
	$LSD_{0.05}$	2.7	6.2	6.7	5.3	--
Interaction		Significance				
Species&Source		ns	ns	ns	ns	--
Species&Age		*	ns	ns	ns	--
Species&Irrigation		ns	ns	ns	ns	--
Source&Age		ns	ns	ns	ns	--
Source&Irrigation		ns	ns	ns	ns	--
Age&Irrigation		*	*	***	***	--
Species&Source&Age		ns	ns	ns	ns	--
Source&Age&Irrigation		ns	ns	ns	ns	--
Species&Age&Irrigation		ns	ns	ns	ns	--
Species&Source&Irrigation		ns	ns	ns	ns	--
Species&Source&Age&Irrigation		ns	ns	ns	ns	--

[@] Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

[#] Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

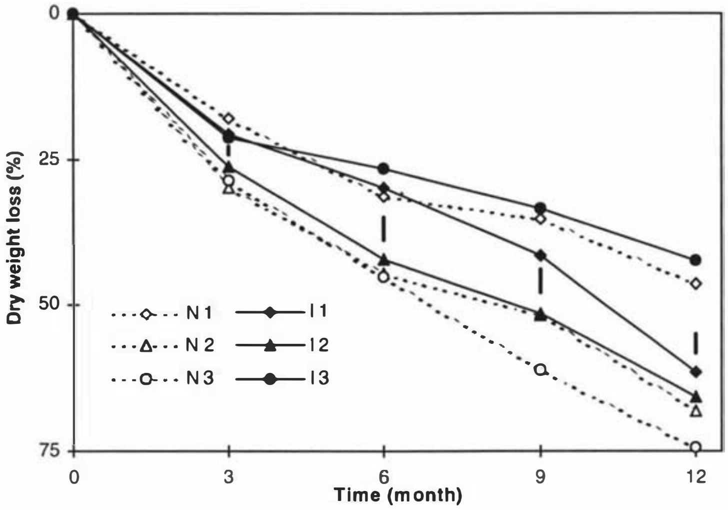

Figure 6.3 Leaf litter dry weight loss (%) from the bagged litter under 1, 2, and 3 year old stands without irrigation or irrigated with effluent (N = without irrigation; I = irrigated with effluent; the number 1, 2, and 3 after N or I is the plantation age. Vertical bars indicate $LSD_{0.05}$).

6.3.2 Nutrient release

Nutrients in the litter were released as decomposition occurred. Six nutrients, nitrogen, phosphorus, potassium, calcium, magnesium and manganese, were monitored.

6.3.2.1 Nitrogen

All four factors tested (species, litter source, plantation age and irrigation) significantly influenced the nitrogen release from bagged litter during the whole year period (Table 6.4). After the first three month period, all interactions among the four factors were significant. Thereafter, most interactions were not significant except for species with litter source, and plantation age with irrigation.

Species and litter source

Nitrogen release from leaf litter varied amongst the three species studied and between leaf litter sources. The release was highest from *E. globulus* leaf litter with an average of 72% initial nitrogen content lost after the 12 month period (Table 6.4). The leaf litter from trees irrigated with effluent released nitrogen faster than the litter from trees without irrigation, though the differences had declined by the end of the 12 month period (Figure 6.4a).

Table 6.4 Nitrogen release (%) from leaf litter after periods of 3, 6, 9, and 12 months under eucalypt stands.

Duration (month)		3	6	9	12	LSD$_{0.05}$
Species	*E. botryoides*	-4.0	2.8	16.6	38.9	9.1
	E. globulus	3.3	17.8	41.1	72.0	15.3
	E. ovata	-24.6	-19.8	-13.8	6.2	11.4
	LSD$_{0.05}$	3.3	7.6	8.0	6.5	--
Litter source[@]	C	-25.3	-17.2	-0.3	28.9	17.4
	E	8.5	17.8	29.6	49.2	8.8
	LSD$_{0.05}$	3.6	11.8	12.4	7.8	--
Plantation age	1	3.2	2.4	10.4	37.3	9.6
	2	0.7	14.4	27.8	53.4	11.0
	3	-29.2	-16.0	5.8	26.3	16.0
	LSD$_{0.05}$	4.3	14.4	15.2	9.5	--
Irrigation[#]	N	3.4	17.0	28.4	49.4	9.9
	I	-20.3	-16.4	0.9	28.6	12.9
	LSD$_{0.05}$	3.6	11.8	12.4	7.8	--
Interaction			Significance			
Species$^{\&}$Source		***	***	***	***	--
Species$^{\&}$Age		**	ns	ns	ns	--
Species$^{\&}$Irrigation		**	ns	ns	*	--
Source$^{\&}$Age		**	ns	ns	ns	--
Source$^{\&}$Irrigation		***	ns	ns	ns	--
Age$^{\&}$Irrigation		***	***	***	***	--
Species$^{\&}$Source$^{\&}$Age		*	ns	ns	ns	--
Source$^{\&}$Age$^{\&}$Irrigation		***	ns	ns	ns	--
Species$^{\&}$Age$^{\&}$Irrigation		***	ns	ns	ns	--
Species$^{\&}$Source$^{\&}$Irrigation		***	ns	ns	ns	--
Species$^{\&}$Source$^{\&}$Age$^{\&}$Irrigation		***	ns	ns	ns	--

-: accumulation;

[@] Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

[#] Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

There was no significant difference between *E. botryoides* litter sources (Figure 6.4a). About 40% of the initial nitrogen content was released after the 12 month period. The nitrogen release from *E. ovata* leaf litter from trees irrigated with effluent was similar to *E. botryoides* litter being average 33%. However, *E. ovata* litter from trees without irrigation accumulated significantly more nitrogen than its initial content. This accumulation reached as high as 60% more than the initial nitrogen content after three months, then, reduced to 20% at the end of the 12 month period.

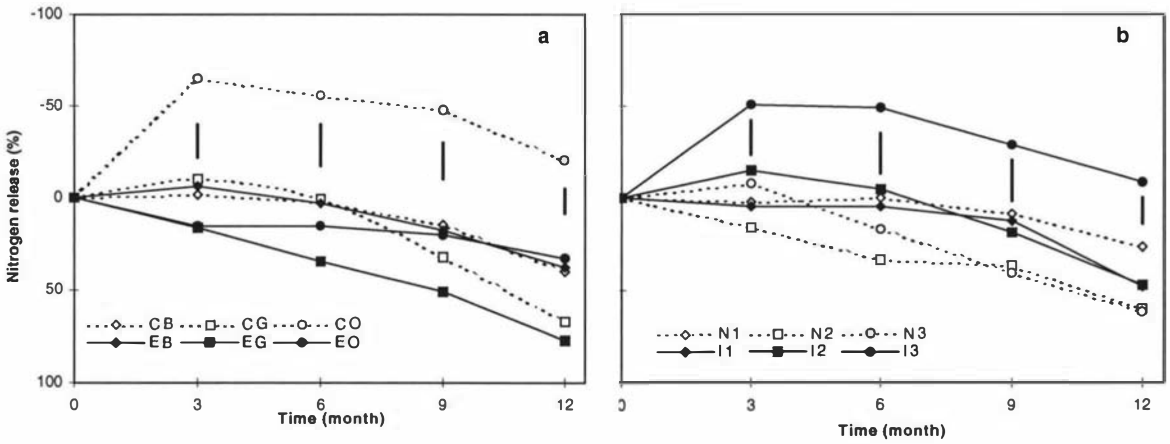

Figure 6.4 Nitrogen release (%) from eucalypt leaf litter: (a) between litter sources amongst the studied species (C = litter from trees without irrigation; E = litter from trees irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*), and (b) under 1, 2, and 3 year old stands without irrigation or irrigated with effluent (N = without irrigation; I = irrigated with effluent; the number 1, 2, and 3 after N or I is the plantation age. Vertical bars indicate $LSD_{0.05}$).

Plantation age and irrigation

The nitrogen release from leaf litter was significantly affected by plantation age and effluent irrigation, and they interacted with each other (Table 6.4). In the stands without effluent irrigation, nitrogen was released slowest under 1 year old stands and lost 26% at the end of the 12 month period. Under 2 and 3 year old stands, 60% of the initial nitrogen was released (Figure 6.4b).

Effluent irrigation increased the nitrogen release from 26% to 48% after the 12 month period under 1 year old stands, but reduced it from 60% to 47% under 2 year old stands. The most significant difference between without irrigation and irrigated with effluent was found under the 3 year old stands where effluent irrigation facilitated nitrogen accumulation (10% more than the initial content) after the 12 month period. The accumulation was as high as 50% after the first 3 to 6 months. Some accumulation during the first few months was also found under 2 years old stands irrigated with effluent and 3 year old stands without irrigation, but the release occurred at the end of the year.

6.3.2.2 Phosphorus

All four factors tested significantly influenced the phosphorus release from the litter over the 12 month period (Table 6.5). After the first three months, all interactions among the four factors were significant, and then most declined. The two important interactions were species with litter source, and plantation age with irrigation.

Species and litter source

Phosphorus release from leaf litter varied amongst the studied species and between leaf litter sources. Phosphorus was released fastest from *E. globulus* litter (Table 6.5) giving 49% release for litter from trees without irrigation and 72% for litter from trees irrigated with effluent. The former accumulated up to 66% more phosphorus than the initial content during the first 3 to 6 months (Figure 6.5a). For *E. botryoides*, more than 30% of the initial phosphorus content was released from litter from trees both without irrigation and irrigated with effluent. Only 20% of the initial phosphorus content was released from *E. ovata* litter from trees irrigated with effluent. More than double the initial phosphorus content was accumulated in the *E. ovata* litter from trees without irrigation, even at the end of the 12 month period.

Table 6.5 Phosphorus release (%) from leaf litter after periods of 3, 6, 9, and 12 months under eucalypt stands.

Duration (month)		3	6	9	12	LSD$_{0.05}$
Species	*E. botryoides*	-1.8	0.1	8.4	32.6	13.1
	E. globulus	-31.3	-27.3	12.2	60.5	36.2
	E. ovata	-51.1	-69.4	-56.1	-45.1	23.9
	LSD$_{0.05}$	28.8	46.0	35.5	24.7	--
Litter source$^{@}$	C	-61.8	-73.3	-48.0	-10.4	28.6
	E	6.9	7.6	24.3	42.4	13.0
	LSD$_{0.05}$	28.3	40.8	28.3	22.8	--
Plantation age	1	7.6	7.8	10.4	17.1	ns
	2	11.9	4.5	14.0	40.9	15.0
	3	-104.7	-110.8	-57.1	-10.0	38.2
	LSD$_{0.05}$	31.2	45.0	39.0	26.4	--
Irrigation$^{\#}$	N	-0.4	-6.0	13.6	29.5	16.9
	I	-54.5	-59.6	-37.3	2.5	26.4
	LSD$_{0.05}$	24.4	39.4	32.0	22.4	--
Interaction		Significance				
Species$^{\&}$Source		***	***	***	***	--
Species$^{\&}$Age		***	ns	ns	*	--
Species$^{\&}$Irrigation		***	*	ns	ns	--
Source$^{\&}$Age		***	**	ns	ns	--
Source$^{\&}$Irrigation		***	ns	ns	ns	--
Age$^{\&}$Irrigation		***	*	***	***	--
Species$^{\&}$Source$^{\&}$Age		***	ns	ns	ns	--
Source$^{\&}$Age$^{\&}$Irrigation		***	*	ns	ns	--
Species$^{\&}$Age$^{\&}$Irrigation		***	***	ns	ns	--
Species$^{\&}$Source$^{\&}$Irrigation		***	ns	ns	ns	--
Species$^{\&}$Source$^{\&}$Age$^{\&}$Irrigation		***	*	ns	ns	--

-: accumulation;

$^{@}$Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

$^{\#}$Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

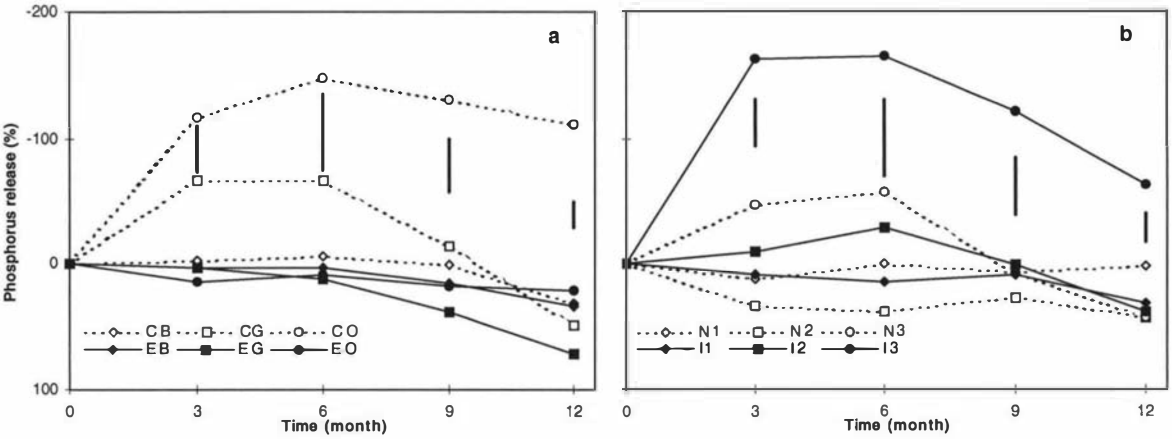

Figure 6.5 Phosphorus release (%) from eucalypt leaf litter: (a) between litter sources among the studied species (C = from trees without irrigation; E = from trees irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*), and (b) under 1, 2, and 3 year old stands without irrigation or irrigated with effluent (N = without irrigation; I = irrigated with effluent; the number 1, 2, and 3 after N or I is the plantation age. Vertical bars indicate $LSD_{0.05}$).

Plantation age and irrigation

Plantation age and effluent irrigation significantly influenced phosphorus release, but they interacted with each other on the effects of phosphorus release (Table 6.5). In the stands without irrigation, only 2% of the initial phosphorus content was released from the litter after the 12 month period under 1 year old stands, while 40% was released under 2 and 3 year old stands (Figure 6.5b).

Effluent irrigation increased the phosphorus release from 2% to 32% under 1 year old stands, but had little effect under 2 year old stands. The most significant difference between the stands without irrigation and irrigated with effluent was found under 3 year old stands, where litter accumulated 63% more than the initial content responding to the effluent irrigation. The accumulation was as high as 160% more than the initial content after the first 3 to 6 months. Phosphorus accumulation also occurred under 2 years old stands irrigated with effluent and under 3 year old stands without irrigation during the first 6 months, but this had all been released again by the end of the 12 month period.

6.3.2.3 Potassium

Fewer samples were analysed for potassium (and also for calcium, magnesium, and manganese) than for nitrogen and phosphorus (details in section 6.2.4).

Among the four factors tested, species and plantation age significantly influenced potassium release after the 12 month period (Table 6.6). *E. globulus* litter released potassium fastest amongst three species litter. The litter under 2 year old stands released potassium fastest amongst the three age stands.

The litter source interacted with species to affect the potassium release. Litter from trees irrigated with effluent released relatively more potassium than the litter from trees without irrigation, but this is only significant in *E. ovata* (Table 6.6).

Similarly, irrigation interacted with plantation age. Effluent irrigation reduced potassium release under 3 year old stands, increased it under 1 year old stands and made no difference under 2 year old stands (Table 6.6).

After the 12 month period, *E. ovata* litter from trees without irrigation under 3 year old stands (CO$^{\&}$N3 and CO$^{\&}$I3, Table 6.1) released 50% of its initial potassium content, which was lower than in all others (more than 70%) (Figure 6.6). That resulted in other two interactions, species with plantation age, and species with plantation age plus litter source (Table 6.6).

Among the leaf litter from trees without irrigation under 3 year old stands without irrigation (CB$^{\&}$N3, CG$^{\&}$N3, and CO$^{\&}$N3, Table 6.1), *E. globulus* litter released potassium rapidly (Figure 6.6). More than 75% of the initial potassium content in the litter had been released after the first 3 months, and nearly all of it by the end of the 12 month period. The litter from other two species released half of its initial content after the first 3 months. Then, the release was slowed down. The release from *E. botryoides* litter was sped up from 60% to 88% during the last three months.

Among the litter from trees irrigated with effluent under 3 year old stands irrigated with effluent (EB$^{\&}$I3, EG$^{\&}$I3, and EO$^{\&}$I3, Table 6.1), *E. ovata* released more than 75% of the initial potassium content after the first 3 months, then the release was slowed down. *E. botryoides* and *E. globulus* released 50% and 63% of the initial amount respectively after the first 3 months, and 68% and 87% by the end of the 12 month period.

Table 6.6 Internal and external factors on potassium release (%) after the 12 month period under eucalypt stands.

Internal factor	Species	*E. botryoides*	*E. globulus*	*E. ovata*	$LSD_{0.05}$
Litter source[@]	C	79.7	93.2	66.9	6.2
	E	81.1	93.4	88.2	3.6
	$LSD_{0.05}$	ns	ns	6.5	--
External factor	Age	1	2	3	
Irrigation[#]	N	81.3	89.5	85.5	6.0
	I	85.7	89.6	70.8	4.8
	$LSD_{0.05}$	3.7	ns	5.1	--

Interaction	Significance
Species&Source	***
Species&Age	***
Species&Irrigation	ns
Source&Age	ns
Source&Irrigation	ns
Age&Irrigation	***
Species&Source&Age	**
Source&Age&Irrigation	ns
Species&Age&Irrigation	ns
Species&Source&Irrigation	ns
Species&Source&Age&Irrigation	ns

[@] Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

[#] Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

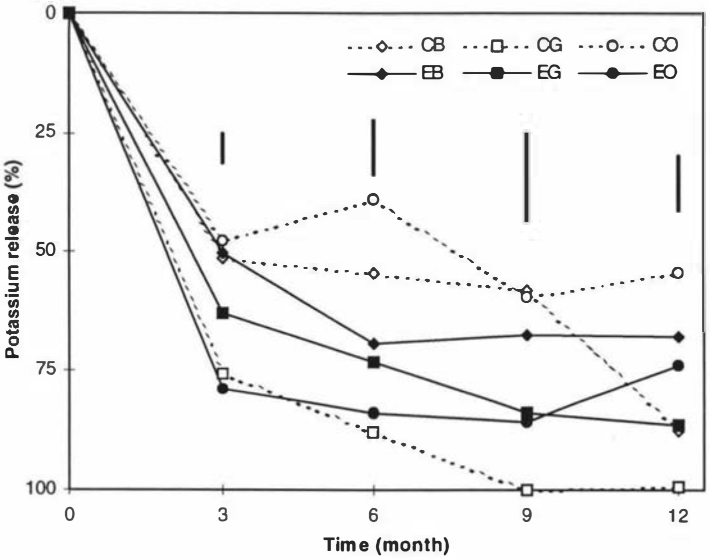

Figure 6.6 Potassium release (%) from eucalypt leaf litter under 3 year old stands (C = the litter from trees without irrigation under stands without irrigation; E = the litter from trees irrigated with effluent under stands irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*. Vertical bars indicate $LSD_{0.05}$).

6.3.2.4 Calcium

Among the four factors tested, species and plantation age, significantly influenced calcium release from bagged litter after the 12 month period (Table 6.7). Calcium was released quickest from *E. globulus* litter and slowest from *E. ovata* litter.

The effect of litter source interacted with the effect of species on the calcium release from leaf litter. *E. ovata* litter from trees irrigated with effluent accumulated calcium. A significant release occurred from *E. ovata* litter from trees without irrigation. There was no significant difference between litter sources in other two species.

The effects of irrigation interacted with the effects of plantation age on calcium release from leaf litter. Effluent irrigation enhanced the calcium release under 1 year old stands, reduced the release under 3 year old stands and made no difference under 2 year old stands. In the stands without effluent irrigation, calcium was released slowest under 1 year old stands. In the stands irrigated with effluent, it was released slowest under 3 year old stands.

The significant differences between the *E. ovata* litter sources, especially under 3 year old stands, also resulted in other three interactions, i.e. source with age, source with age and irrigation, and source with age, irrigation and species .

Among the leaf litter from trees without irrigation under 3 year old stands without irrigation (CB$^{\&}$N3, CG$^{\&}$N3, and CO$^{\&}$N3, Table 6.1), *E. globulus* litter released calcium rapidly (Figure 6.7). At the end of the 12 month period, nearly all of the initial calcium content had been released. Litter from the other two species released calcium slowly during the first nine months, even some accumulation occurred in *E. ovata.* Then, the release reached 78% for *E. botryoides* and 24% for *E. ovata* after the 12 month period.

Among the litter from trees irrigated with effluent under 3 year old stands irrigated with effluent (EB$^{\&}$I3, EG$^{\&}$I3, and EO$^{\&}$I3, Table 6.1), *E. botryoides* and *E. globulus* litter released calcium slowly or even with some accumulation occurring during the first nine months. Then, the release reached 30% and 43% by the end of the 12 month period. On the contrary, *E. ovata* litter accumulated much more calcium than the initial calcium content, being 100% even by the end of the 12 month period.

Table 6.7 Internal and external factors on calcium release (%) after the 12 month period under eucalypt stands.

Internal factor	Species	*E. botryoides*	*E. globulus*	*E. ovata*	LSD$_{0.05}$
Litter source[@]	C	37.4	76.3	21.5	12.8
	E	38.0	70.9	-28.0	21.5
	LSD$_{0.05}$	ns	ns	26.5	--
External factor	Age	1	2	3	
Irrigation[#]	N	13.4	52.6	56.7	17.6
	I	36.4	46.0	11.1	22.3
	LSD$_{0.05}$	19.0	ns	26.2	--

Interaction	Significanc
Species$^{\&}$Source	***
Species$^{\&}$Age	ns
Species$^{\&}$Irrigation	ns
Source$^{\&}$Age	*
Source$^{\&}$Irrigation	ns
Age$^{\&}$Irrigation	***
Species$^{\&}$Source$^{\&}$Age	ns
Source$^{\&}$Age$^{\&}$Irrigation	*
Species$^{\&}$Age$^{\&}$Irrigation	ns
Species$^{\&}$Source$^{\&}$Irrigation	ns
Species$^{\&}$Source$^{\&}$Age$^{\&}$Irrigation	**

-: accumulation;

[@]Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

[#]Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

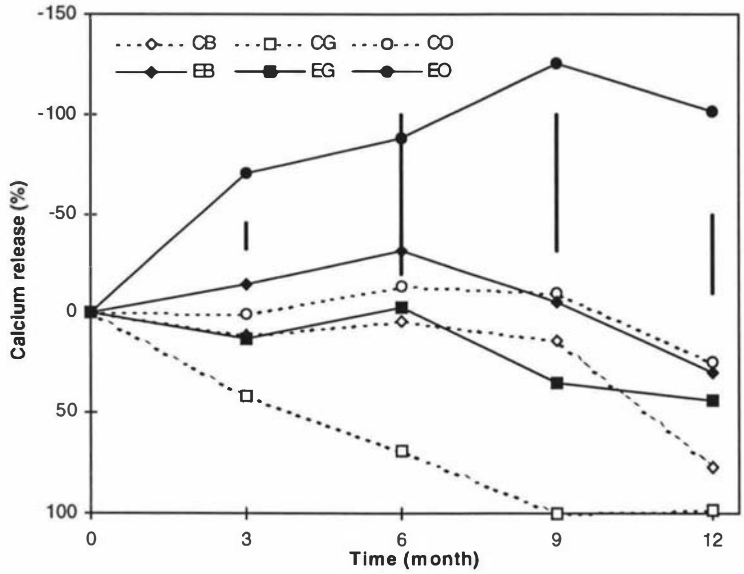

Figure 6.7 Calcium release (%) from eucalypt leaf litter under 3 year old stands (C = the litter from trees without irrigation under stands without irrigation; E = the litter from trees irrigated with effluent under stands irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*. Vertical bars indicate LSD$_{0.05}$).

6.3.2.5 Magnesium

Species and plantation age significantly influenced litter magnesium release over the 12 month period (Table 6.8). Significant magnesium accumulation occurred in *E. ovata* litter, but its release was found in *E. globulus* litter.

The effects of litter source interacted with the effects of species on the magnesium release. *E. botryoides* litter from trees without irrigation released 38.7% of the initial magnesium content, but *E. botryoides* litter from trees irrigated with effluent accumulated 9.1% more than the initial content. Conversely, *E. ovata* litter from trees irrigated with effluent accumulated less magnesium than *E. ovata* litter from trees without irrigation. There was no significant difference between *E. globulus* litter sources.

The effects of irrigation interacted with the effects of plantation age on magnesium release. Effluent irrigation resulted in magnesium accumulation under 3 year old stands, but made little difference under 1 and 2 year old stands.

The effects of species also interacted with the effects of plantation age. *E. ovata* litter was more sensitive to plantation age than were the other two species. Its litter accumulated 74% more than the initial magnesium content under 1 year old stands, 21% more under 2 year old stands, and 110% more under 3 year old stands. Magnesium release from the other two species litter also fluctuated with plantation age. Their maximum magnesium release occurred under 2 year old stands.

Among the leaf litter from trees without irrigation under 3 year old stands without irrigation (CB$^{\&}$N3, CG$^{\&}$N3, and CO$^{\&}$N3, Table 6.1), *E. globulus* litter released nearly all its magnesium content over the 12 month period (Figure 6.8). *E. botryoides* litter accumulated more magnesium during the first 9 months, and then released up to 70% of it by the end of the 12 month period. *E. ovata* litter accumulated magnesium four times more than its initial content during the first 6 months, and maintained nearly three times more even at the end of the 12 month period.

Table 6.8 Internal and external factors on magnesium release (%) after the 12 month period under eucalypt stands.

Internal factor	Species	*E. botryoides*	*E. globulus*	*E. ovata*	$LSD_{0.05}$
Source[@]	C	38.7	81.0	-99.3	29.5
	E	-9.1	74.1	-37.2	24.1
	$LSD_{0.05}$	19.4	ns	41.2	--
External factor	Age	1	2	3	
Irrigation[#]	N	-13.4	31.1	13.6	32.1
	I	6.6	41.0	-30.6	26.0
	$LSD_{0.05}$	ns	ns	30.8	--

Interaction	Significance
Species&Source	***
Species&Age	***
Species&Irrigation	ns
Source&Age	ns
Source&Irrigation	ns
Age&Irrigation	***
Species&Source&Age	**
Source&Age&Irrigation	*
Species&Age&Irrigation	ns
Species&Source&Irrigation	ns
Species&Source&Age&Irrigation	*

-: accumulation;

[@] Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

[#] Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

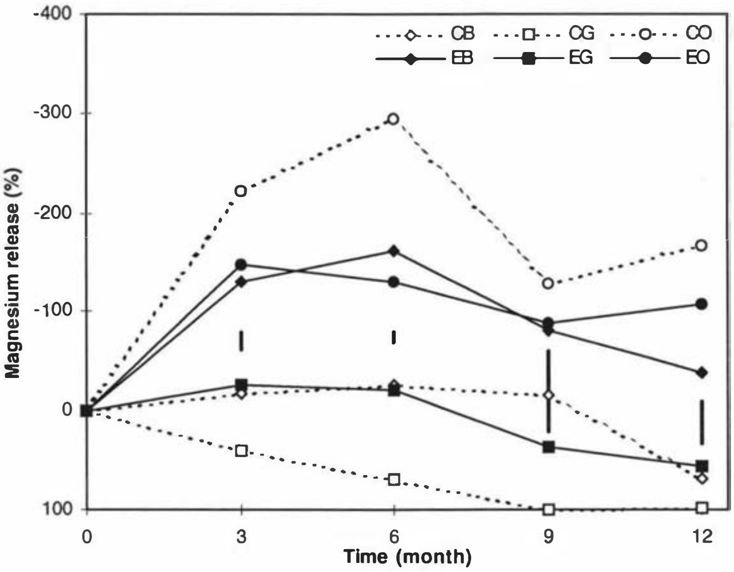

Figure 6.8 Magnesium release (%) from eucalypt leaf litter under 3 year old stands (C = the litter from trees without irrigation under stands without irrigation; E = the litter from trees irrigated with effluent under stands irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*. Vertical bars indicate $LSD_{0.05}$).

Among the litter from trees irrigated with effluent under 3 year old stands irrigated with effluent (EB&I3, EG&I3, and EO&I3, Table 6.1), magnesium was only released from *E. globulus* with 56% of the initial content, though accumulation occurred at first (Figure 6.8). On the contrary, the litter of other two species accumulated magnesium 139% and 207% more than the initial content respectively by the end of the 12 month period.

6.3.2.6 Manganese

Species and plantation age had significant effects on manganese release from leaf litter (Table 6.9). Manganese was released quickest from *E. globulus* litter and slowest from *E. ovata* litter. The effects of litter source had some interaction with the effects of species on manganese release. The effects of plantation age interacted with the effects of irrigation on the release. In stands without irrigation, manganese was released slowest under 1 year old stands. Conversely in the stands irrigated with effluent, it was released quickest under 1 year old stands.

Table 6.9 Internal and external factors on manganese release (%) after the 12 month period under eucalypt stands.

Internal factor	Species	*E. botryoides*	*E. globulus*	*E. ovata*	$LSD_{0.05}$
Source[@]	C	60.9	89.1	42.5	9.1
	E	72.9	89.3	40.3	13.7
	$LSD_{0.05}$	10.5	ns	ns	--
External factor	Age	1	2	3	
Irrigation[#]	N	63.7	73.4	78.6	10.0
	I	70.7	58.8	49.8	11.6
	$LSD_{0.05}$	ns	9.5	16.6	--

Interaction	Significance
Species&Source	*
Species&Age	***
Species&Irrigation	**
Source&Age	ns
Source&Irrigation	ns
Age&Irrigation	***
Species&Source&Age	ns
Source&Age&Irrigation	ns
Species&Age&Irrigation	ns
Species&Source&Irrigation	**
Species&Source&Age&Irrigation	***

[@] Litter source: C = from trees without irrigation; E = from trees irrigated with effluent;

[#] Irrigation: N = stands without irrigation; I = stands irrigated with effluent;

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

There were also some other interactions, but all four factors were highly interacted (Table 6.9). Among the litter from trees without irrigation and placed on the forest floor under the stands without irrigation (CB$^{\&}$N1, CB$^{\&}$N2, CB$^{\&}$N3, CG$^{\&}$N1, CG$^{\&}$N2, CG$^{\&}$N3, CO$^{\&}$N1, CO$^{\&}$N2, and CO$^{\&}$N3 in Table 6.1), *E. ovata* litter released manganese slowest and the release decreased as the plantation age increased (Figure 6.9a). Under 1 year old stands, *E. botryoides* litter released same percentage of the initial manganese content with *E. ovata* litter, but the release increased as the age increased.

Among the litter from trees without irrigation and placed on the forest floor under the stands irrigated with effluent (CB$^{\&}$I1, CB$^{\&}$I2, CB$^{\&}$I3, CG$^{\&}$I1, CG$^{\&}$I2, CG$^{\&}$I3, CO$^{\&}$I1, CO$^{\&}$I2, and CO$^{\&}$I3 in Table 6.1), *E. ovata* litter released manganese the slowest of the three species (Figure 6.9b). It released more manganese under 3 year old stands than under 1 and 2 year old stands. Conversely, *E. globulus* litter released less manganese under 1 year old stands than under 2 and 3 year old stands.

Among the litter from trees irrigated with effluent and placed on the forest floor under the stands without irrigation (EB$^{\&}$N1, EB$^{\&}$N2, EB$^{\&}$N3, EG$^{\&}$N1, EG$^{\&}$N2, EG$^{\&}$N3, EO$^{\&}$N1, EO$^{\&}$N2, and EO$^{\&}$N3 in Table 6.1), *E. globulus* litter released much more manganese than litter from other two species under all three age stands (Figure 6.9c).

Among the litter from trees irrigated with effluent and placed on the forest floor under the stands irrigated with effluent (EB$^{\&}$I1, EB$^{\&}$I2, EB$^{\&}$I3, EG$^{\&}$I1, EG$^{\&}$I2, EG$^{\&}$I3, EO$^{\&}$I1, EO$^{\&}$I2, and EO$^{\&}$I3 in Table 6.1), *E. ovata* litter released the least manganese, and the release decreased as the plantation age increased. There was even some accumulation under 3 year old stands (Figure 6.9d).

Among the leaf litter from trees without irrigation under 3 year old stands without irrigation (CB$^{\&}$N3, CG$^{\&}$N3, and CO$^{\&}$N3, Table 6.1), *E. globulus* litter released most of its initial manganese content, with less than 1% remaining at the end of the 12 month period (Figure 6.10). The litter of the other two species released much less manganese. *E. botryoides* litter released from 35% to 85% of the original content during the last three months of the 12 month period.

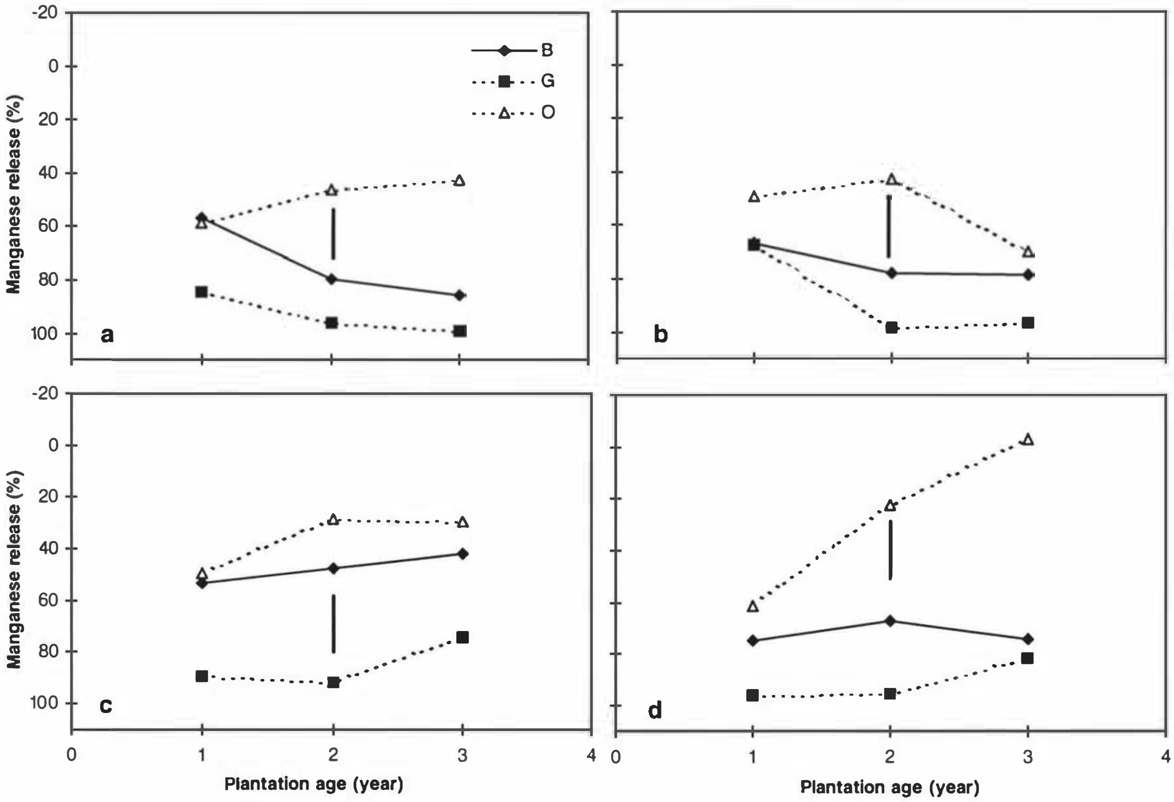

Figure 6.9 Manganese release (%) after the 12 month period from eucalypt leaf litter: (a) CN, (b) CI, (c) EN, and (d) EI (C = the litter from trees without irrigation; E = the litter from trees irrigated with effluent; N = under stands without irrigation; I = under stands irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*. Vertical bars indicate $LSD_{0.05}$).

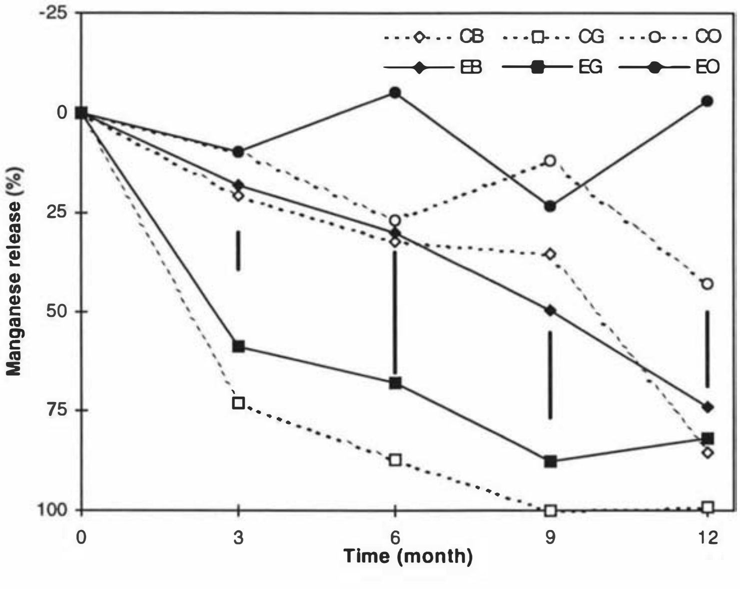

Figure 6.10 Manganese release (%) from eucalypt leaf litter under 3 year old stands (C = the litter from trees without irrigation under stands without irrigation; E = the litter from trees irrigated with effluent under stands irrigated with effluent; B = *E. botryoides*; G = *E. globulus*; O = *E. ovata*. Vertical bars indicate $LSD_{0.05}$).

Among the leaf litter from trees irrigated with effluent under 3 year old stands irrigated with effluent (EB$^{\&}$I3, EG$^{\&}$I3, and EO$^{\&}$I3, Table 6.1), *E. globulus* litter released more than half of its initial manganese content during the first 3 months, then slowed down with 82% released after 12 months. *E. botryoides* litter released manganese slower than *E. globulus* litter at first, but nearly caught up with 74% at the end of the 12 month period. The manganese content in *E. ovata* litter fluctuated during the 12 month period.

6.3.3 Correlation between litter decomposition and the nutrient release

Litter dry weight loss and nutrient release were significantly different between litter types (Table 6.10). Furthermore, there were significant differences in the percentage of the initial content between litter decomposition and nutrient release. After the 12 month period, potassium was released quickest of the six nutrients and the dry weight loss. It was followed by manganese and dry weight loss. The release of the other four nutrients varied between the different litter types. For all three species, the litter from trees without irrigation released phosphorus slowest in the six nutrients and dry weight loss. Nutrient accumulation mainly occurred in *E. ovata* litter, especially in the litter from trees without irrigation.

Table 6.10 Litter dry weight loss and nutrient release (%) after the 12 month period between litter from trees without irrigation and irrigated with effluent for each of three eucalypt species.

Species	*E. botryoides*		*E. globulus*		*E. ovata*		
Litter source	C	E	C	E	C	E	$LSD_{0.05}$
dry weight loss	56.5	53.7	83.9	83.5	36.8	44.3	8.8
nitrogen	40.2	37.6	67.1	77.0	-20.5	3.29	13.3
phosphorus	31.3	34.0	49.0	71.9	-111.4	21.2	20.8
potassium	79.7	81.1	93.2	93.4	66.9	88.2	4.7
calcium	37.4	38.0	76.3	70.9	21.5	-28.0	17.6
magnesium	38.7	-9.1	81.0	74.1	-99.3	-37.2	25.4
manganese	60.9	72.9	89.1	89.3	42.5	40.3	10.7
$LSD_{0.05}$	12.7	13.2	13.9	7.9	23.6	14.7	--

-: accumulation; C = the litter from trees without irrigation; E = the litter from trees irrigated with effluent; n = 12.

Nutrients were normally released from litter simultaneously with litter decomposition, but variation existed between the nutrients. On the other hand, the release of some nutrients correlated with each other during the litter decomposition.

6.3.3.1 Litter decomposition effects on nutrient release

Positive relationships were found between litter dry weight loss and the release of all six nutrients measured (Figure 6.11). The greater the weight loss resulting from decomposition, the more the nutrient release. However, variation existed among the six monitored nutrients. The litter dry weight loss correlated closer with the release of manganese, magnesium and nitrogen ($R^2 > 0.8$) than with the release of calcium, potassium and phosphorus ($R^2 < 0.7$).

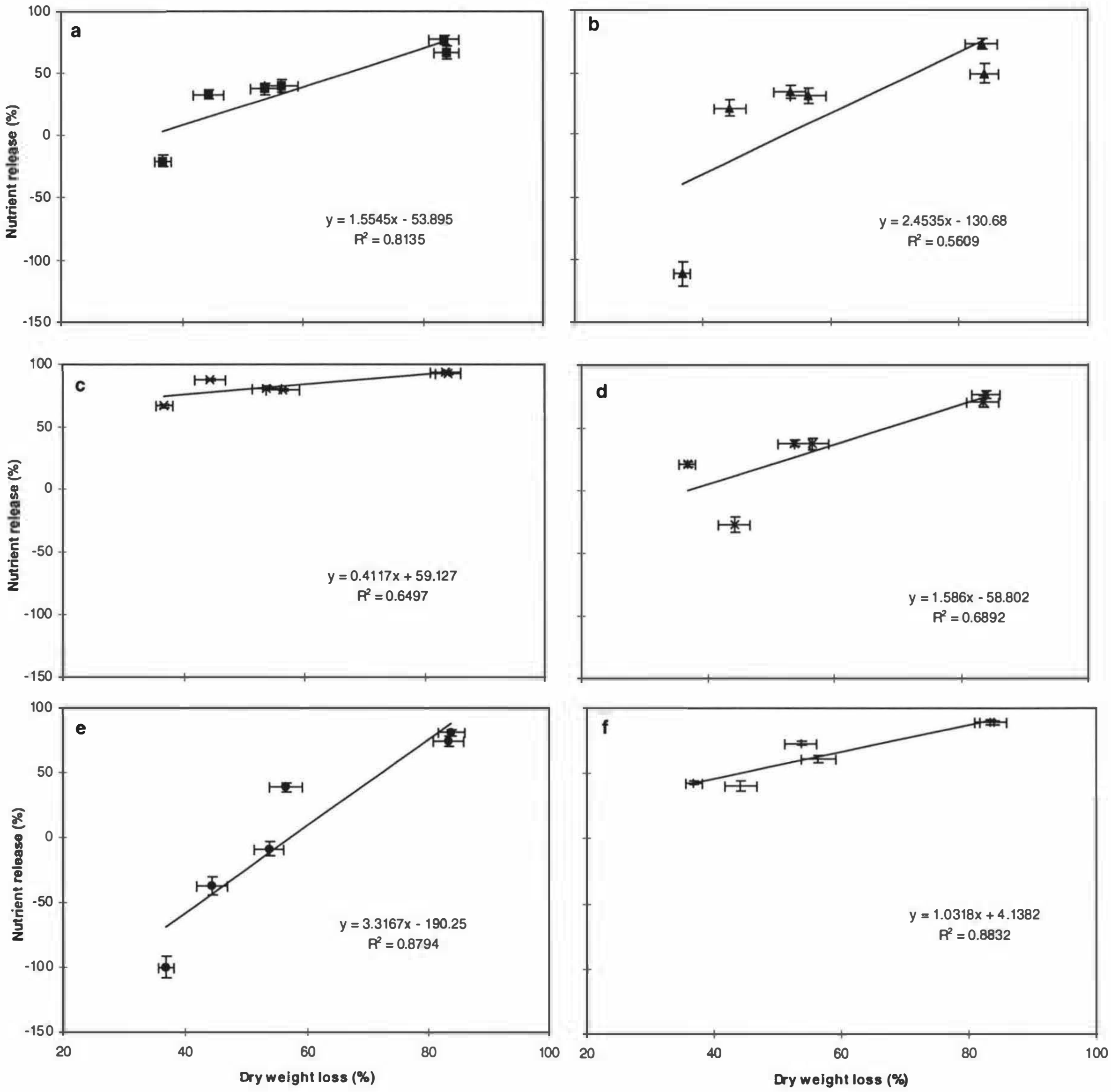

Figure 6.11 Relationships between litter dry weight loss and nutrient release after the 12 month period: (a) nitrogen, (b) phosphorus, (c) potassium, (d) calcium, (e) magnesium, and (f) manganese (Horizontal and vertical bars indicate s.e.m; n = 12).

6.3.3.2 Correlation between nutrient release during litter decomposition

Magnesium release had a significant positive correlation with the release of nitrogen, phosphorus and manganese (Figure 6.12a, b, c). Nitrogen, phosphorus and potassium were released simultaneously for they had close positive relationship with each other (Figure 6.12a, b). Calcium release only had a positive relationship with manganese release (Figure 6.12c).

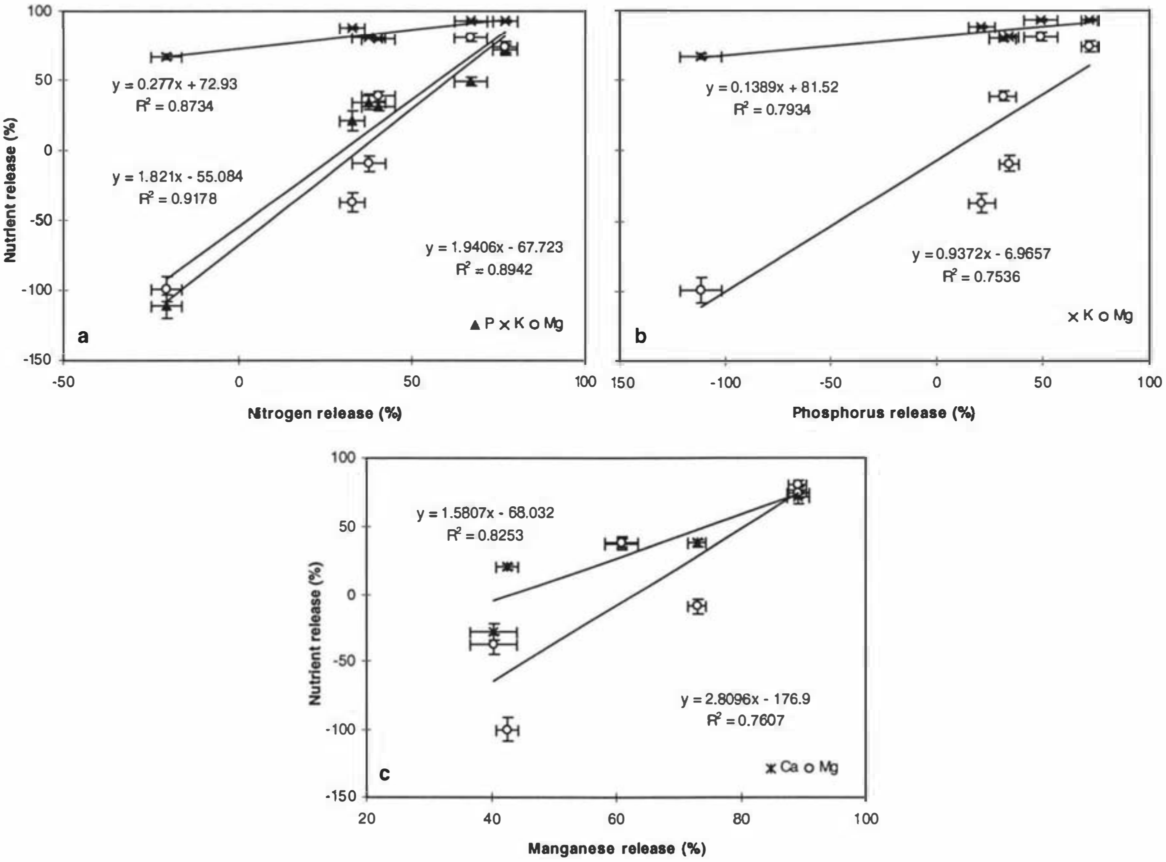

Figure 6.12 Relationships between nutrient release during litter decomposition after the 12 month period: (a) nitrogen with phosphorus, potassium and magnesium; (b) phosphorus with potassium and magnesium; (c) manganese with calcium and magnesium (Horizontal and vertical bars indicate s.e.m; n = 12).

6.3.4 Internal effects on litter decomposition and nutrient release

The differences of litter decomposition and nutrient release from the litter between species and the litter sources should be influenced by the litter's internal characteristics, especially the initial chemical composition (Table 6.2). Carbon content in the leaf litter was consistently between 460 to 470 mg/g in all six litter types. As a result, carbon in the litter had no effect on the variations of litter decomposition and nutrient release between the six litter types.

Furthermore, the ratio of carbon with other litter chemical characteristics, such as carbon:nitrogen, also had less impact on the variations compared with the other chemical characteristics.

Magnesium, lignin and cellulose had shown some independent influence on litter dry weight loss or nutrient release. Within the six nutrients studied, only magnesium influenced its own release. Some of other nutrients influenced their own release through their ratio with other characteristics.

6.3.4.1 Effects on litter decomposition

The data analysis from the current study showed that initial magnesium, cellulose and lignin content influenced the litter decomposition. The relationships between litter dry weight loss after the 12 months and the initial magnesium, cellulose and lignin contents are shown in Figure 6.13. The more magnesium in the litter, the greater the litter dry weight loss. The losses decreased in litter that had higher initial lignin and cellulose contents. Cellulose content had the highest correlation coefficient.

No other litter initial chemical compositions had influence on the dry weight loss, nor did the ratios between the compositions, e.g. lignin:nitrogen and nitrogen:phosphorus.

6.3.4.2 Effects on nitrogen release

The initial nitrogen content had no effect on nitrogen release, but the ratio of ADF (acid detergent fibre):nitrogen, and especially lignin:nitrogen, influenced nitrogen release (Figure 6.14a). The higher the ratio, the less the nitrogen release. In addition, nitrogen release also correlated with the ratio of lignin:phosphorus and the trend was similar to the former one (Figure 6.14b). Furthermore, the nitrogen release had a positive relationship with the magnesium content in the litter ($y = 67.07x - 33.286$, $R^2 = 0.63$).

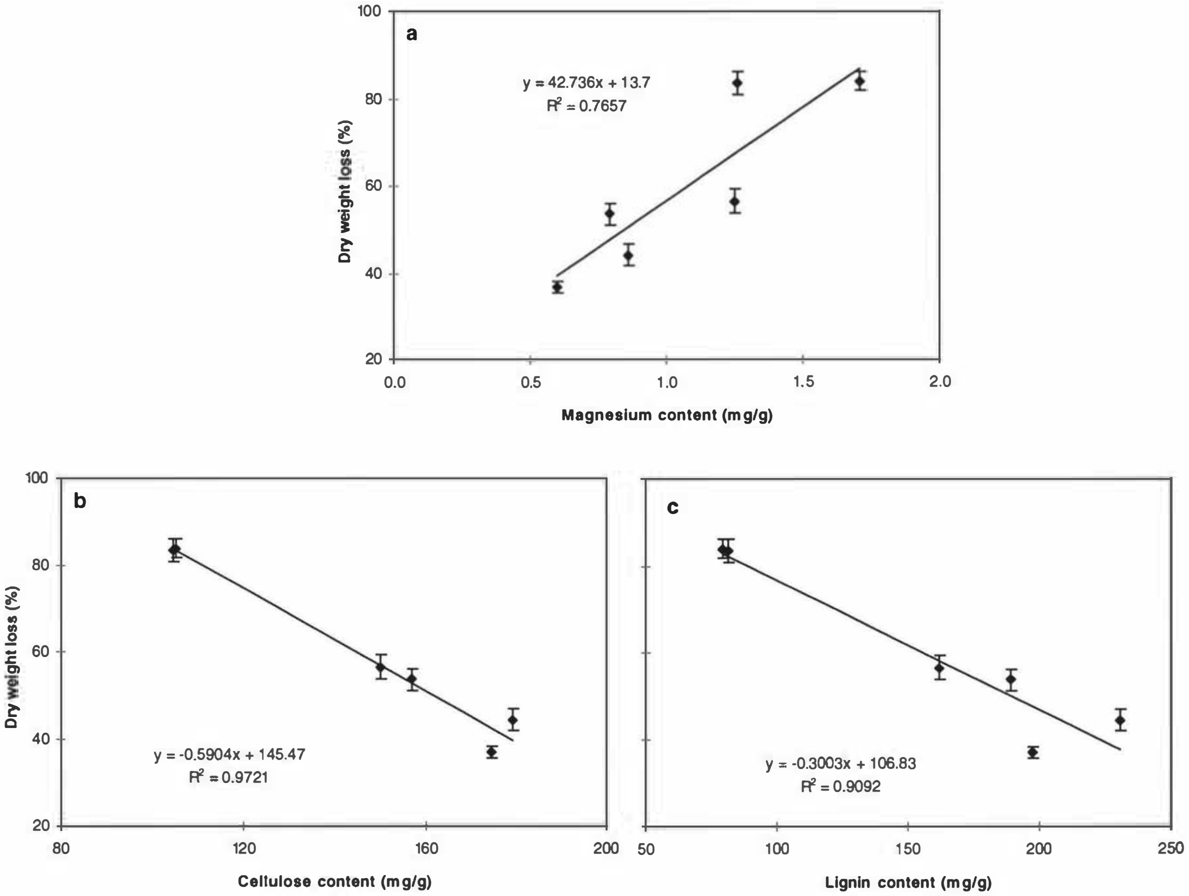

Figure 6.13 Relationships between litter dry weight loss after the 12 month period and (a) magnesium, (b) cellulose, and (c) lignin contents in the initial litter (Vertical bars indicate s.e.m; n = 12).

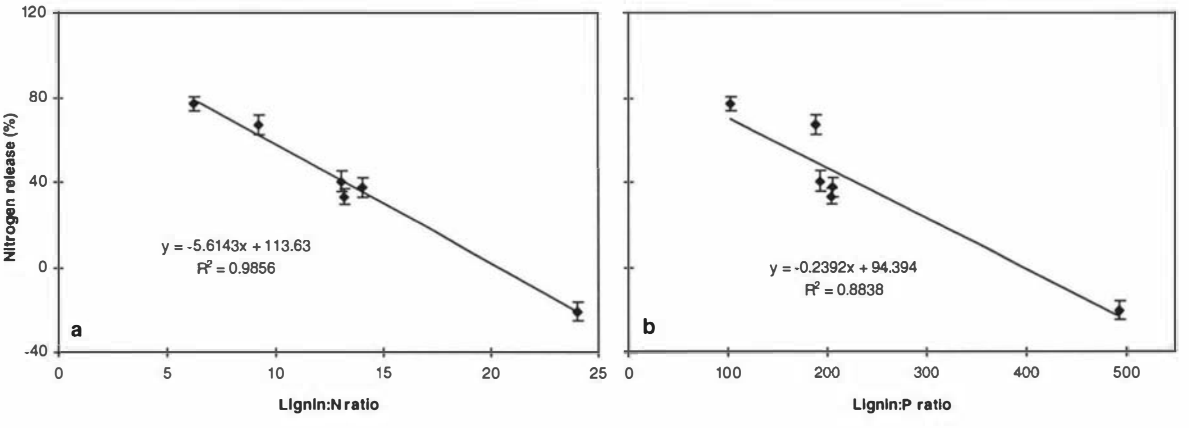

Figure 6.14 Relationships between litter nitrogen release after the 12 month period and the ratios of (a) lignin:N, and (b) lignin:P in the initial litter (Vertical bars indicate s.e.m; n = 12).

6.3.4.3 Effects on phosphorus release

Initial ratios of ADF with nitrogen and phosphorus correlated with the phosphorus release. Among them, ADF:nitrogen and lignin:phosphorus had high significant negative relationships with phosphorus release (Figure 6.15a, b). The higher the ratios, the slower the phosphorus released.

None of the six nutrients evaluated individually had a significant correlation with phosphorus release. Only the ratio of calcium:magnesium had a significant negative relationship with phosphorus release (Figure 6.15c).

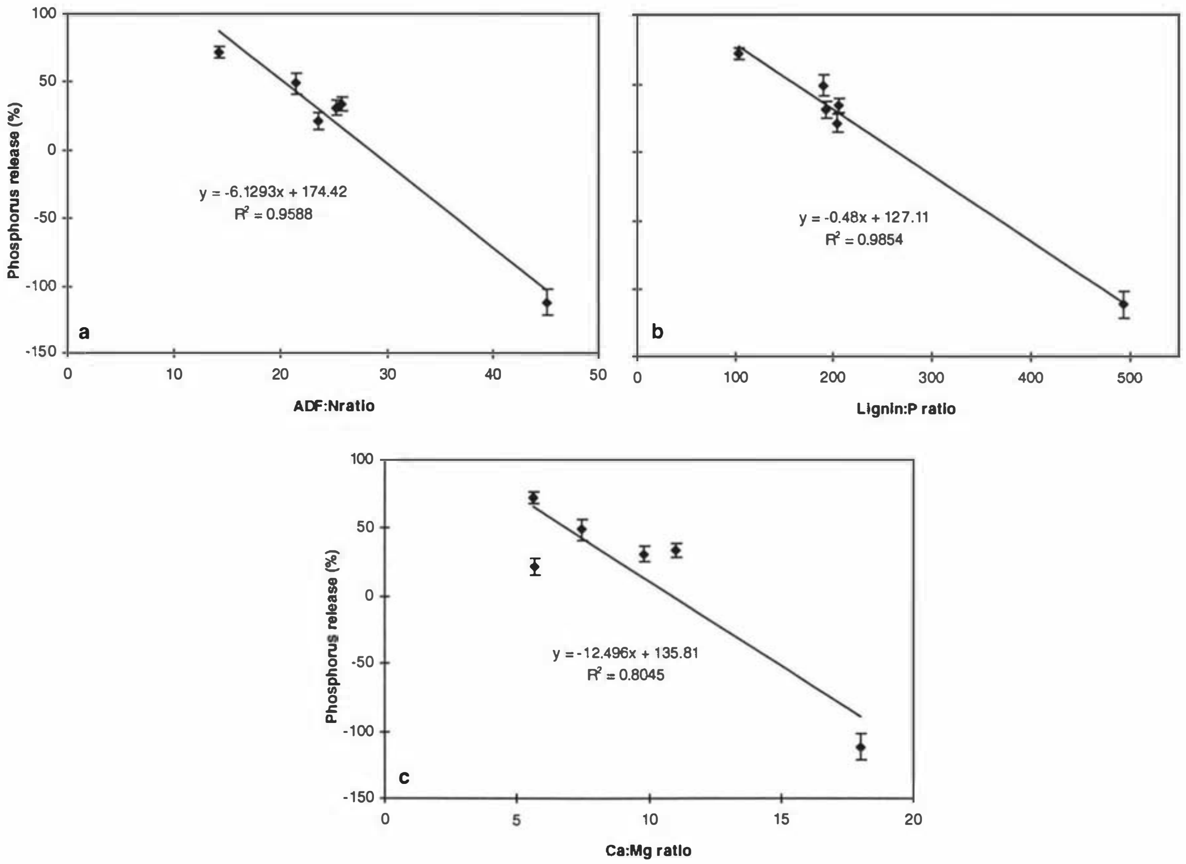

Figure 6.15 Relationships between annual phosphorus release after the 12 month period and the ratios of (a) ADF:N, (b) lignin:P, and (c) Ca:Mg in the initial litter (ADF = acid detergent fibre; vertical bars indicate s.e.m; n = 12).

6.3.4.4 Effects on potassium release

As for the effects on phosphorus release, the ratios of ADF with nitrogen and potassium correlated with potassium release. Among them, ADF:nitrogen and lignin:potassium had significant negative relationships with the potassium release (Figure 6.16a, b). Similarly, the ratio of calcium:magnesium had a significant negative relationship with the release (Figure 6.16c).

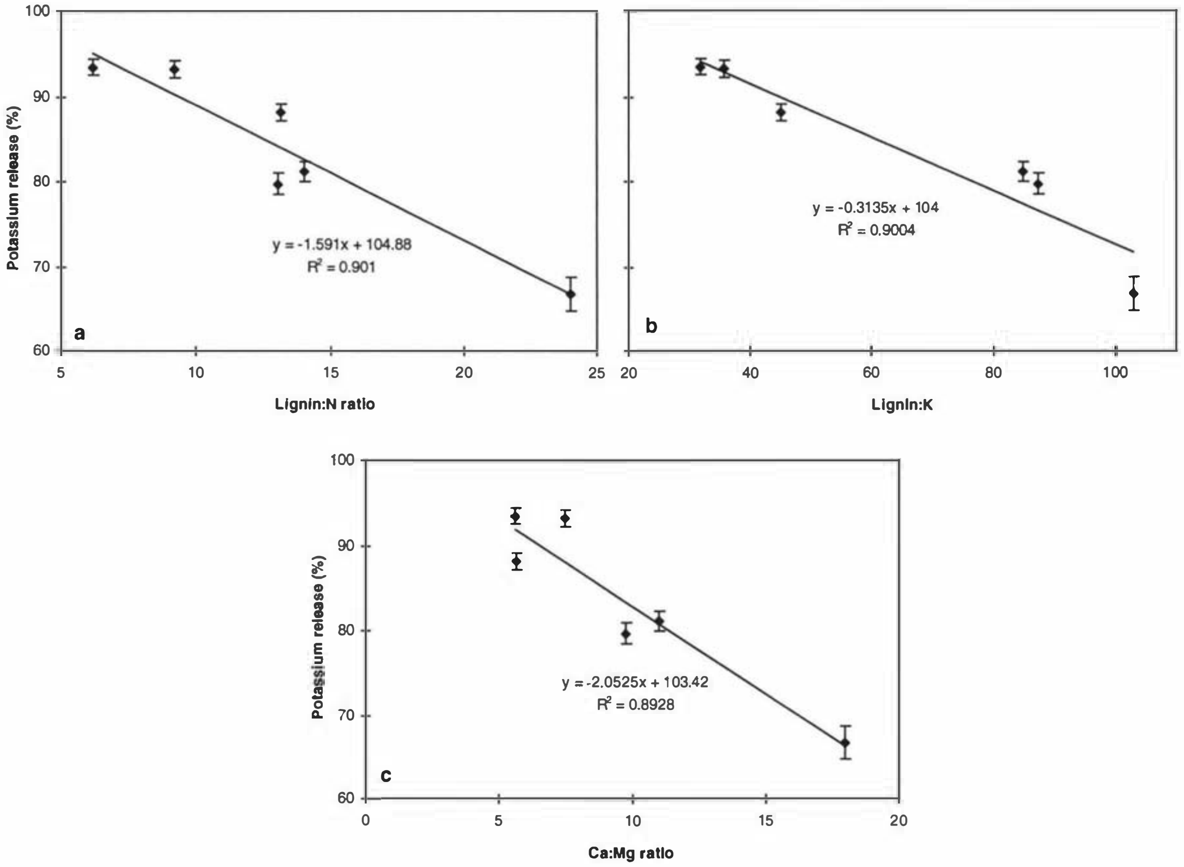

Figure 6.16 Relationships between potassium release after the 12 month period and the ratios of (a) lignin:N, (b) lignin:K, and (c) Ca:Mg in the initial litter (Vertical bars indicate s.e.m; n = 12).

6.3.4.5 Effects on calcium release

Initial lignin and cellulose content in the litter had a significant negative relationship with calcium release, and a high correlation coefficient in lignin content (Figure 6.17a, b).

In spite of none of the six nutrients individually having a significant correlation with calcium release, the ratio of lignin:calcium (Figure 6.17c) and the ratios between the nutrients had significant relationships with the calcium release. This was especially so for the ratios of nitrogen, phosphorus or potassium with magnesium or manganese, such as the ratios of nitrogen:magnesium, potassium:magnesium and potassium:manganese (Figure 6.17d, e, f).

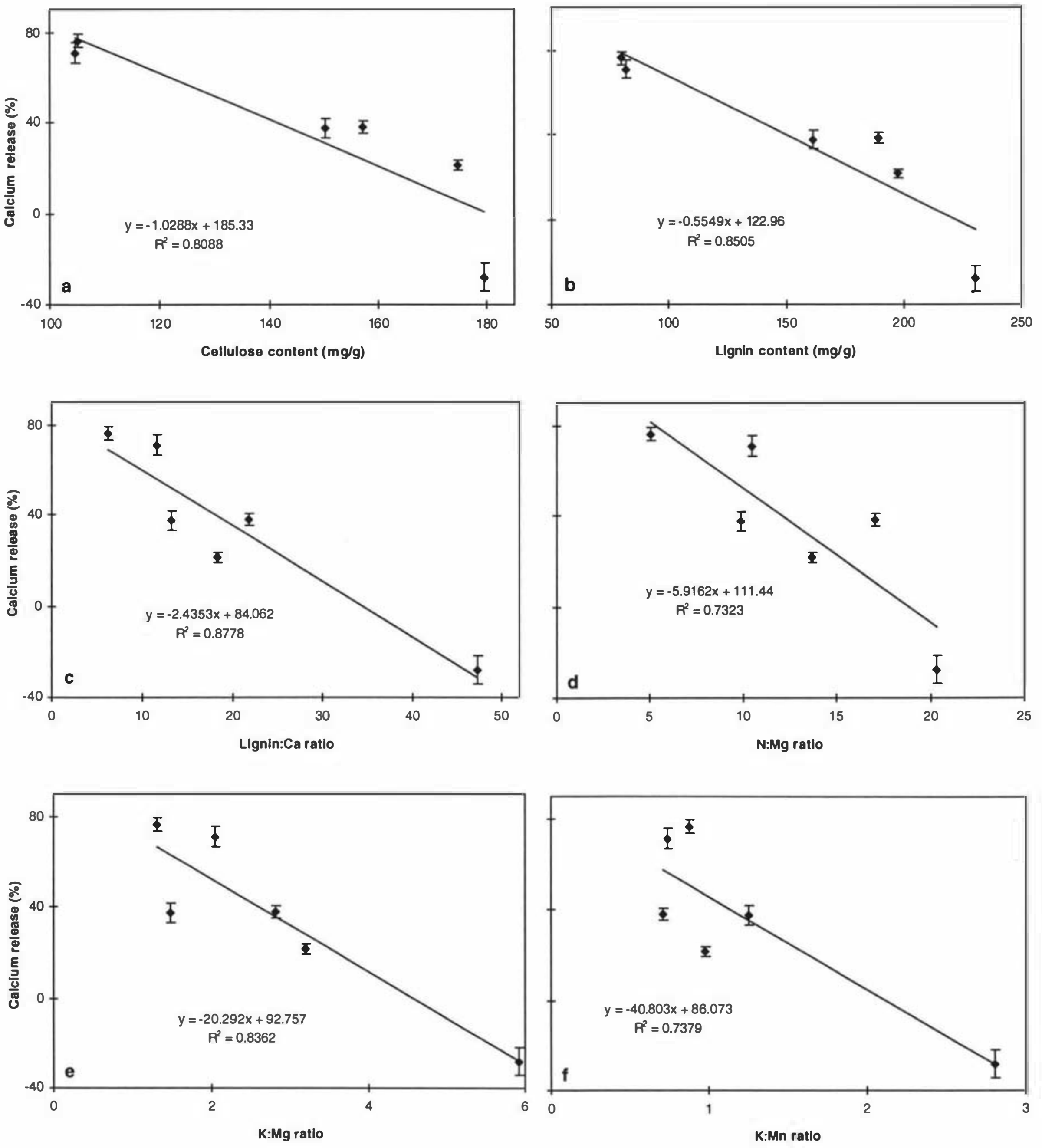

Figure 6.17 Relationships between calcium release after the 12 month period and (a) cellulose, (b) lignin content, (c) lignin:Ca ratio, (d) N:Mg ratio, (e) K:Mg ratio, (f) K:Mn ratio in the initial litter (Vertical bars indicate s.e.m; n = 12).

6.3.4.6 Effects on magnesium release

The pattern of magnesium release was similar to the litter dry weight loss. Magnesium release correlated with the initial magnesium, lignin and cellulose contents, but more closely correlated with the ratios of lignin:nitrogen and cellulose:magnesium. The relationships between magnesium release and the magnesium, lignin:nitrogen and cellulose:magnesium are shown in Figure 6.18. The initial magnesium content of the litter had a significant positive relationship with the magnesium release. Conversely, the ratios of lignin:nitrogen and especially cellulose:magnesium in the initial litter had significantly negative relationships with magnesium release.

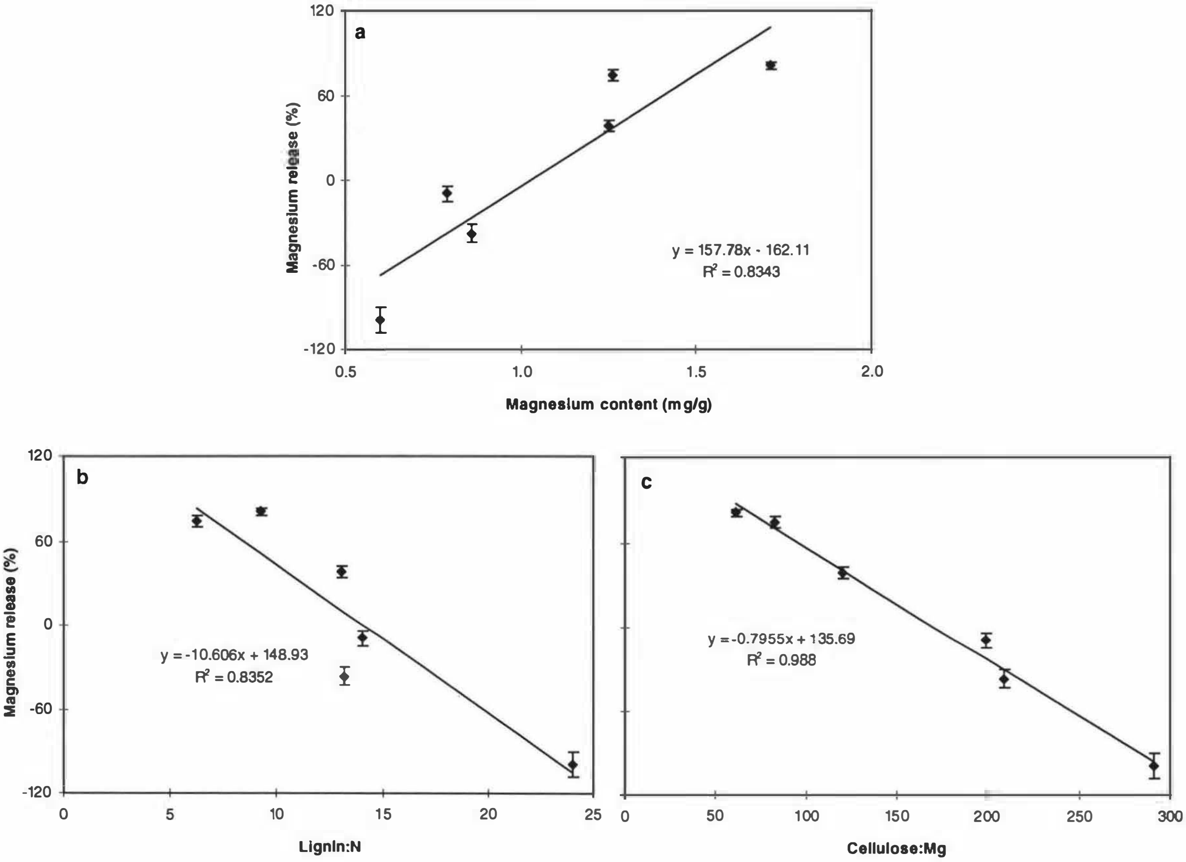

Figure 6.18 Relationships between magnesium release after the 12 month period and (a) magnesium content, (b) lignin:N ratio, (c) cellulose:Mg ratio in the initial litter (Vertical bars indicate s.e.m; n = 12).

6.3.4.7 Effects on manganese release

Cellulose in particular and lignin content in the initial litter had significantly negative relationships with manganese release (Figure 6.19a). The initial manganese content only influenced its own release via the lignin:manganese ratio (Figure 6.19b).

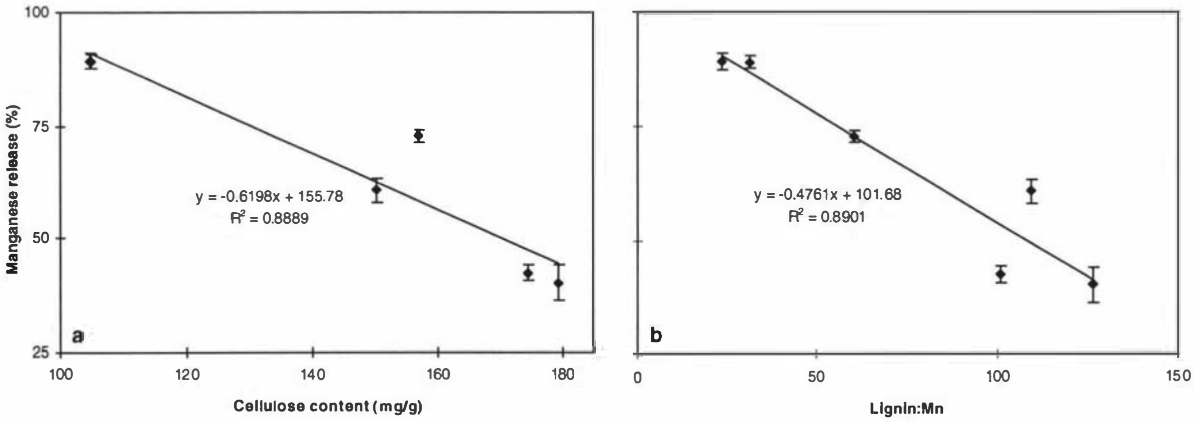

Figure 6.19 Relationships between manganese release after the 12 month period and (a) cellulose content, (b) lignin:Mn ratio in the initial litter (Vertical bars indicate s.e.m; n = 12).

6.4 DISCUSSION

Among the factors that control litter decomposition in forests, the influences of climate (temperature, humidity and moisture) and litter composition (lignin-to-N, C-to-N, the availability of N and P) have been well documented (Nagy & Macauley 1982; Taylor et al. 1991; Attiwill & Adams 1993; Prescott 1996). In the current study, all four internal and external factors tested significantly influenced litter decomposition and nutrient release from the litter.

6.4.1 Litter decomposition and nutrient release

Although there were variations between internal and external factors in the present study, potassium was consistent in being released quickest in all litter types and under all environments. The release from the litter reached as high as 70% to 80% after only the first three months (Figure 6.6). Similar trends were reported in eucalypt forests (Lisanework & Michelsen 1994; O'Connell & Grove 1996), in pine forests (Will et al. 1983; Zielinski 1984), in a beech forest (Swift et al. 1979), in an *Alnus nepalensis* plantation (Sharma & Ambash 1987), and in rain forests (Anderson et al. 1983). Therefore, potassium is the most mobile nutrient during litter decomposition. O'Connell (1988b) suggested the rapid potassium loss was associated with its leaching in advance of microbial decay.

The sequence of dry weight loss and other nutrients' release varied in different studies:

- K > Ca > Mg > P > N in a beech forest (Swift et al. 1979);
- K > P > dry weight loss > Mg = Ca = Mn > N from *P. radiata* litter (Will et al. 1983);
- K > Mg > Ca > dry weight loss > N > P in rain forest (Anderson et al. 1983);
- K > Ca > P > N in *Alnus nepalensis* plantation (Sharma & Ambash 1987); and
- K > Mg > Ca > N > P from the leaf litter of *E. marginata*, *E. calophylla* and *E. diversicolor* (O'Connell & Grove 1996).

The priority sequence in the current study was K > Mn > dry weight loss > N = Ca > P > Mg, but significant variation existed between different litter sources and species (Table 6.10).

Lisanework & Michelsen (1994) found that the sequence of nutrient element release and dry weight loss from *E. globulus* leaf litter was: K > Mg > Ca > dry weight loss > P = N, only 7.2% of litter dry matter being left after 24 months. In the current study, approximately 20% dry matter of *E. globulus* litter was left after 12 months (Table 6.3). In the litter from trees without irrigation, the sequence was K ≥ Mn = dry weight loss = Mg ≥ Ca ≥ N > P. In the litter from trees irrigated with effluent it was K ≥ Mn ≥ dry weight loss ≥ N ≥ Mg = P = Ca (Table 6.10).

O'Connell (1988b) suggested that nutrient release or accumulation in the litter during decomposition was the net result of mineralization, leaching, and the import and export of nutrients through animal activity, translocation in fungal hyphae and abiotic processes. Will et al. (1983) found little or no loss of nitrogen from *P. radiata* litter during the first 97 weeks. O'Connell (1988b) reported the accumulation of nutrients to be rapid, reaching two and three times the initial N and P contents in eucalypt litter. Similar accumulations were found in *E. botryoides* and *E. brookerana* leaf litter in the current study (section 4.3.2.2).

Nutrient accumulation in the current study was not found for potassium only (Figure 6.6, Table 6.6), but all the other nutrients were accumulated at some stage for specific litter under certain stand. In particular, accumulation occurred for phosphorus (Figure 6.5, Table 6.5), magnesium (Figure 6.8, Table 6.8), nitrogen (Figure 6.4, Table 6.4) and calcium (Figure 6.7, Table 6.7).

Adams & Attiwill (1986) indicated that it was important to manipulate litter decomposition in highly-productive plantation forests. Similarly, it is important to manipulate each nutrient during litter decomposition. The management of both short and long rotation forests should be based on nutrient cycling, the purpose of growing the plantation, the soil condition and soil nutrient status.

Nutrient cycling in a forest can be manipulated through management. For example, the litter should be removed from site as soon as possible after litter fall if potassium is the key nutrient to be removed from the system. More phosphorus or nitrogen can be removed if the litter stays on the soil surface for some time since their accumulation occurs at the initial stage of litter decomposition. So, litter could be collected from the site a few months after litter fall to reduce potassium removal, and to increase nitrogen and phosphorus removal.

In addition, nutrient cycling could be successfully manipulated by managing the internal and external factors, such as species selection, irrigation, fertilization and effluent irrigation.

6.4.2 The effect of internal factors on litter decomposition and nutrient release

Species and litter source

In litter decomposition studies, the instantaneous decay constant (*k*) has been commonly used to compare litter decomposition rates between species or environments using an exponential model (Olson 1963; section 4.3.2.1).

The instantaneous decay constant (*k*) was 1.81 for *E. globulus*, 0.80 for *E. botryoides*, and 0.52 for *E. ovata* (*k* was calculated using the mean dry weight loss after the 12 month period for each species in Table 6.3). The dry weight loss as shown by the decay constant for *E. ovata* litter was comparable with some studies on various species in this genus:

- *E. dives* ($k = 0.47$), *E. pauciflora* ($k = 0.53$) and *E. delegatensis* ($k = 0.68$) (Woods & Raison 1983);
- *E. obliqua* ($k = 0.39$ and 0.59) (Baker & Attiwill 1985); and
- *E. diversicolor* ($k = 0.54$) (O'Connell 1987).

The dry weight loss from *E. botryoides* litter was higher than from above results, but similar to that from *E. brookerana* litter (*k* from 0.76 to 0.94, Table 4.2). The decay constant for *E. globulus* was obviously much higher than the ones for the above species. It confirmed the similar finding that there exist the variations between eucalypt species on the litter decomposition in section 4.3.2.1 where *E. brookerana* litter decomposed faster than *E. botryoides* litter.

Therefore, the results from the current study support two totally opposite opinions, that *Eucalyptus* litter decays very slowly (Wood 1974; Adams & Attiwill 1986) or quite rapidly (Penfold & Willis 1961; Briones & Ineson 1996) since it appears to be species dependent. In the current study *E. globulus* decayed quickly while *E. ovata* decayed slowly. Further variations must exist as there are at least 500 species in the genus (Brooker & Kleinig 1990; Boland et al. 1992).

For sustainable production, a plantation species should be selected according to the nutrient demands on the manipulation of litter decomposition besides the demands on wood or biomass production. To speed up the nutrient cycling in a short rotation forest, the suitable species should have a quick litter decomposition and nutrient release (e.g. *E. globulus*) for consistently supplying nutrients for crop growth. Conversely for a short rotation forest linked with land treatment and the litter is to be collected for some usage, such as an energy source or a mulch, the most suitable species should have a slow litter decomposition rate (e.g. *E. ovata*). This would result in the storage of more litter in the forest floor for removing nutrients.

Within species, the litter decomposition may vary if the trees are grown in different environments, such as litter from the trees without irrigation and the trees irrigated with effluent in the current study. The differences were only significant during the first 3 month period (Table 6.3). Differences were also found in litter decomposition between *E. botryoides* litter from trees without irrigation and from trees irrigated with effluent, but were only significant in the first 6 months (section 4.3.2.1). Prescott et al. (1993) reported that fertilization of Douglas fir forests did not improve the quality of litter sufficiently to increase the rate at which it decays and releases nutrients to the forest floor.

Usually, nutrients are released at the same time as litter decomposes, but some nutrients are actually accumulated during some stages of litter decomposition. O'Connell (1988a) reported that the changes in the contents of magnesium were closely related to changes in litter dry weight while the contents of nitrogen and phosphorus either changed little or increased as decomposition proceeded. In the current study, nitrogen, magnesium and manganese were released depending on litter decomposition rate. Phosphorus, potassium and calcium only had a marginal correlation with the dry weight loss (Figure 6.11). In addition, some nutrients were released simultaneously, for example, nitrogen, phosphorus and magnesium (Figure 6.12). These factors should be also considered according to whether the objective of the plantation is to collect litter or to remove nutrients.

Both species and litter source significantly influenced the nutrient release from the litter though litter source had a small effect on litter decomposition (Figures 6.4 - 6.10, Tables 6.4 - 6.9). The release of all six nutrients from litter among the three species after the 12 month period was *E. globulus* > *E. botryoides* > *E. ovata*, the same sequence for litter decomposition. After 12 months, more nitrogen and phosphorus were released from the litter from the trees irrigated with effluent than from the litter from the trees without irrigation though there was little difference in *E. botryoides.* The litter source also influenced the release of four other nutrients, but highly depended on the species. For example, more potassium and less calcium were released from the litter from trees irrigated with effluent than from the litter from trees without irrigation but this was only significant in *E. ovata*.

Initial chemical composition

Jensen (1974) indicated that the concentration of plant nutrients in litter is important because of its influence both on the rate of decomposition of the litter and on the amounts of nutrients liberated during the decomposition. Hence, the variations of litter decomposition and nutrient release between the species and between litter sources must be caused by the litter characteristics, such as nutrient concentration and lignin content.

Significant positive linear relationships are normally found between the initial nutrient concentrations in litter leaves and their decomposition, for example, nitrogen (Woods & Raison 1983; O'Connell 1988a; Taylor et al. 1989; Taylor et al. 1991; Bloomfield et al. 1993; Briones & Ineson 1996), phosphorus (Woods & Raison 1983), magnesium (Briones & Ineson 1996), and manganese (Berg et al. 1995). Recently, much interest has been directed towards the initial concentration of manganese as it is essential for the activity of the enzymes degrading the lignin (Fioretto et al. 1998). However, in the current study, only the initial magnesium content had a relatively weak positive relationship with litter dry weight loss (Figure 6.13).

Carbon content has also been reported to have some effect on litter decomposition (Bloomfield et al. 1993) and also via its ratio with other nutrients, such as carbon:nitrogen (Miller 1989; Taylor et al. 1989). In the current study, it had no effect on the variations of litter decomposition and nutrient release since carbon content was consistent across the six litter types (Table 6.2) and *E. brookerana* litter in section 4.2.2.2 (data not shown). Baker & Attiwill (1985) assumed that carbon constitutes 50% of organic matter in their eucalypt litter study, which was close to the results from the current study. Further study should be carried out to test whether the consistent carbon content is a common characteristic of *Eucalyptus* leaf litter. If it is, then carbon content could be excluded from the factors influencing the leaf litter decomposition in this genus.

Facelli & Pickett (1991) reviewed the contents of lignin, nitrogen, hemicellulose, cellulose, and secondary compounds (particularly phenolic acids) to be the most conspicuous variables. Short-lived organs, such as leaves, usually have less lignin and secondary chemicals and consequently decompose faster. In contrast, long-lived organs usually have more lignin and secondary compounds, and the litter produced lasts longer; older leaves usually contain more lignin and less protein.

Taylor et al. (1991) pointed out that lignin content is the most reliable indicator of decomposition rate. Miller (1989) concluded that the lignin:nitrogen ratio is one of the main internal factors retarding decomposition. Other studies also showed that initial lignin content or the lignin:nitrogen ratio had significant effects on litter decomposition (Melillo et al. 1982; O'Connell 1988a; Taylor et al. 1989; Bloomfield et al. 1993). In the current study, the ratio of lignin:nitrogen did not show any influence on the litter decomposition. However, the initial cellulose content had a closer negative relationship with litter decomposition than did the initial lignin content (Figure 6.13).

In summary, it was found that cellulose was the strongest predictor of litter decomposition, followed by lignin and then magnesium. Therefore, the higher the cellulose content in litter, the slower the litter decomposition.

O'Connell & Grove (1996) proposed that the low mobility of N and P was due in part to the high carbon:nitrogen and carbon:phosphorus ratios in the litter. There was no evidence to support this in the current study as the carbon content was consistent across the six litter types. The nitrogen and phosphorus content had no influence on the release of nitrogen or phosphorus, which varied between the litter types.

Lignin and cellulose content, or their combination (ADF) played important roles concerning nutrient release. Cellulose had a direct influence over manganese release (Figure 6.19) and both lignin and cellulose over calcium release (Figure 6.17). The ratio of lignin with each nutrient influenced the nutrient release:

* lignin:nitrogen over nitrogen (Figure 6.14);
* lignin:phosphorus over phosphorus (Figure 6.15);
* lignin:potassium over potassium (Figure 6.16);
* lignin:calcium over calcium (Figure 6.17), and
* lignin:manganese over manganese (Figure 6.19).

Cellulose:magnesium had a strong relationship with magnesium release (Figure 6.18). In addition to the above correlation between the ratios and nutrient release:

* lignin:nitrogen had a relationship with the release of potassium and magnesium (Figures 6.16, 6.18);
* lignin:phosphorus with nitrogen release (Figure 6.14); and
* ADF:nitrogen with phosphorus (Figure 6.15).

All of the above were negative linear relationships. The higher the initial lignin or cellulose content, or the higher the ratio of them with other nutrients, the slower the nutrient release.

Magnesium was the only nutrient to have a relationship between its initial concentration and its release (Figure 6.18). On the other hand, its ratios with other nutrients had some relationships with certain nutrient releases, such as, calcium:magnesium over the release of phosphorus and potassium (Figures 6.15 - 6.17), and nitrogen:magnesium and potassium over calcium release (Figure 6.17). Moreover, potassium:manganese had some influence over calcium release.

In summary, the nutrient release was mainly depending on the initial magnesium, lignin and cellulose contents or their ratios with other nutrients.

Nutrient accumulation prediction

O'Connell (1988b) indicated that import of N and P into decomposing litter from external sources occurred for substrata with initial lignin:N and lignin:P ratios greater than 26 and 1100. However, in the present study these ratios for all litter types were well under these levels being from 6 to 24 for lignin:N and 100 to 494 for lignin:P. Even so, there was still some accumulation of both nitrogen and phosphorus (Tables 6.4 - 6.5). The accumulation by the end of the 12 month period was mainly found in *E. ovata* litter from the trees without irrigation (Table 6.10), which the litter with the highest ratio of both lignin:N and lignin:P in the six litter types (Table 6.2). According to the nitrogen linear regression, accumulation after 12 months should only occur in litter with lignin:nitrogen ratios greater than 20 (Figure 6.14) and phosphorus in litter with lignin:phosphorus greater than 265 (Figure 6.15).

Accumulation was also found for calcium and magnesium in the litter (Tables 6.7 - 6.8). At the end of the 12 month period, calcium accumulation only happened in the *E. ovata* litter from the trees irrigated with effluent (Table 6.10). Accumulation can best be predicted by the lignin:calcium ratio. It may happen if the ratio is greater than 35 (Figure 6.17).

Significant magnesium accumulation occurred in *E. botryoides* litter from trees irrigated with effluent and *E. ovata* litter (Table 6.10). Its best prediction can come from the cellulose:magnesium ratio. The accumulation should be found only in the litter with a ratio greater than 170 (Figure 6.18).

According to the main reason for establishing the plantation, litter decomposition or nutrient cycling can be adjusted by selecting the species, with either quick or slow leaf litter decomposition and nutrient release. The litter decomposition and nutrient release can be predicted via litter internal factors, e.g. initial cellulose content, lignin:nitrogen or lignin:phosphorus ratios. To predict nutrient accumulation may be more important in a land treatment system if the litter is to be removed from the site. However, the external factors may interfere with the prediction since the relative control by lignin over the decomposition rate is not uniform over different climatic regions (Meentemeyer 1978).

6.4.3 The external factors on litter decomposition and nutrient release

The two most important external factors, moisture and temperature, have been well investigated (Williams & Gray 1974; Miller 1989; Bloomfield et al. 1993). Ericsson et al. (1992) found that decomposition and mineralization of eucalypt leaves proceeded remarkably fast, with 30 to 50% weight loss during the first year after a favourable soil moisture content for microbial activity was provided. For a given site or forest, the moisture and temperature can be significantly varied while the trees are growing. Therefore, plantation age can significantly influence litter decomposition on the forest floor, especially before canopy closure.

Bargali et al. (1993) reported that the greatest weight loss occurred in a 1 year old plantation and decreased with plantation age in *E. tereticornis* plantations up to 8 years old. However in the current study, the slowest litter decomposition occurred in the 1 year old plantation stands and increased with plantation age in the stands without irrigation (Figure 6.3). The canopy interfering with direct light penetration could provide suitable or unsuitable conditions due to a change of temperature and moisture affecting microbes which aid litter decomposition, and it varies from site by site.

Effluent irrigation affects the litter decomposition by changing moisture, temperature, and even the nutrient storage on the forest floor. O'Connell (1994) reported that the P addition increased the rate of dry weight loss of decomposing litter, and the N addition decreased it. Baker et al. (1990) found that irrigation with effluent significantly increased the rate of loss of organic matter and nutrients from *P. radiata* needles in litter-bags. They suggested this increase resulted from increases in nutrient and moisture availability and from greater solubility at higher pH of some organic fractions of litter after effluent was supplied.

Effluent irrigation in the current study increased the litter decomposition until the plantation was more than 2 years old (Figure 6.3), which was about the time of canopy closure. Effluent irrigation retarded litter decomposition under 3 year old stands. Nutrient and moisture from the effluent applied could possibly increase microbial activity, but the activity may be slowed down soon after the canopy interferes with direct light penetration to the forest floor. This could change some other environmental factors, such as soil temperature and soil moisture and would explain why so much litter accumulation (39 OD t/ha) under the six year old *E. botryoides* plantation stands irrigated with effluent (section 3.3.3).

It is therefore likely, the decomposition rate would be accelerated after clear-cutting or thinning the trees thereby exposing the forest floor to more direct light. Clear cutting the trees at the end of each rotation in a coppice regime may therefore reduce the overall litter accumulation. For example, no more litter accumulated on the soil surface one year after clear cutting the six year old *E. botryoides* plantation stands irrigated with effluent in section 3.3.3 (data not shown). Longer rotation forests linked with effluent land treatment system may be practical if collecting litter from the forest floor for some purposes because more litter would be accumulated after canopy closure. Otherwise, the trees should be harvested as soon as their canopy closes to prevent nutrient accumulation in the litter on the top soil. Hence, the ground water or waterways would be protected from any sudden nutrient release from a forest land treatment system soon after some environment change (e.g. tree harvesting).

Plantation age and effluent irrigation significantly influenced the release of all six nutrients monitored (Tables 6.4 - 6.9, Figures 6.4 - 6.5). In the stands without irrigation, all nutrients were released least under the 1 year old stands. There were no differences on the release of all nutrients under the 2 and 3 year old stands except for manganese, which was released more under 3 year old than under 2 year old stands. Therefore, nutrient cycling in the stands without irrigation was increased after canopy closure. This trend may be carried forward in a longer rotation.

Effluent irrigation reversed the above trend. The slowest release of all six nutrients was found under the 3 year old stands. There was no difference in nitrogen, phosphorus, potassium and calcium release from litter under 1 and 2 year old stands. More magnesium was released under 2 year old stands than under 1 year old stands. Conversely, more manganese was released under the 1 year old stands. Therefore, the nutrient cycling in the stands irrigated with effluent was retarded after canopy closure. On the other hand, the nutrient release could be accelerated greatly after clear-cutting or thinning the trees in the stands and exposing the forest floor to light.

In summary, nutrient cycling can be manipulated through plantation management techniques, such as thinning, clear-cutting, or irrigation, according to the objectives of growing the plantations.

Accumulation of nitrogen, phosphorus and magnesium was found mainly in litter under 3 year old stands irrigated with effluent even though magnesium accumulation also occurred under 1 year old stands without irrigation (Figures 6.4 - 6.5, 6.8). Since effluent irrigation retarded litter decomposition after canopy closure (Figure 6.3), the nutrients from effluent (section 3.2.1) may enhance the nutrient accumulation in the litter. O'Connell (1994) found that the application of P enhanced P uptake into decaying litter, while the application of N enhanced N uptake. Nutrients can be imported into the litter through various sources, such as rainfall, throughfall, stemflow, frass from herbivores or translocation in fungal hyphae from both surface soil and the lower strata of the litter layer (O'Connell & Grove 1996). Nutrients could be also imported from the effluent directly in forests linked with effluent land treatment, such as the case in the current study. Nutrient accumulation in the litter may be more important in the effluent land treatment if the litter is removed from the site for nutrient stripping, especially in longer rotations as it is the main nutrient output before harvesting or thinning.

Anderson et al. (1983) indicated that litter decomposition and nutrient cycling in terrestrial ecosystems involved complex long-term processes, and cannot be quantified by short-term studies. The results of this present study however do provide a basis for comparing decomposition processes in short rotation forests, especially the ones linked with effluent land treatment, and provide a better understanding of their operation at the ecosystem level of organization.

6.5 CONCLUSIONS

Litter decomposition and nutrient release were significantly influenced by the external factors of plantation age and effluent irrigation as well as the internal factors, species and litter source. In the initial chemical composition of leaf litter, acid detergent fibre (cellulose and lignin) and magnesium were the key factors to influence litter decomposition and nutrient release via its initial content or its ratios with other nutrients. Thus, nutrient cycling was affected as a result. Therefore, plantation forests can be managed according to their purpose, whether nutrient retention or nutrient stripping is desirable. Forest management includes species selection, irrigation (of effluent or water), fertilization, and thinning or harvesting. Hence, the nutrient cycling in the forest system can be manipulated to give sustainable biomass production and sustainable land use.

Canopy closure was a key external factor to litter decomposition and nutrient release in the plantation forests as it restricts light penetration to the forest floor. However, light penetration does not only influence the light intensity at the forest floor, but it also involves soil temperature and soil moisture change, which may further affect litter decomposition. Therefore, further study needs to be conducted on light condition and its interactions with temperature and irrigation (effluent or water) affecting litter decomposition. This was the main objective of the research described in chapter 7.

7. ENVIRONMENTAL EFFECTS ON SOIL, TREE GROWTH, TREE NUTRIENT UPTAKE, AND LITTER DECOMPOSITION

7.1 INTRODUCTION

Effluents from dairy farms, food processing industries, and municipal sewage treatment plants contain high levels of nutrients, such as nitrogen and phosphorus. On the other hand, poor nutrient availability is often the major reason for plants not achieving their potential growth capacity (Mitchell & Ford-Robertson 1992). Therefore, effluent irrigated to crop growing land can be a replacement for commercial fertilizers (Marecos do Monte et al. 1989). However, continued effluent irrigation can change soil properties, e.g. pH, nutrient concentration (Waly et al. 1987; Russell et al. 1988; Falkiner & Smith 1997). These changes may influence the sustainable use of the land in the long term.

Effluent irrigation significantly increased the yields of crops, e.g. ryegrass pasture (Russell et al. 1988), and forestry (Sopper & Kardos 1973; Sopper 1980; Lowe 1994). In eucalypt short rotation forests, it increased the leaf litter fall and branch components of the harvestable biomass (sections 5.3.2.2 and 5.3.4.1). Effluent irrigation can also influence litter decomposition on the forest floor (Baker et al. 1990).

Effluent applied changes soil moisture content, and adds nutrients and organic matter, which may cause further changes in soil properties, tree growth, tree nutrient uptake, and litter decomposition. Schipper et al. (1996) found that the changes in the soils receiving effluent were attributed to nutrient inputs rather than to the additional water loading. O'Connell (1994) reported that P addition from fertilizer increased the rate of dry weight loss of decomposing litter whereas N addition decreased it.

The results from the field experiments undertaken as part of the current study showed that effluent irrigation and tree age had significant effects on soil changes (sections 3.3.1 and 5.3.1), tree growth (section 5.3.2), tree nutrient uptake (sections 5.3.2 and 5.3.5), and litter decomposition (sections 4.3.2.1 and 6.3.1). Both the water and nutrients of the effluent played important roles in these effects. In particular, effluent application increased the litter decomposition, but not until the stand age was more than two years old (section 6.3.1), which was around the time of canopy closure. Effluent irrigation retarded the litter decomposition under 3 year old plantations. This was possible due to the light penetration affecting temperature and moisture redistribution on the forest floor since litter decomposition is regulated mainly by temperature and water regimes, and soil fertility may be secondarily important (Staaf 1987).

Therefore, it was necessary to determine the effects of environmental factors (temperature, water and effluent irrigation, and light reaching the forest floor) on the soil properties, tree growth, tree nutrient uptake and litter decomposition.

7.1.1 Objectives

To test the effects of the environmental factors on the soil properties, tree growth, tree nutrient uptake and litter decomposition, a study was conducted using growth cabinets. The objectives were to determine:

1. the effects of temperature, water and effluent irrigation on soil properties, tree growth, and tree nutrient uptake;
2. the effects of temperature, water and effluent irrigation, and light intensity on litter decomposition;
3. the effects of the nutrient content of the effluent on soil properties, tree growth, tree nutrient uptake and litter decomposition by comparing effluent irrigation with water irrigation; and
4. the interactions between these environmental factors on soil properties, tree growth, tree nutrient uptake and litter decomposition.

7.2 MATERIALS AND METHODS

7.2.1 Experimental design

The experiment was conducted in three growth cabinets for a 13 week period from 28 June to 27 September 1996 at Massey University.

A factorial design was used in this experiment to test the effects of the imposed external environmental factors. Three factors were investigated to assess their effects on soil properties, tree growth, and tree nutrient uptake (Table 7.1), and four on litter decomposition (Table 7.2):

i) temperature:

- 2.5°C in the dark, 7.5°C in the light;
- 12.5°C in the dark, 17.5°C in the light; and
- 22.5°C in the dark, 27.5°C in the light.

(Note: these three temperature regimes represented winter/spring (or autumn)/summer in the field. For ease of reporting they have been termed "5°C", "15°C" and "25°C" from here on).

ii) irrigation type: tap water or meatworks effluent;

iii) irrigation rate: the water and the effluent were irrigated at 0 (control), 10, 20, 30 or 40 mm/week.

iv) light or shaded (for litter only): two light intensities were applied to the litter on the soil surface.

Table 7.1 Treatment labels for a 3-factorial experiment designed to test the effects of temperature, irrigation type and irrigation rate on soil change, tree growth and tree nutrient uptake.

Temperature		5°C		15°C		25°C	
Irrigation type		Water	Effluent	Water	Effluent	Water	Effluent
Irrigation rate	0	5C0		15C0		25C0	
(mm/week)	10	5W10	5E10	15W10	15E10	25W10	25E10
	20	5W20	5E20	15W20	15E20	25W20	25E20
	30	5W30	5E30	15W30	15E30	25W30	25E30
	40	5W40	5E40	15W40	15E40	25W40	25E40

Table 7.2 Treatment labels for a 4-factorial experiment designed to test the effects of temperature, irrigation type, irrigation rate and light on litter decomposition.

Temperature		5°C		15°C		25°C	
Irrigation type		Water	Effluent	Water	Effluent	Water	Effluent
	Irrigation rate						
Light	0 mm/week	L5C0		L15C0		L25C0	
	10	L5W10	L5E10	L15W10	L15E10	L25W10	L25E10
	20	L5W20	L5E20	L15W20	L15E20	L25W20	L25E20
	30	L5W30	L5E30	L15W30	L15E30	L25W30	L25E30
	40	L5W40	L5E40	L15W40	L15E40	L25W40	L25E40
Shaded	0 mm/week	S5C0		S15C0		S25C0	
	10	S5W10	S5E10	S15W10	S15E10	S25W10	S25E10
	20	S5W20	S5E20	S15W20	S15E20	S25W20	S25E20
	30	S5W30	S5E30	S15W30	S15E30	S25W30	S25E30
	40	S5W40	S5E40	S15W40	S15E40	S25W40	S25E40

7.2.2 Materials

Soil medium was sandy loam, taken from the top soil under the 2 year old *Eucalyptus globulus* plantation stand without effluent irrigation at Oringi, Dannevirke (details about the site and the soil were presented in section 3.2.1). Litter (a mixture of fresh and decaying) was collected from the forest floor under the same stand. Roots and gravels were removed from the soil medium before planting the tree seedlings. A *E. globulus* seedling (three months old in root trainers) was planted into each pot (top diameter 160 mm, bottom diameter 125 mm; height 150 mm), which was then filled with soil medium up to 25 mm from the top. A 20 mm even layer of litter was placed on the top of the soil in each pot to represent the actual forest floor soil profile.

Freshly abscised leaf litter was collected from the forest floor under the same stand of *E. globulus* in February 1996. Two grams of air-dried litter leaf material were weighed to the nearest 0.01 g and placed in a nylon bag (50 × 100 mm) of 1 mm square mesh (Gallardo & Merino 1993). Two litter bags were put into the litter layer on the soil surface in each pot. One was shaded with the shading cloth (Figure 7.1).

There were four replicates in this experiment. Overall, 108 tree seedlings were planted in pots and 216 litter bags were used. Four extra tree seedlings planted in pots with eight litter bags on the soil surface were retained before the experiment started to determine the initial characteristics of the soil and the tree seedling, together with the moisture content of the bagged litter.

The initial mean soil characteristics were: 5.17 (pH), 5.30 mg N/g and 1.00 mg P/g. The initial mean tree seedling characteristics were: 2.8 mm (stem diameter at ground level), 2.0 g/tree (biomass: leaves 0.7 g; branches 0.9 g; and roots 0.4 g), 50 cm^2/tree (leaf area), 20.2 mg N/tree (leaves 10.5 mg; branches 5.5 mg; and roots 4.2 mg), and 4.5 mg P/tree (leaves 1.3 mg; branches 2.2 mg; and roots 1.0 mg).

Figure 7.1 A sample of a pot showing the labelled eucalypt tree seedling stem, one leaf litter bag placed in the litter layer on top of the soil, and the shading cloth covering the second litter bag.

The pots were moved into three growth cabinets as soon as the seedlings were planted and the litter and litter bags placed on the soil surface. They were randomly arranged within each cabinet. The temperature was adjusted to give the required settings in each of the three growth cabinets for the mean of 5°C, 15°C, and 25°C. In all cases, a 12 hour period of light followed by a 12 hour period of darkness was used. The light intensity was 48240 lux, but it was < 1 lux in the dark (measured using Hagner Universal Photometer (Model S3)). Less than 1% (< 85 lux) light penetrated through the shading cloth to the litter underneath. Water or effluent was irrigated manually onto each pot at the required rates with 10 mm each time. Therefore, the water or effluent was irrigated two times each week for 20 mm/week pots, three and four times for 30 and 40 mm/week pots, respectively.

The effluent applied to the pots was collected weekly from the anaerobic effluent treatment pond at the Richmond Meat Packing & Processing Plant, Oringi, Dannevirke. Three samples from each effluent collection were analysed for total Kjeldahl nitrogen and total phosphorus. The total inputs of nitrogen and phosphorus to the soil in the pots from the effluent irrigation over the 13 week trial period are shown in Table 7.3. The pH of tap water and the effluent was 7.8 and 6.8, respectively.

Table 7.3 The total inputs of nitrogen (TKN) and phosphorus (TP) over a 13 week period of effluent irrigation to the soil in the pots

Irrigation rate mm/week	Effluent l/pot	TKN	TP
		g/pot	
10	2.07	0.28	0.04
20	4.15	0.56	0.07
30	6.22	0.84	0.11
40	8.29	1.12	0.14

7.2.3 Laboratory analysis

At the end of the experimental period, the soil samples were taken from each pot, air-dried and passed through a 2 mm sieve to provide material for pH, total Kjeldahl nitrogen, and total phosphorus analysis.

All seedlings were harvested on completion of the experiment and divided into three components: leaves, branches (including stem), and roots. Roots were washed using tap water. Leaf area was measured by a LI-Cor LI-3100 Leaf Area Meter (Lambda Instruments Co, Lincoln, NE, USA). All tree components were oven-dried at 80°C overnight before weighing, and then were ground to pass through a 1 mm sieve for total nitrogen and total phosphorus analysis.

Soil samples were analysed for pH using a soil to water ratio of 1:2.5 according to Nicholson (1984). Total nitrogen and total phosphorus for effluent, soil, and tree components were analysed using a Technicon Auto Analyser following Kjeldahl digestion (details see section 3.2.3).

From the above primary data for the trees, the following parameters were then derived:

i) leaf weight ratio (LWR, leaf dry weight / total plant dry weight, g/g);

ii) branch weight ratio (BWR, branch dry weight / total plant dry weight, g/g);

iii) root weight ratio (RWR, root dry weight / total plant dry weight, g/g);
iv) leaf nitrogen ratio (LNR, nitrogen in leaves / nitrogen in total plant, mg/mg);
v) branch nitrogen ratio (BNR, nitrogen in branches / nitrogen in total plant, mg/mg);
vi) root nitrogen ratio (RNR, nitrogen in roots / nitrogen in total plant, mg/mg);
vii) leaf phosphorus ratio (LPR, phosphorus in leaves / phosphorus in total plant, mg/mg);
viii) branch phosphorus ratio (BPR, phosphorus in branches / phosphorus in total plant, mg/mg);
ix) root phosphorus ratio (RPR, phosphorus in roots / phosphorus in total plant, mg/mg).
x) shoot:root ratio ((branch dry weight + leaf dry weight) / root dry weight, g/g);
xi) leaf area ratio (LAR, leaf area / total plant dry weight, cm^2/g); and
xii) specific leaf area (SLA, leaf area / leaf dry weight, cm^2/g).

On completion of the trial, the litter from the litter bags was gently brushed and made free of foreign materials by hand, then oven-dried (80°C) overnight before weighing to ascertain dry weight loss.

Litter dry weight loss was calculated as follows:

$$L\ (\%) = 100*(W_0 - W_t) / W_0$$

where L is litter dry weight loss; W_0 is the initial litter dry weight; W_t is the dry weight of the remaining litter in litter bag when the experiment finished.

7.2.4 Statistical analysis

All data were analysed using the SAS GLM procedure (SAS Institute 1990). A model for a 3-factorial combination was used to analyse the changes of soil pH, total Kjeldahl nitrogen, and total phosphorus, and tree growth and nutrient uptake. The litter dry weight loss from bagged leaf litter was analyzed by using a model for a 4-factorial combination. The litter decomposition was modelled exponentially (Olson 1963):

$$W_t = W_o e^{-kt}$$

where W_o is the initial leaf litter dry weight, W_t the dry weight at time t, and k the annual instantaneous decay constant.

7.3 RESULTS

7.3.1 Soil changes

7.3.1.1 Soil pH

The soil pH changed significantly after either water or effluent irrigation under all three different temperature regimes. All factors tested affected the soil pH level (Table 7.4). Soil pH value decreased at the higher temperature and was higher with water irrigation than with effluent irrigation. Soil pH increased as the irrigation rate increased. Furthermore, interactions between the three factors were significant.

After 13 weeks, the pH in the soil without any irrigation (5C0 in Table 7.1) decreased from 5.32 to 5.12 at the 5°C temperature. The higher the temperature, the lower the soil pH, with 5.06 and 4.96 being obtained at the two higher temperatures (15C0 and 25C0 in Table 7.1), respectively.

At the 5°C temperature (Figure 7.2a), the soil pH increased when more water or effluent was irrigated. The value was lower under effluent irrigation than under water irrigation though there was only a significant difference at the 10 mm/week rate.

At the 15°C temperature (Figure 7.2b), water irrigation increased the soil pH as the irrigation rate increased. On the contrary, effluent irrigation increased the soil pH at 10 mm/week, then significantly reduced the pH value thereafter.

At the 25°C temperature (Figure 7.2c), water irrigation increased the soil pH at 10 mm/week, then there was little further increase in pH with increase in irrigation rate. Effluent irrigation reduced the soil pH though not consistently with the irrigation rate.

Table 7.4 The variations of soil pH, nitrogen and phosphorus concentration of the soil in the pots after the 13 week period under various temperatures and with water or effluent applied at a range of application rates.

Soil	Factor	Level					$LSD_{0.05}$
pH	**Temperature (°C)**	**5**	**15**	**25**			
		5.26	5.12	4.97			0.05
	Irrigation type	**Water**	**Effluent**				
		5.22	5.02				0.04
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		5.05	5.10	5.15	5.11	5.17	0.06
	Interaction	**Significance**					
	Temperature&Type	**					
	Temperature&Rate	*					
	Type&Rate	***					
	Temperature&Type&Rate	**					
Nitrogen (mg/g)	**Temperature (°C)**	**5**	**15**	**25**			
		5.17	5.20	5.30			ns
	Irrigation type	**Water**	**Effluent**				
		5.18	5.36				0.09
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		5.03	5.23	5.28	5.22	5.38	0.15
	Interaction	**Significance**					
	Temperature&Type	ns					
	Temperature&Rate	**					
	Type&Rate	ns					
	Temperature&Type&Rate	ns					
Phosphorus (mg/g)	**Temperature (°C)**	**5**	**15**	**25**			
		1.00	1.04	1.07			0.03
	Irrigation type	**Water**	**Effluent**				
		1.04	1.08				0.03
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.94	1.05	1.05	1.05	1.09	0.08
	Interaction	**Significance**					
	Temperature&Type	ns					
	Temperature&Rate	***					
	Type&Rate	ns					
	Temperature&Type&Rate	ns					

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

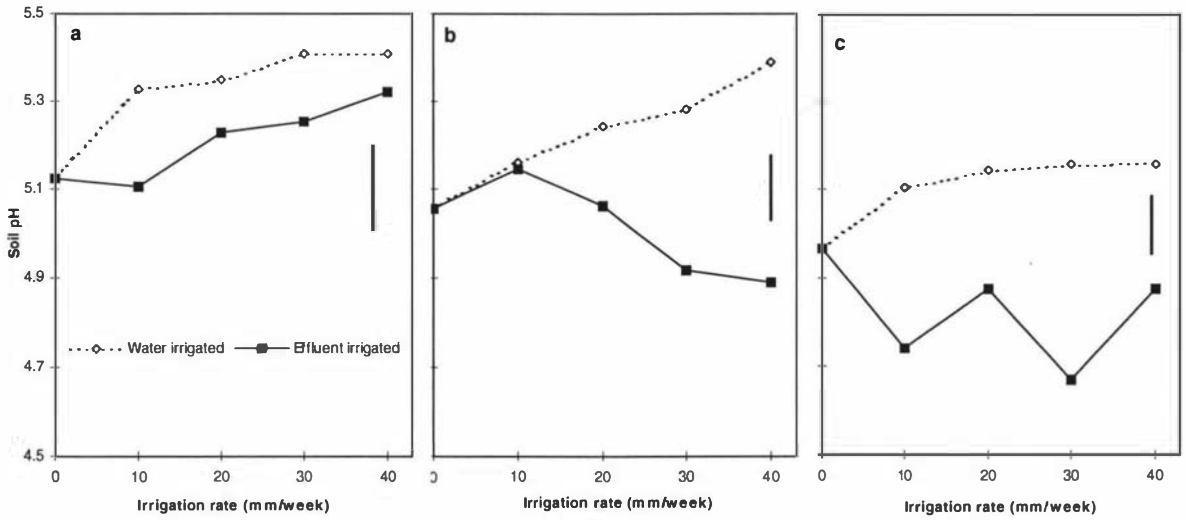

Figure 7.2 The effects of water or effluent irrigation on soil pH under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; Vertical bars indicate $LSD_{0.05}$).

7.3.1.2 Soil nitrogen

After the 13 week period, the irrigation type and irrigation rate had significant effects on soil nitrogen concentration, but the temperature did not (Table 7.4). Nitrogen concentrations were higher in the soils with effluent irrigation than with water irrigation. There were no significant differences between the irrigation rates except for the controls (5C0, 15C0, and 25C0 in Table 7.1). This resulted in an interaction between temperature and irrigation rate.

7.3.1.3 Soil phosphorus

Temperature, irrigation type and irrigation rate significantly affected the soil phosphorus concentration (Table 7.4). The phosphorus concentration increased as the temperature was increased. It was higher under effluent irrigation than under water irrigation. There were no significant differences between the irrigation rates except for the controls (5C0, 15C0, and 25C0 in Table 7.1). This also resulted in an interaction between temperature and irrigation rate.

7.3.2 Tree growth and nutrient accumulation

Seedlings without irrigation (5C0 in Table 7.1) survived for the whole 13 week period at the 5°C temperature. Those (15C0 in Table 7.1) at the 15°C temperature survived only for about 4 weeks and those (25C0 in Table 7.1) at 25°C temperature wilted and died within one week.

7.3.2.1 Tree stem diameter at ground level

After 13 weeks, all factors tested (temperature, irrigation type, and irrigation rate) significantly affected the tree stem diameter at ground level (Table 7.5). The highest stem diameter value was found at the 15°C temperature and the order was: 15°C > 25°C > 5°C. Larger stem diameters were found in the trees irrigated with effluent than in the trees irrigated with water. The stem diameter increased as the irrigation rate was increased. Furthermore, the factors interacted with each other significantly: temperature with irrigation type, temperature with irrigation rate, and irrigation type with irrigation rate.

Table 7.5 Tree stem diameter (mm) at ground level after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Factor	Level					LSD$_{0.05}$
Temperature (°C)	**5**	**15**	**25**			
	3.5	6.2	4.6			0.3
Irrigation type	**Water**	**Effluent**				
	4.9	5.6				0.3
Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
	2.8	4.1	5.1	5.7	6.2	0.6
Interaction						**Significance**
Temperature$^{\&}$Type						**
Temperature$^{\&}$Rate						***
Type$^{\&}$Rate						**
Temperature$^{\&}$Type$^{\&}$Rate						ns

, * and ns denote $P < 0.01$, $P < 0.001$ and not significant.

At the 5°C temperature (Figure 7.3a), there was no significant difference in seedling stem diameter at ground level between irrigation types or between irrigation rates (including trees at the control -- 5C0 in Table 7.1).

At the 15°C temperature, the stem diameter increased as the irrigation rate was increased (Figure 7.3b). There was no difference in the stem diameter between water and effluent irrigation for the 10 mm/week rate (15W10 and 15E10 in Table 7.1). Then, the stem diameter of trees irrigated with effluent was consistently larger than the stem diameter of trees irrigated with water.

At the 25°C temperature, the tree stem diameter increased as the irrigation rate was increased from 0 mm/week to 40 mm/week, and there was only a small difference between water irrigation and effluent irrigation (Figure 7.3c).

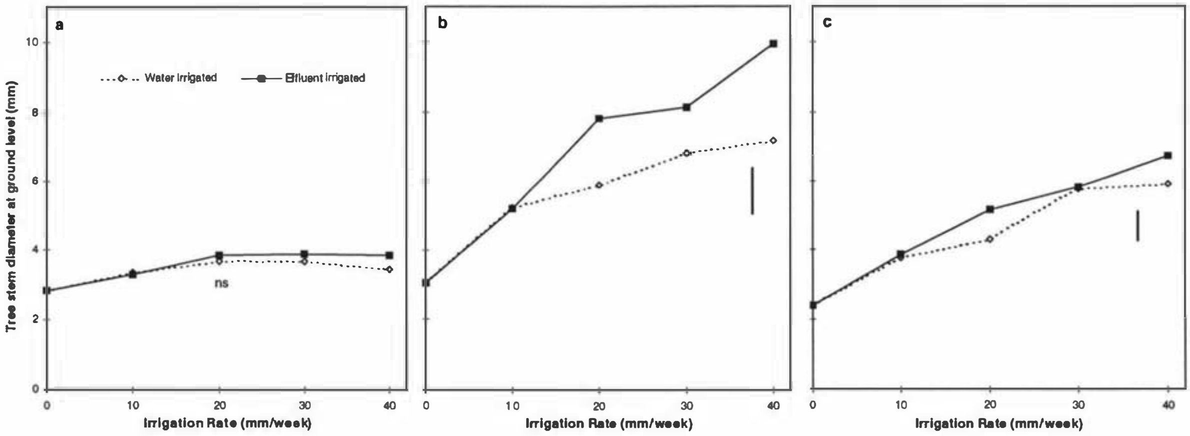

Figure 7.3 Tree stem diameters at ground level under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; ns = not significant. Vertical bars indicate $LSD_{0.05}$).

There were positive relationships between tree stem diameter and irrigation rate under the two higher temperature regimes (Figure 7.4), but not at the 5°C temperature. Effluent irrigation at the 15°C temperature had the highest correlation coefficient with tree stem diameter.

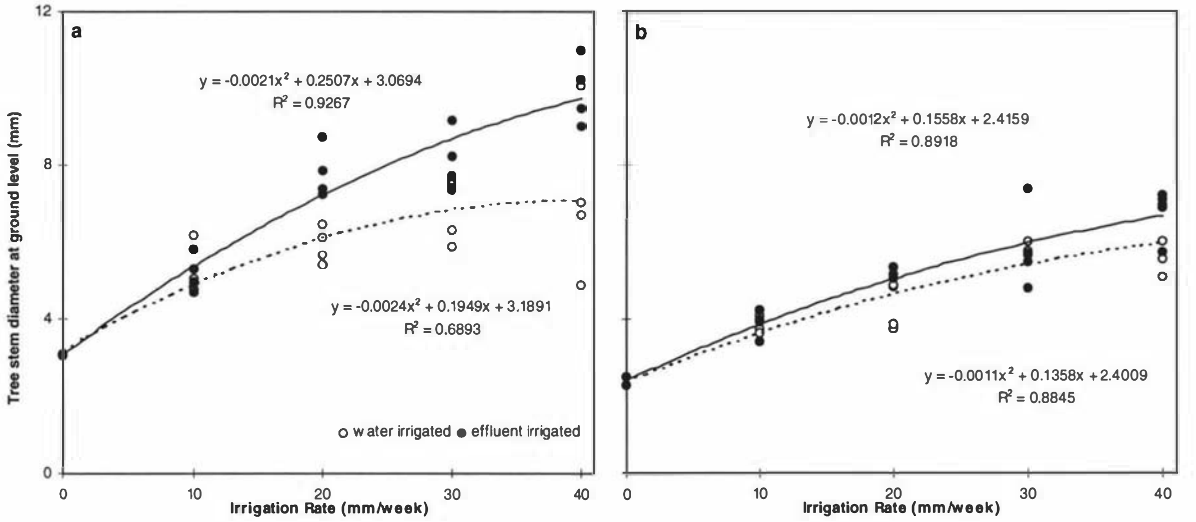

Figure 7.4 Relationships between tree stem diameter and irrigation rate under the two temperature regimes: (a) 15°C, and (b) 25°C.

7.3.2.2 Total biomass accumulation

After 13 weeks, all factors tested (temperature, irrigation type, and irrigation rate) significantly affected the tree total biomass, which included foliage, branches, and roots (Table 7.6). The highest biomass dry weight accumulation was found at the 15°C temperature and the order was: 15°C > 25°C > 5°C (Figure 7.5). The dry weight of trees irrigated with effluent was greater than the dry weight of trees irrigated with water. The dry weight increased as the irrigation rate was increased. Furthermore, all the interactions between the factors were highly significant.

At the 5°C temperature, the highest dry weight (5.5 g/tree) occurred in the trees with 20 mm/week effluent irrigation (Figure 7.6a). There was a small difference between other treatments, even the ones without any irrigation (5C0 in Table 7.1).

At the 15°C temperature, the dry weight increased as the effluent irrigation rate was increased, but there were no changes in the dry weight as water irrigation rate was increased from 10 mm/week to 40 mm/week (Figure 7.6b). The biomass in the trees with effluent irrigation was significantly greater than the biomass in the trees with water irrigation except at the 10 mm/week irrigation rate. Some growth occurred initially in the trees without any irrigation (15C0 in Table 7.1), then the trees wilted and died after 4 weeks.

Table 7.6 Tree total biomass, nitrogen and phosphorus accumulation after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Accumulation	Factor	Level					LSD$_{0.05}$
Biomass	**Temperature (°C)**	**5**		**15**		**25**	
(g/tree)		3.7		22.5		14.9	1.3
	Irrigation type	**Water**			**Effluent**		
		11.9			20.6		1.4
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		3.1	8.2	15.3	18.8	22.5	1.7
	Interaction				**Significance**		
	Temperature$^{\&}$Type				***		
	Temperature$^{\&}$Rate				***		
	Type$^{\&}$Rate				***		
	Temperature$^{\&}$Type$^{\&}$Rate				***		
Nitrogen	**Temperature (°C)**	**5**		**15**		**25**	
(mg/tree)		48		241		186	15
	Irrigation type	**Water**			**Effluent**		
		90			288		15
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		37	101	176	203	275	19
	Interaction				**Significance**		
	Temperature$^{\&}$Type				***		
	Temperature$^{\&}$Rate				***		
	Type$^{\&}$Rate				***		
	Temperature$^{\&}$Type$^{\&}$Rate				***		
Phosphorus	**Temperature (°C)**	**5**		**15**		**25**	
(mg/tree)		6.1		16.4		23.9	1.6
	Irrigation type	**Water**			**Effluent**		
		13.3			23.0		1.7
	Irrigation rate(mm/week)	**0**	**10**	**20**	**30**	**40**	
		4.7	9.1	16.1	22.2	25.2	2.1
	Interaction				**Significance**		
	Temperature$^{\&}$Type				***		
	Temperature$^{\&}$Rate				***		
	Type$^{\&}$Rate				***		
	Temperature$^{\&}$Type$^{\&}$Rate				***		

*** denotes $P < 0.001$.

Figure 7.5 Tree growth with 30 mm/week water (left) or effluent irrigation (right) under the three temperature regimes: 5°C (top), 15°C (middle), and 25°C (bottom).

At the 25°C temperature, the tree biomass continued to increase as the irrigation rate was increased from 0 mm/week to 40 mm/week (Figure 7.6c). The difference in tree growth between water and effluent irrigation increased at the higher irrigation rates. No dry weight was accumulated in the trees without any irrigation (25C0 in Table 7.1) as they wilted and died soon after the experiment started.

Overall, the trees with higher effluent application at 15°C temperature performed best in terms of growth rate.

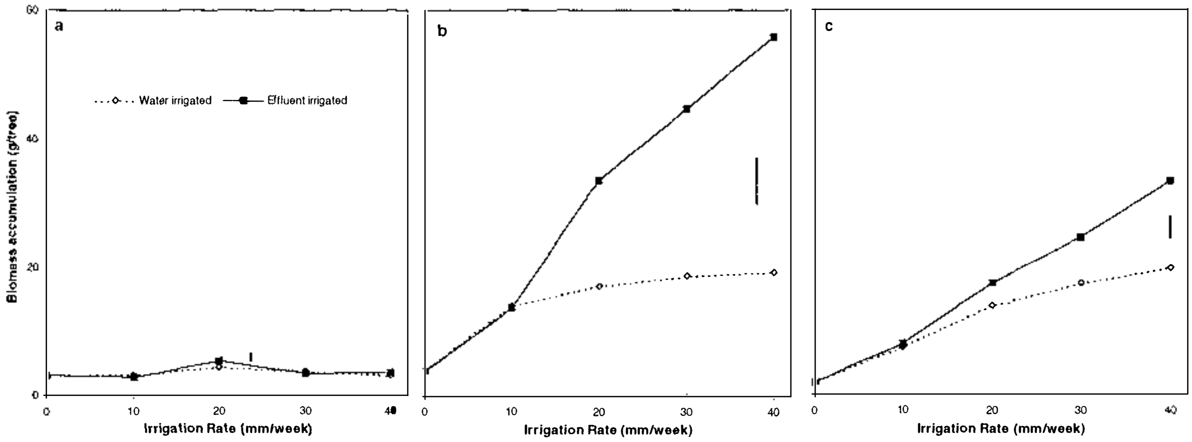

Figure 7.6 Tree total biomass accumulation under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; Vertical bars indicate $LSD_{0.05}$).

At both 15°C and 25°C temperatures, the biomass accumulated in the trees with effluent irrigation was correlated with the effluent irrigation rate; the more effluent supplied, the more biomass produced (Figure 7.7). This trend may have continued if more than 40 mm/week effluent was irrigated. A weaker correlation was found in the trees with water irrigation, especially at the 15°C temperature where little more biomass accumulated when irrigated above the 20 mm/week rate.

Even though both tree stem diameter and biomass were affected by temperature, irrigation type, and irrigation rate independently, they were highly correlated with each other (Figure 7.8). The trees with larger stem diameters had more total biomass weight per tree.

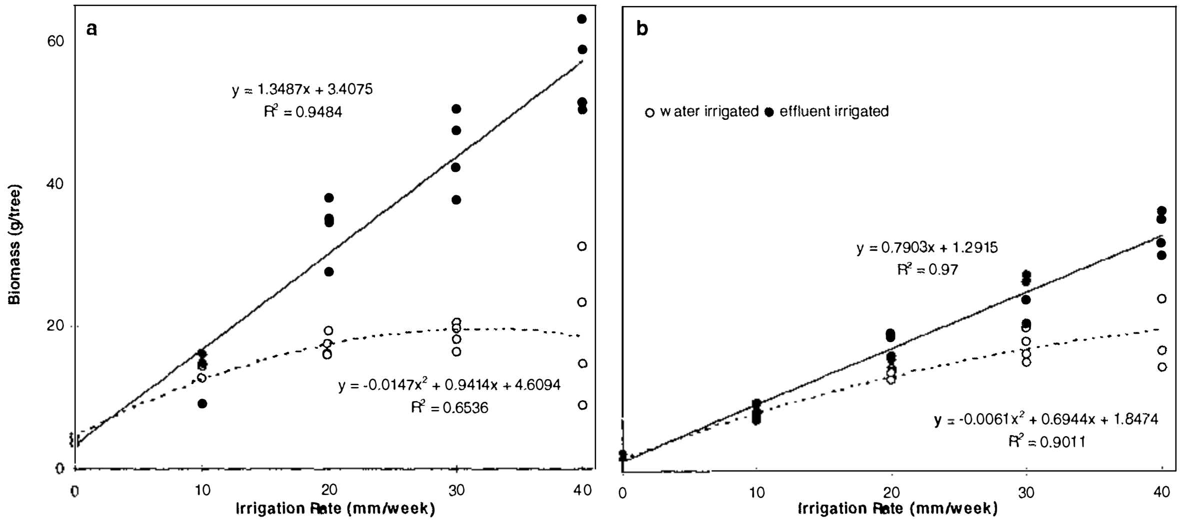

Figure 7.7 Relationship between tree total biomass and irrigation rate under the two temperature regimes: (a) 15°C, and (b) 25°C

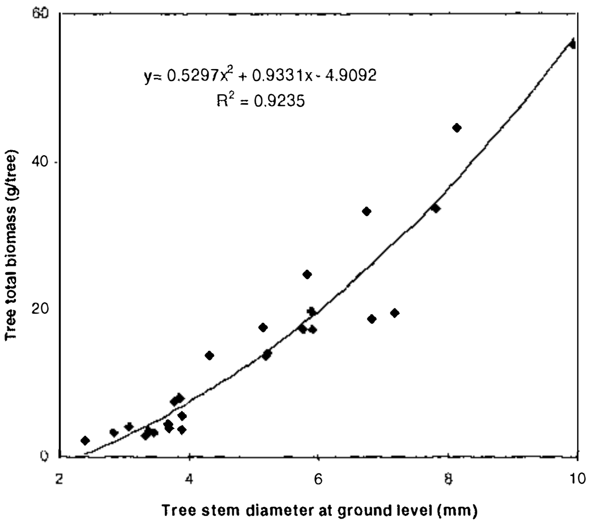

Figure 7.8 The relationship between tree total biomass accumulation and stem diameter at ground level.

7.3.2.3 Nitrogen accumulation

After 13 weeks, all factors tested (temperature, irrigation type, and irrigation rate) affected the tree nitrogen accumulation significantly (Table 7.6). The highest accumulation was found at the 15°C temperature and the order was: 15°C > 25°C > 5°C. More nitrogen was found in the trees irrigated with effluent than in trees irrigated with water. The nitrogen accumulation increased as the irrigation rate was increased. Furthermore, the three factors highly interacted.

At the 5°C temperature, the highest nitrogen accumulation (84 mg/tree) was found in the trees with 20 mm/week effluent irrigation (5E20 in Table 7.1), with only about half of this level found in the other trees (Figure 7.9a). At the 15°C temperature, the accumulation significantly increased as effluent irrigation rate was increased, but no change occurred as water irrigation rate was increased (Figure 7.9b). A similar trend was also found at the 25°C temperature (Figure 7.9c).

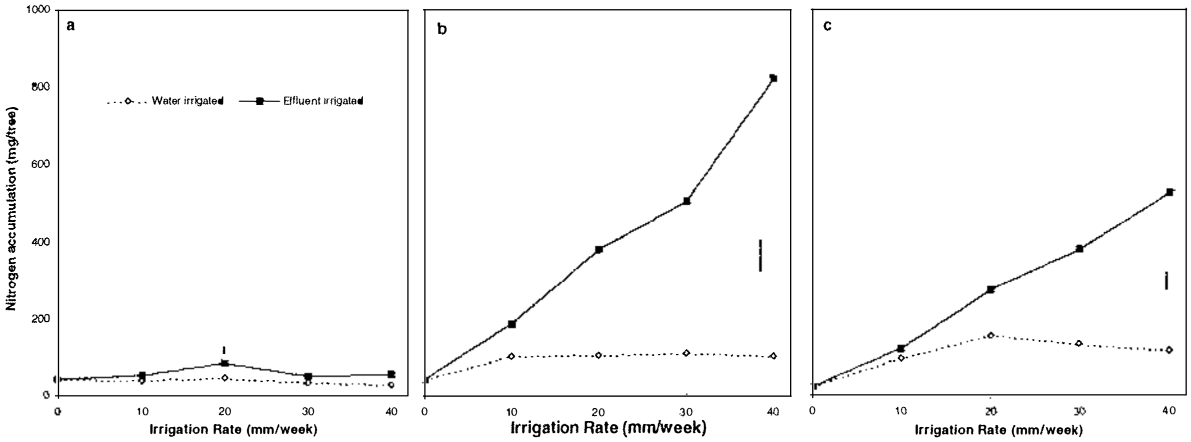

Figure 7.9 Nitrogen accumulation in the trees under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; Vertical bars indicate $LSD_{0.05}$).

7.3.2.4 Phosphorus accumulation

After 13 weeks, all factors tested (temperature, irrigation type, and irrigation rate) affected the tree phosphorus accumulation significantly (Table 7.6). The pattern was similar to nitrogen accumulation. The highest accumulation occurred at the 15°C temperature and the order was: 15°C > 25°C > 5°C. More phosphorus was accumulated in trees irrigated with effluent than in trees irrigated with water. The phosphorus accumulation increased as the irrigation rate was increased. Furthermore, the three factors highly interacted.

At the 5°C temperature, the highest phosphorus accumulation (9.0 mg/tree) was also found in the trees with 20 mm/week effluent irrigation (5E20 in Table 7.1) and the next in the trees with 40 mm/week effluent irrigation (5E40 in Table 7.1) (Figure 7.10a). At the 15°C temperature, the accumulation significantly increased as irrigation rate was increased, especially with effluent irrigation (Figure 7.10b). A similar trend was also found at the 25°C temperature, but the accumulation decreased as water irrigation was increased from 30 mm/week to 40 mm/week though not significantly (Figure 7.10c).

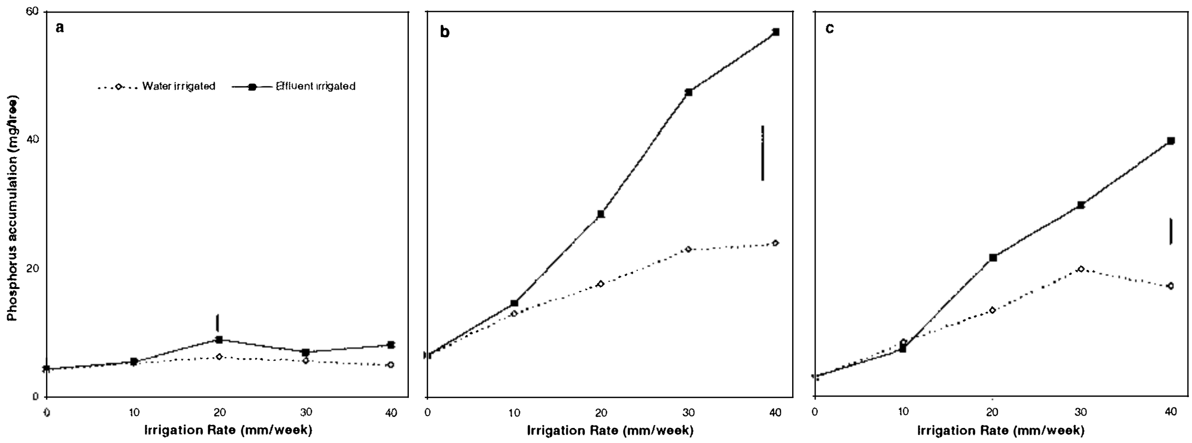

Figure 7.10 Phosphorus accumulation in the trees under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; Vertical bars indicate $LSD_{0.05}$).

7.3.2.5 Biomass and nutrient distribution in tree parts

The young trees consisted of three components, roots, branches (including stem), and leaves. The percentage of each component in the total accumulation of biomass, nitrogen and phosphorus was analysed separately.

Biomass distribution

After 13 weeks, all three factors tested affected the root weight ratio (RWR) significantly (Table 7.7). The temperature effect was: 15°C > 25°C ≈ 5°C. Lower RWR was found in trees irrigated with effluent than in trees irrigated with water. Irrigation rates showed little effect except for the trees at the controls (5C0, 15C0, and 25C0 in Table 7.1). Only temperature interacted with irrigation type.

At 5°C temperature, there were no significant differences on RWR between trees irrigated with water and with effluent whereas at the two higher temperatures, RWR was higher in the trees irrigated with water than irrigated with effluent, especially at 15°C temperature (Figure 7.11a). Under effluent irrigation, there were no differences on RWR between the three temperatures.

Table 7.7 Leaf weight ratio (LWR), branch weight ratio (BWR) and root weight ratio (RWR) in the trees (g/g) after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Tree part	Factor	Level					LSD$_{0.05}$
LWR	**Temperature (°C)**	**5**	**15**	**25**			
		0.43	0.45	0.48			0.03
	Irrigation type	**Water**	**Effluent**				
		0.42	0.51				0.03
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.34	0.48	0.50	0.48	0.48	0.04
	Interaction				**Significance**		
	Temperature$^{\&}$Type				*		
	Temperature$^{\&}$Rate				ns		
	Type$^{\&}$Rate				ns		
	Temperature$^{\&}$Type$^{\&}$Rate				ns		
BWR	**Temperature (°C)**	**5**	**15**	**25**			
		0.40	0.34	0.36			0.02
	Irrigation type	**Water**	**Effluent**				
		0.35	0.34				ns
	Irrigation rate(mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.44	0.35	0.33	0.36	0.35	0.03
	Interaction				**Significance**		
	Temperature$^{\&}$Type				ns		
	Temperature$^{\&}$Rate				***		
	Type$^{\&}$Rate				ns		
	Temperature$^{\&}$Type$^{\&}$Rate				ns		
RWR	**Temperature (°C)**	**5**	**15**	**25**			
		0.17	0.21	0.16			0.02
	Irrigation type	**Water**	**Effluent**				
		0.19	0.15				0.02
	Irrigation rate(mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.22	0.17	0.17	0.16	0.17	0.03
	Interaction				**Significance**		
	Temperature$^{\&}$Type				*		
	Temperature$^{\&}$Rate				ns		
	Type$^{\&}$Rate				ns		
	Temperature$^{\&}$Type$^{\&}$Rate				ns		

*, *** and ns denote $P < 0.05$, $P < 0.001$ and not significant.

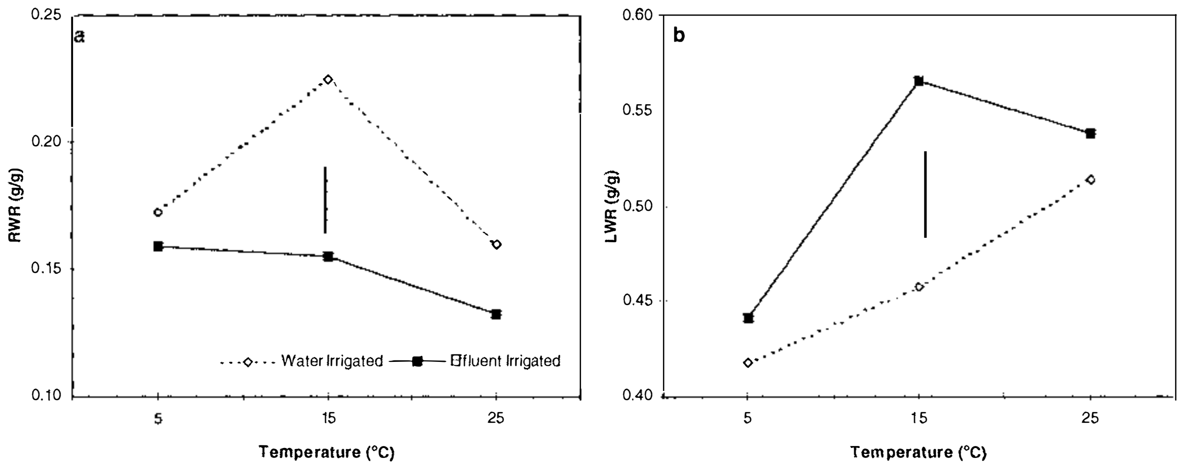

Figure 7.11 Tree part dry weight ratio with the total biomass: (a) root weight ratio (RWR), and (b) leaf weight ratio (LWR) (n = 32; Vertical bars indicate $LSD_{0.05}$).

After 13 weeks, only temperature and irrigation rate significantly influenced the branch weight ratio (BWR) (Table 7.7). The highest BWR was found at the 5°C temperature and the order was: 5°C > 25°C > 15°C. No difference existed between the irrigation rates except for the controls (5C0, 15C0, and 25C0 in Table 7.1). This also caused an interaction between temperature and irrigation type.

After 13 weeks, all factors tested significantly affected the leaf weight ratio (LWR) (Table 7.7). The LWR order under the three temperature regimes was: 25°C > 15°C ≈ 5°C. A higher LWR was found in trees irrigated with effluent than in trees irrigated with water. Little change occurred between the various irrigation rates except for the controls (5C0, 15C0, and 25C0 in Table 7.1). Only temperature interacted with irrigation type. Under water irrigation, higher LWR was found at higher temperature (Figure 7.11b). A similar trend was also found in the trees irrigated with effluent irrigation, but there was no difference between the two higher temperatures.

Nitrogen distribution

After 13 weeks, all factors tested (temperature, irrigation type and irrigation rate) significantly affected the leaf nitrogen ratio (LNR), the branch nitrogen ratio (BNR) and the root nitrogen ration (RNR) except for irrigation type on the BNR (Table 7.8). However, there was no difference in these ratios between irrigation rates if the controls (5C0, 15C0, and 25C0 in Table 7.1) were excluded. The LNR order under the three temperature regimes was: 25°C > 5°C ≈ 15°C. Lower LNRs were found in trees irrigated with water than in trees irrigated with effluent. Temperature interacted with irrigation type and irrigation rate. All three factors also significantly interacted together.

The BNR at the 15°C temperature was only slightly lower than at the other two temperatures. However, temperature interacted with irrigation type and irrigation rate. All three factors also significantly interacted together.

The RNR order under three temperature regimes was: 15°C > 5°C > 25°C. Lower RNR was found in trees irrigated with effluent than in trees irrigated with water. Some interactions were found among the factors, especially the one for all three factors together.

At the 5°C temperature, the LNR increased as the effluent irrigation rate was increased from 0 mm/week to 10 mm/week, then it decreased significantly as the irrigation rate was increased from 20 mm/week to 40 mm/week (Figure 7.12a). However, the LNR decreased as water irrigation rate was increased from 0 mm/week to 20 mm/week, and increased as the rate was increased from 20 mm/week to 40 mm/week. BNR followed the change of LNR, but in opposite way. There was no significant difference in the RNR.

At the 15°C temperature, the LNR increased while irrigation rate was increased from 0 mm/week to 10 mm/week. Then, the LNR in the trees irrigated with effluent fluctuated from 20 mm/week to 40 mm/week, but the LNR in the trees irrigated with water showed little change until the irrigation rate up to 30 mm/week, then it decreased slightly (Figure 7.12b). The LNR in the trees irrigated with water was consistently lower than in the trees irrigated with effluent. Conversely, the RNR in the trees irrigated with water was higher than in the trees irrigated with effluent. There was only a slightly significant difference in BNR as the irrigation rates were increased above 10 mm/week.

At the 25°C temperature, there were small but significant differences in the LNR, the BNR and the RNR (Figure 7.12c). The BNR was consistently higher in the trees irrigated with effluent than in the trees irrigated with water though this was not significant under some irrigation rates.

Overall, leaf was the main component of the trees to accumulate nitrogen.

Table 7.8 Leaf nitrogen ratio (LNR), branch nitrogen ratio (BNR) and root nitrogen ratio (RNR) in the trees (mg/mg) after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Tree	Factor	Level					$LSD_{0.05}$
LNR	**Temperature (°C)**	**5**	**15**	**25**			
		0.63	0.60	0.66			0.03
	Irrigation type	**Water**	**Effluent**				
		0.64	0.68				0.03
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.53	0.65	0.67	0.66	0.65	0.04
	Interaction	**Significance**					
	Temperature&Type	**					
	Temperature&Rate	***					
	Type&Rate	ns					
	Temperature&Type&Rate	***					
BNR	**Temperature (°C)**	**5**	**15**	**25**			
		0.20	0.18	0.20			0.02
	Irrigation type	**Water**	**Effluent**				
		0.18	0.18				ns
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.26	0.18	0.17	0.18	0.18	0.02
	Interaction	**Significance**					
	Temperature&Type	**					
	Temperature&Rate	***					
	Type&Rate	ns					
	Temperature&Type&Rate	***					
RNR	**Temperature (°C)**	**5**	**15**	**25**			
		0.17	0.21	0.14			0.02
	Irrigation type	**Water**	**Effluent**				
		0.19	0.15				0.02
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.21	0.17	0.16	0.16	0.18	0.03
	Interaction	**Significance**					
	Temperature&Type	***					
	Temperature&Rate	*					
	Type&Rate	ns					
	Temperature&Type&Rate	**					

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

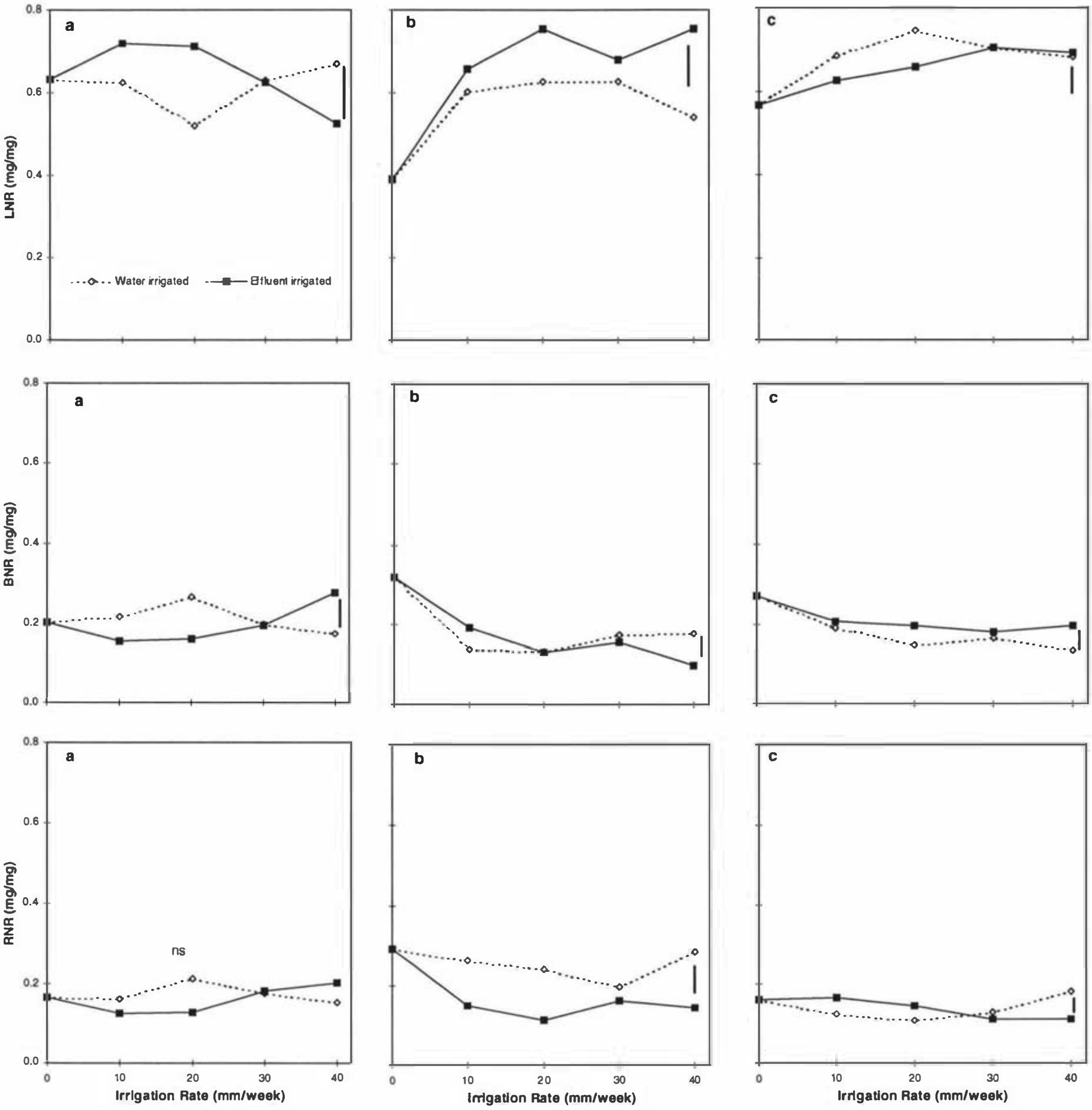

Figure 7.12 Nitrogen ratio between tree parts and the total under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (LNR = leaf nitrogen ratio; BNR = branch nitrogen ratio; RNR = root nitrogen ratio; n = 4; ns = not significant; Vertical bars indicate $LSD_{0.05}$).

Phosphorus distribution

After 13 weeks, all tested factors significantly affected the leaf phosphorus ratio (LPR), the branch phosphorus ratio (BPR) and the root phosphorus ratio (RPR) (Table 7.9). The LPR was higher at the 25°C temperature than at the other two temperature regimes. Lower LPR was found in trees irrigated with water than in trees irrigated with effluent. The lowest LPR occurred in the controls (5C0, 15C0, and 25C0 in Table 7.1) and highest was found in the trees with 10 mm/week irrigated. Then it decreased as the irrigation rate was increased. All tested factors had interactions between each other, especially all three factors together.

The BPR was higher at the 5°C temperature than at the 25°C temperature, with the 15°C temperature in between. Higher BPR was found in trees irrigated with water than in trees irrigated with effluent. The highest BPR occurred in the trees for the controls (5C0, 15C0, and 25C0 in Table 7.1) and decreased as irrigation rate was increased. All tested factors had interactions between each other, especially the three factors, which significantly interacted together.

The RPR order under the three temperature regimes was: 15°C ≈ 5°C > 25°C. Lower RPR was found in trees irrigated with effluent than in trees irrigated with water. There was no difference in the RPR between irrigation rates if the controls (5C0, 15C0, and 25C0 in Table 7.1) were excluded. There were some interactions between the three factors.

At the 5°C temperature, the LPR showed little change when effluent irrigation rate was increased from 0 mm/week to 20 mm/week, but it decreased significantly as the irrigation rate was increased from 20 mm/week to 40 mm/week (Figure 7.13a). There was little difference in LPR between irrigation rates in the trees with water irrigation. Under water irrigation, the BPR increased sharply as irrigation rate was increased from 0 mm/week to 20 mm/week, then there was little further change. Conversely, BPR increased sharply only as irrigation rate was increased from 30 mm/week to 40 mm/week. There was no significant difference in RPR.

At the 15°C temperature, the LPR was consistently lower in the trees irrigated with water than in the trees irrigated with effluent, but the BPR and RPR were higher (Figure 7.13b). The higher the irrigation rate, the greater the difference. A similar trend was found at the 25°C temperature, but the range was much smaller (Figure 7.13c).

Table 7.9 Leaf phosphorus ratio (LPR), branch phosphorus ratio (BPR) and root phosphorus ratio (RPR) in the trees (mg/mg) after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Tree part	Factor	Level					LSD$_{0.05}$
LPR	**Temperature (°C)**	**5**	**15**	**25**			
		0.46	0.47	0.52			0.03
	Irrigation type	**Water**	**Effluent**				
		0.44	0.53				0.02
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.37	0.56	0.53	0.51	0.45	0.04
	Interaction	**Significance**					
	Temperature$^{\&}$Type	***					
	Temperature$^{\&}$Rate	***					
	Type$^{\&}$Rate	***					
	Temperature$^{\&}$Type$^{\&}$Rate	***					
BPR	**Temperature (°C)**	**5**	**15**	**25**			
		0.30	0.29	0.27			0.02
	Irrigation type	**Water**	**Effluent**				
		0.29	0.24				0.02
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.38	0.22	0.25	0.27	0.31	0..3
	Interaction	**Significance**					
	Temperature$^{\&}$Type	**					
	Temperature$^{\&}$Rate	***					
	Type$^{\&}$Rate	*					
	Temperature$^{\&}$Type$^{\&}$Rate	***					
RPR	**Temperature (°C)**	**5**	**15**	**25**			
		0.24	0.24	0.21			0.02
	Irrigation type	**Water**	**Effluent**				
		0.26	0.19				0.02
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		0.25	0.22	0.22	0.22	0.24	0.03
	Interaction	**Significance**					
	Temperature$^{\&}$Type	**					
	Temperature$^{\&}$Rate	***					
	Type$^{\&}$Rate	**					
	Temperature$^{\&}$Type$^{\&}$Rate	ns					

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

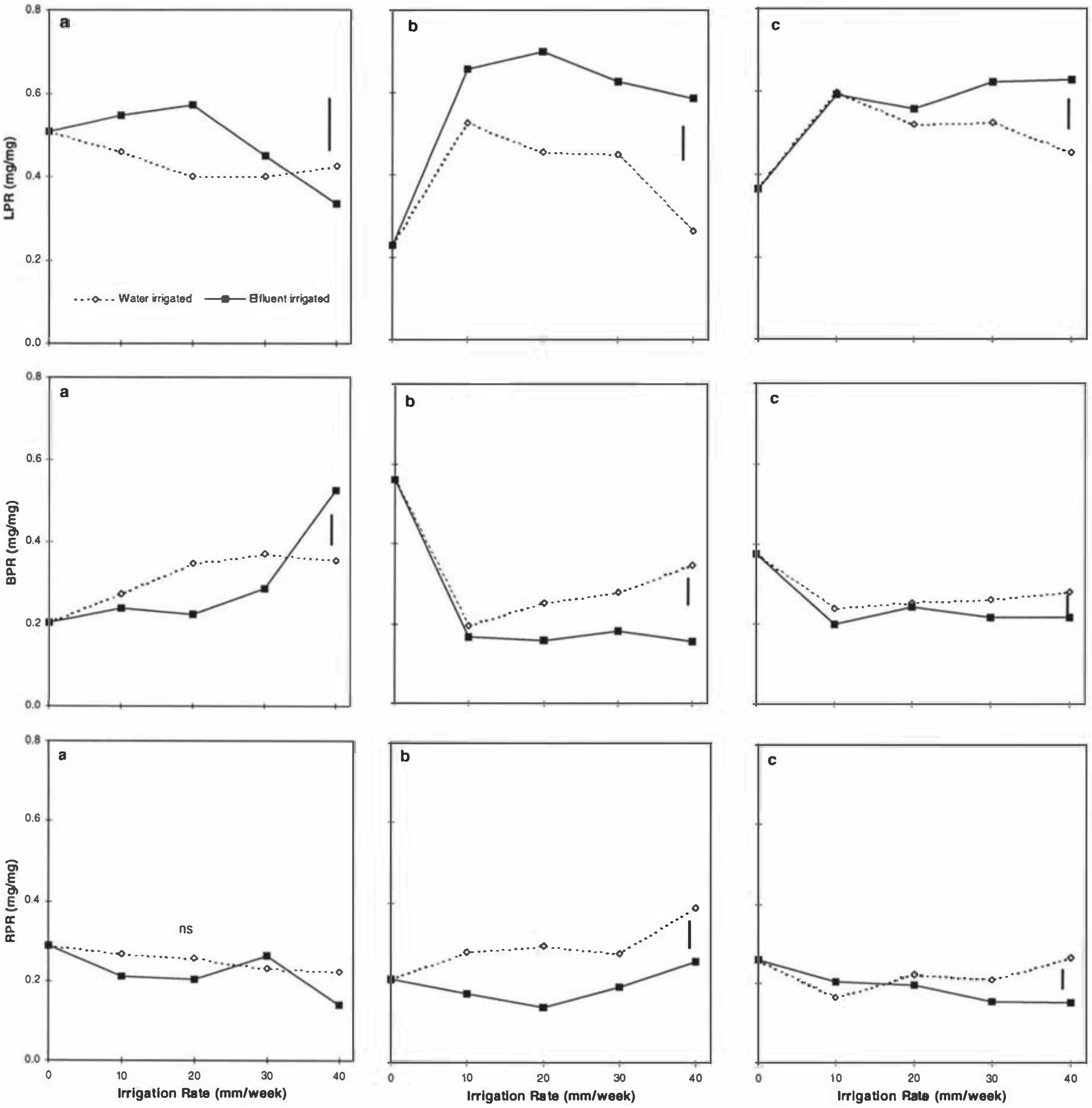

Figure 7.13 Phosphorus ratio between tree parts and the total under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (LPR = leaf phosphorus ratio; BPR = branch phosphorus ratio; RPR = root phosphorus ratio; n = 4; ns = not significant; Vertical bars indicate $LSD_{0.05}$).

Shoot:root dry weight ratio

After 13 weeks, all tested factors (temperature, irrigation type, and irrigation rate) significantly affected the shoot:root dry weight ratio (Table 7.10). The lowest ratio was found at 15°C temperature and the ratios were similar at the other two temperature regimes. The ratios were higher in the trees irrigated with effluent than in trees irrigated with water. There was no difference in the shoot:root ratio if the controls (5C0, 15C0, and 25C0 in Table 7.1) were excluded. All three factors interacted together significantly.

Table 7.10 Shoot:root dry weight ratios in the trees (g/g) after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Factor	Level					$LSD_{0.05}$
Temperature (°C)	**5**	**15**	**25**			
	5.3	4.2	5.8			0.6
Irrigation type	**Water**	**Effluent**				
	4.8	6.1				0.6
Irrigation rate(mm/week)	**0**	**10**	**20**	**30**	**40**	
	3.8	5.2	5.3	5.7	5.6	0.8

Interaction	**Significance**
Temperature&Type	ns
Temperature&Rate	ns
Type&Rate	ns
Temperature&Type&Rate	*

* and ns denote $P < 0.05$ and not significant.

There was no significant difference in the dry weight shoot:root ratio at 5°C temperature (Figure 7.14a), but at the 15°C temperature, the ratios were higher in the trees irrigated with effluent irrigation than in the trees irrigated with water (Figure 7.14b). At the 25°C temperature, the difference in the ratio between water and the effluent irrigation increased as irrigation rate was increased (Figure 7.14c). The higher the irrigation rate, the higher the ratio in the trees with effluent irrigation.

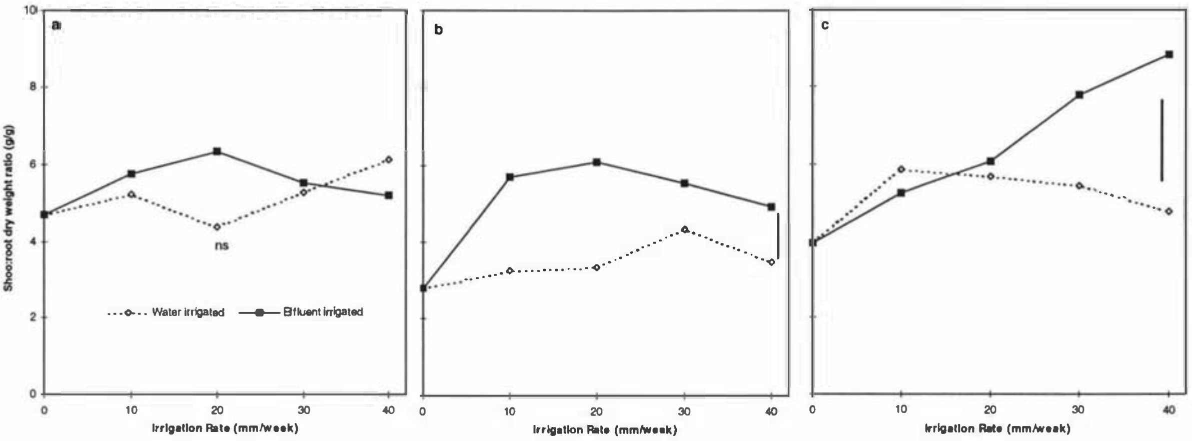

Figure 7.14 Tree shoot:root dry weight ratio under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; ns = not significant; Vertical bars indicate $LSD_{0.05}$).

7.3.2.6 Leaf area

After 13 weeks, all factors tested (temperature, irrigation type and irrigation rate) significantly affected the leaf area (Table 7.11). The order of leaf area found under the three temperature regimes was: 15°C > 25°C > 5°C. More than twice the leaf area was found in the trees irrigated with effluent than in trees irrigated with water. Leaf area increased as irrigation rate was increased. All interactions between the three factors were highly significant.

At the 5°C temperature, there was no difference in leaf area between all the trees except for those trees with the 20 mm/week effluent irrigation (5E20 in Table 7.1), which had about twice the leaf area than the others (Figure 7.15a). At 15°C temperature, the difference in leaf area between water and effluent irrigation increased as the irrigation rate was increased (Figure 7.15b). The greater the effluent irrigation rate, the more the leaf area. There was little change under the various water irrigation rates. A similar pattern was evident at the 25°C temperature (Figure 7.15c).

Table 7.11 Leaf area, leaf area ratio (LAR) and specific leaf area (SLA) on the trees after the 13 week period of treatments with various temperatures, irrigation types and irrigation rates.

Tree part	Factor	Level					$LSD_{0.05}$
Leaf area (cm^2)	**Temperature (°C)**	**5**	**15**	**25**			
		149	1018	784			100
	Irrigation type	**Water**	**Effluent**				
		465	1123				103
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		76	374	785	923	1095	130
	Interaction	**Significance**					
	Temperature&Type	***					
	Temperature&Rate	***					
	Type&Rate	***					
	Temperature&Type&Rate	***					
LAR (cm^2/g)	**Temperature (°C)**	**5**	**15**	**25**			
		40.0	37.4	46.4			4.3
	Irrigation type	**Water**	**Effluent**				
		39.0	51.6				4.0
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		25.1	46.2	47.2	45.8	42.0	5.5
	Interaction	**Significance**					
	Temperature&Type	ns					
	Temperature&Rate	***					
	Type&Rate	*					
	Temperature&Type&Rate	ns					
SLA (cm^2/g)	**Temperature (°C)**	**5**	**15**	**25**			
		91.9	78.0	93.6			6.9
	Irrigation type	**Water**	**Effluent**				
		83.8	101.1				6.6
	Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
		69.5	95.4	93.3	93.9	87.2	8.9
	Interaction	**Significance**					
	Temperature&Type	ns					
	Temperature&Rate	**					
	Type&Rate	*					
	Temperature&Type&Rate	ns					

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

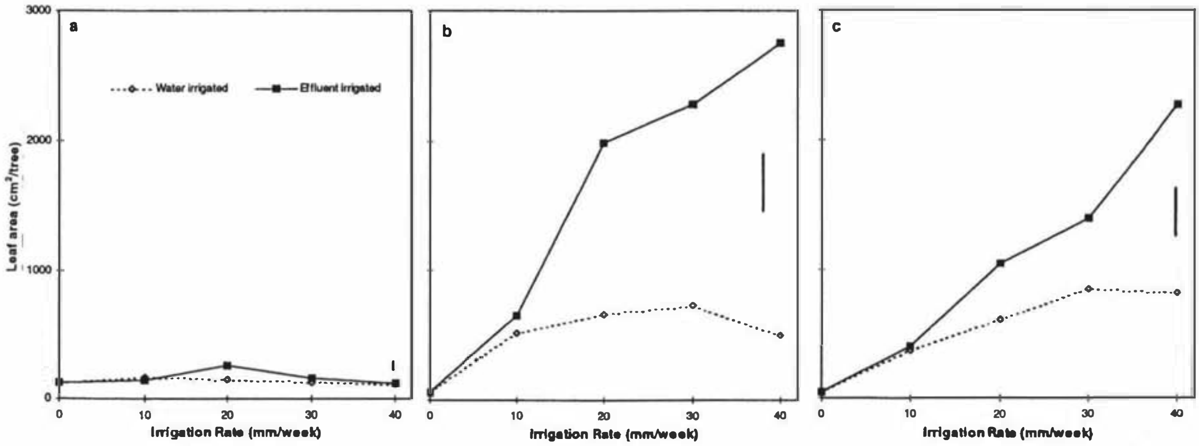

Figure 7.15 Leaf area on the trees under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 4; Vertical bars indicate $LSD_{0.05}$).

Leaf area ratio (LAR)

After 13 weeks, all factors tested (temperature, irrigation type and irrigation rate) significantly affected the LAR (Table 7.11). The LAR order under the three temperature regimes was: 25°C > 5°C ≈ 15°C. A higher LAR was found in trees irrigated with effluent than in trees irrigated with water. The average LAR was 45 cm^2/g in all irrigation rates except 25 cm^2/g for the controls at 5°C temperature (5C0 in Table 7.1). Some interactions were only caused by this difference between irrigation rates.

Specific leaf area (SLA)

After 13 weeks, all factors tested (temperature, irrigation type and irrigation rate) significantly affected the SLA (Table 7.11). The SLA order under the three temperature regimes was: 25°C ≈ 5°C > 15°C. Higher SLA was found in trees irrigated with effluent than in trees irrigated with water. The average SLA was 92 cm^2/g in all the irrigation rates except 70 cm^2/g for the controls at 5°C temperature (5C0 in Table 7.1). This resulted in some interactions.

7.3.3 Litter decomposition

After 13 weeks, overall the average dry weight loss from litter in the bags was only 8.4% (k = 0.36). However, all four factors tested (temperature, light condition, irrigation type, and irrigation rate) significantly influenced litter decomposition (Table 7.12). The instantaneous decay constants (*k*) for litter decomposition rates under the three temperature regimes are shown in Table 7.13. The higher the *k* value, the faster the litter decomposition.

The highest dry weight loss was found at the 15°C temperature and the lowest at the 25°C temperature. The dry weight loss from litter exposed to the light was twice that of the litter in the shaded litter bags. The dry weight loss from litter in the pots irrigated with effluent was greater than in the pots irrigated with tap water. The higher the irrigation rate, the more the litter dry weight loss. Some interactions were found between these factors.

Table 7.12 Litter dry weight loss (%) after the 13 week period of treatments with various temperatures, light conditions, irrigation types and irrigation rates.

Factor	Level					$LSD_{0.05}$
Temperature (°C)	**5**	**15**	**25**			
	8.4	10.7	6.0			1.4
Light condition	**Light**	**Shaded**				
	11.6	5.1				1.1
Irrigation type	**Water**	**Effluent**				
	8.7	11.4				1.1
Irrigation rate (mm/week)	**0**	**10**	**20**	**30**	**40**	
	1.6	5.0	8.0	13.1	14.1	1.8

Interaction	**Significance**
Temperature$^{\&}$Light	ns
Temperature$^{\&}$Type	*
Temperature$^{\&}$Rate	ns
Light$^{\&}$Type	**
Light$^{\&}$Rate	***
Type$^{\&}$Rate	ns
Temperature$^{\&}$Light$^{\&}$Type	ns
Temperature$^{\&}$Light$^{\&}$Rate	***
Temperature$^{\&}$Type$^{\&}$Rate	ns
Light$^{\&}$Type$^{\&}$Rate	ns
Temperature$^{\&}$Light$^{\&}$Type$^{\&}$Rate	ns

*, **, *** and ns denote $P < 0.05$, $P < 0.01$, $P < 0.001$ and not significant.

Table 7.13 Instantaneous decay constants (*k*) for the leaf litter decomposition after 13 weeks of treatments with various temperatures, light conditions, irrigation types and irrigation rates.

Temperature	Irrigation rate (mm/week)	Water Light	Water Shaded	Effluent Light	Effluent Shaded
5°C	0	0.07 ij	0.01 j	0.07 ij	0.01 j
	10	0.23 fghij	0.11 hij	0.44 def	0.13 ghij
	20	0.34 efg	0.12 hij	0.55 cd	0.27 fghi
	30	0.64 bcd	0.29 fgh	0.78 b	0.71 bc
	40	0.65 bc	0.22 fghij	1.08 a	0.54 cde
15°C	0	0.13 g	0.13 g	0.13 g	0.13 g
	10	0.23 fg	0.14 g	0.33 fg	0.27 fg
	20	0.43 efg	0.55 def	0.74 cde	0.14 g
	30	1.16 ab	0.30 fg	1.34 a	0.29 fg
	40	0.86 bcd	0.78 bcde	1.13 abc	0.40 efg
25°C	0	0.04 d	0.02 d	0.04 d	0.02 d
	10	0.25 cd	0.03 d	0.26 cd	0.09 d
	20	0.22 d	0.13 d	0.49 bc	0.15 d
	30	0.49 bc	0.22 d	0.63 b	0.18 d
	40	0.72 b	0.06 d	1.11 a	0.08 d

* Means with the same letter at the same temperature are not significantly different by Duncan grouping (n = 4, $P < 0.05$).

Temperature and irrigation type

The irrigation type interacted with temperature effect on litter decomposition (Table 7.12). Under water irrigation, the dry weight loss from the litter at 15°C temperature was greater than at 5°C and 25°C temperatures (Figure 7.16). Under effluent irrigation, the dry weight loss from the litter at 25°C temperature was less than at 5°C and 15°C temperatures. The dry weight loss from the litter with effluent irrigation was greater than with water irrigation, but this was significant only at the 5°C temperature.

Light condition and irrigation type

The light condition significantly interacted with irrigation type (Table 7.12). When litter was exposed to the light, the dry weight loss was greater from the litter with the effluent irrigation than from the litter with the water irrigation (Figure 7.17). However, there was little difference between water and effluent irrigation when the litter was shaded.

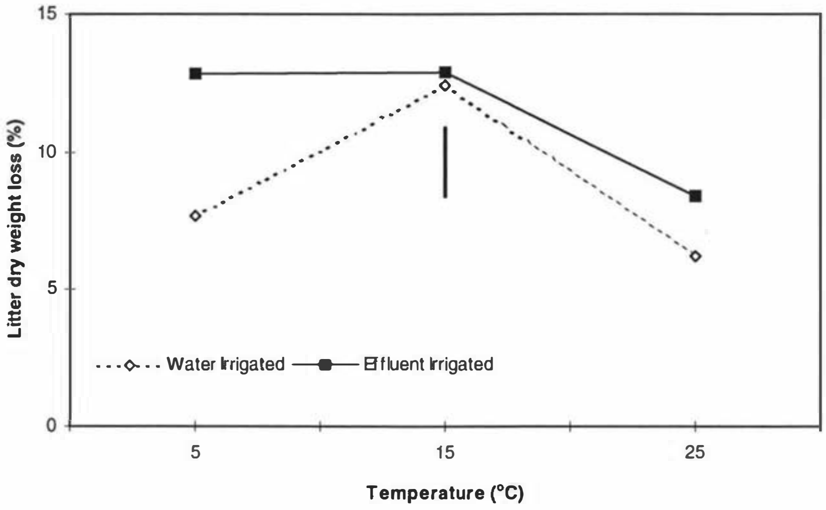

Figure 7.16 The effects of water and effluent irrigation on litter decomposition under the three temperature regimes (n = 32; Vertical bar indicates $LSD_{0.05}$).

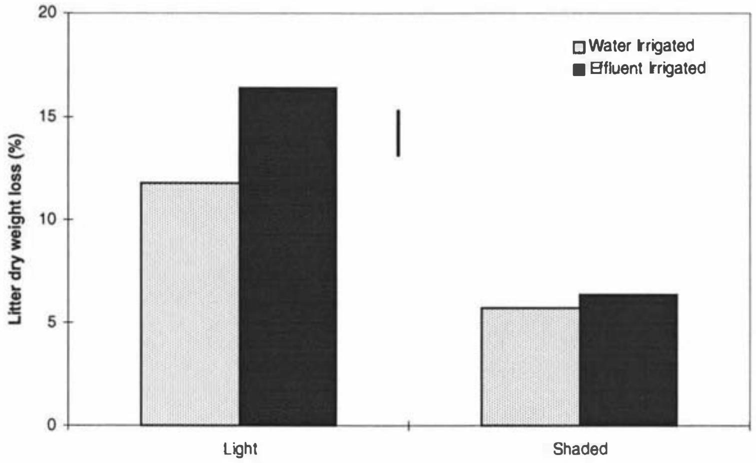

Figure 7.17 The effect of light on litter decomposition when irrigated with either water or effluent (n = 48; Vertical bar indicates $LSD_{0.05}$).

Temperature, light condition and irrigation rate

The light effect significantly interacted with temperature and irrigation rate (Table 7.12) though the dry weight loss from the litter exposed to the light was consistently higher than from the shaded litter (Figure 7.18). At the 5°C temperature, the higher the irrigation rate, the greater the loss of dry weight from the litter except when shaded as the irrigation rate was increased from 30 mm/week to 40 mm/week (Figure 7.18a). Similar trends were also found at 15°C temperature (Figure 7.18b). The higher the irrigation rate, the more the dry weight loss from the litter, but a non-significant reduction in dry weight loss occurred in the litter exposed to light when irrigation rate was increased from 30 mm/week to 40 mm/week. At the 25°C temperature, the weight loss increased with increasing irrigation rates only when the litter exposed to the light (Figure 7.18c). There was a small difference in the dry weight loss from the shaded litter between the irrigation rates.

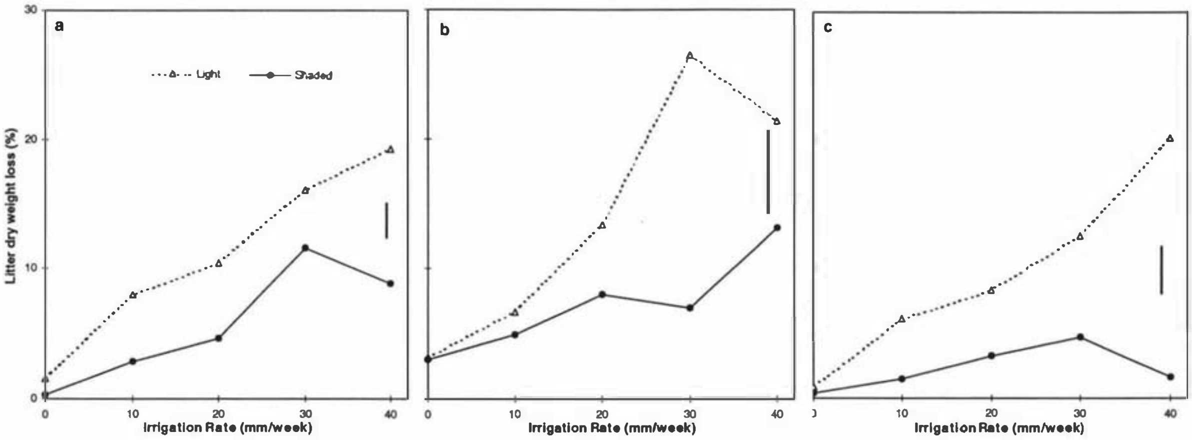

Figure 7.18 The light condition effects on litter decomposition under the three temperature regimes: (a) 5°C, (b) 15°C, and (c) 25°C (n = 8; Vertical bars indicate $LSD_{0.05}$).

7.4 DISCUSSION

7.4.1 Soil changes

Soil pH

Several studies have reported that effluent irrigation reduced soil pH (Waly et al. 1987; Russell et al. 1988; Falkiner & Smith 1997). Similar results were found in the current study although the litter decomposition may also have played some role in the pH reduction (sections 3.3.1.4 and 5.3.1.2). The current pot trial study demonstrated that effluent irrigation reduced the soil pH even in this short period of 13 weeks, but the reduction did not occur at the lowest temperature regime of 5°C (Figure 7.2, Table 7.4). Under the two higher temperature conditions, the higher the application rate, the greater the soil pH decreased. The soil pH increased as more tap water was applied. Hence, the contents of the effluent were responsible for the soil pH reduction. This supports the conclusion that the changes in the soils receiving effluent were attributed to the nutrient inputs rather than to the additional water loading (Schipper et al. 1996).

Waly et al. (1987) found that the pH value of the surface layer decreased gradually in soil treated with sewage water. They suggested this fall could be attributed to the production of CO_2 and organic acids by soil micro-organisms. The nutrients and organic matter in the effluent may enhance their activities.

At the lowest temperature of 5°C, the soil micro-organism activities may have been restricted. The increase of soil pH should be attributed to the higher pH of the effluent (6.8) than the original soil (5.17, see section 7.2.2). Tap water irrigation increased soil pH consistently at all three temperature regimes due to its higher pH (7.8).

In addition, the soil pH decreased as the temperature increased (Table 7.4). This provided evidence for the effects of temperature on soil pH and to the soil pH fluctuation between seasons (Vezina 1965; Wenzel et al. 1995). Hence, the seasonal soil pH change should depend on climate factors, especially the temperature, because they influence the micro-organism activities. The low pH found in the field (section 5.3.1.4) may be partly due to the summer timing of the soil sampling.

Soil nitrogen

The soil nitrogen concentration was 5.30 mg/g before the trial started (section 7.2.2), but was reduced to 5.19 mg/g under water irrigation (Table 7.4). This reduction may be caused by plant uptake, volatilisation or leaching from the soil in the pots. Volatilisation was more likely than leaching since the soil nitrogen concentration decreased to 5.03 mg/g in the controlled pots which received no irrigation. Effluent irrigation not only remedied the loss, but also increased the soil nitrogen concentration slightly. The different irrigation rates had little effect on the soil nitrogen concentration, which shows that the more nitrogen applied, the more its output either via plant uptake (see section 7.4.2) or by volatilisation.

Soil phosphorus

The soil phosphorus concentration was 1.00 mg/g before the experiment began. Both tap water and effluent irrigation increased soil phosphorus concentration although the concentration was higher with effluent (Table 7.4). The irrigation rate had no effect on the concentration. The concentration did not change at the lowest temperature regime, but increased in the other two temperature regimes. There was a tendency for higher phosphorus concentrations at the higher temperature. It is interesting that the phosphorus concentration was also reduced in the soil not receiving any irrigation.

Overall, there was little difference between soil nutrient concentrations under the various irrigation rates in this 13 week experiment, but there could be a greater difference if the experiment had lasted longer.

7.4.2 Tree growth and nutrient accumulation

Tree growth

The growth of *E. globulus* and *E. nitens* is limited by available water in most places they are planted (White et al. 1994), but the water is not the only factor to affect tree growth. In the current study, tree performance was highly affected by all three factors tested, temperature, irrigation type and irrigation rates (Tables 7.5 - 7.6). The differences between water and effluent irrigation were caused principally by the nutrients in the effluent. In other words, the nutrient demand to support tree growth varied under the three different temperature regimes (5°C, 15°C, and 25°C), which depicted the different seasons (winter, spring/autumn, and summer).

Tree growth was determined by tree stem diameter at ground level, and total dry weight biomass, which were closely related (Figure 7.8). At the lowest temperature regime of 5°C, tree growth had virtually no response to water or effluent irrigation regardless of application rate (Figures 7.3, 7.5). Therefore, the lower temperature was the limiting factor, which would also be the case in the field during winter time. This suggests that little or no effluent should be applied during winter time in a land treatment system if plant nutrient uptake is the main objective.

There was a significant difference in tree growth between water and effluent irrigation at the medium temperature regime (15°C) (Figures 7.3 - 7.4). Tree stem diameter increased as irrigation rate was increased, especially when effluent was irrigated. The stem diameter was highly correlated with the amount of effluent applied. Tree biomass showed little response to more water being applied, but was sensitive to effluent irrigation rates (Figures 7.5, 7.7). In addition, the pink colour of the young leaves on the trees irrigated with water may have indicated some nutrient deficiencies (Figure 7.5). Nutrient content of the effluent was responsible for this difference. Hence, tree growth was retarded by the soil nutrient availability as nutrient supply appeared as a major factor limiting tree growth with high water irrigation rates.

At the highest temperature regime (25°C), tree growth was significantly dependent on the irrigation rate, the more water or effluent supplied, the better the growth, especially in stem diameter (Figures 7.3 - 7.4). The difference between water and effluent irrigation was much less than for the medium temperature regime. Hence, water supply became the key limiting factor to tree growth because of the higher evapo-transpiration rates at the higher temperature and at a lower humidity (data not shown). Water availability, such as via irrigation, was essential for tree growth under the high temperature regime.

Nutrient consumption and nutrient recovery rate

For sustainable land use, soil nutrients consumed by plants need to be replaced in normal crop systems by fertilizing. However in land treatment systems, plant nutrient recovery rate is usually used to show how successful the plants are at removing nutrients.

Less nitrogen and phosphorus were accumulated in the trees irrigated with water than in the trees irrigated with effluent though there was little difference at the 5°C temperature (Figures 7.9 - 7.10). In the trees irrigated with water, tree nutrient consumption during the 13 weeks was the nutrient accumulation in the tree between tree planting and harvesting. Theoretically, this would be the amount to be replaced to balance soil nutrient status. Under higher water irrigation rates (above 20 mm/week), more nitrogen was consumed at the 25°C temperature than at the 15°C temperature (Figure 7.19). More phosphorus was consumed at the 15°C temperature than at the 25°C temperature. Less nitrogen and phosphorus were consumed at the 5°C temperature except for the controls (5C0 in Table 7.1).

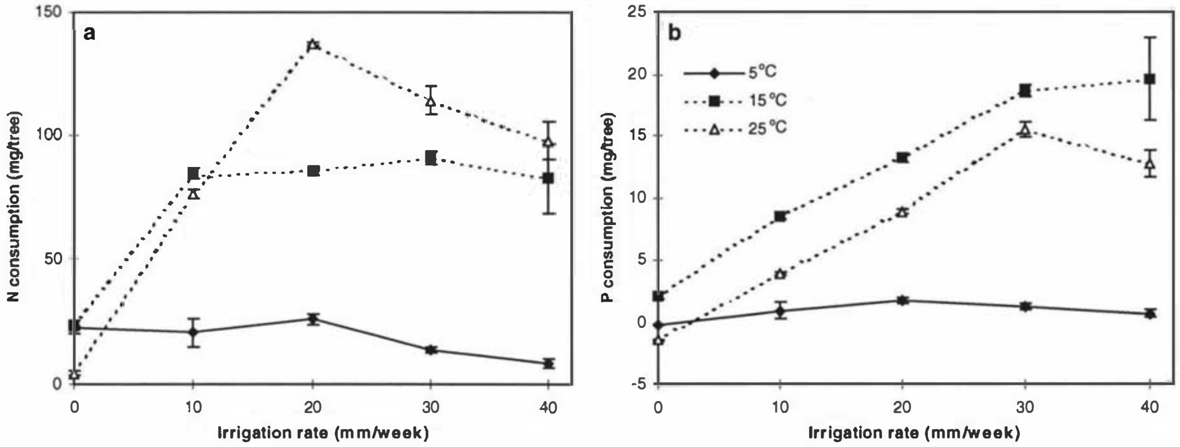

Figure 7.19 Tree nutrient consumption under water irrigation at the three temperatures during the 13 week period: (a) nitrogen, and (b) phosphorus (Vertical bars indicates s.e.m.).

The nutrient accumulation is a key index under effluent irrigation because it is the amount that can be removed by harvesting. However, nutrient recovery rate is the more important index for effluent land treatment to show how successfully the plant can recover the nutrients originating from the effluent. In this pot trial, the recovery rates of both nitrogen and phosphorus were calculated as following:

$$R\ (\%) = 100*(N_t - N_0)/N_e$$

where R is the nutrient recovery rate, N_0 is the initial nutrient accumulation in the seedlings, N_t is the nutrient accumulation in the seedlings when they were harvested, N_e is the nutrient added from the effluent irrigation.

Nutrient accumulation was highly dependent on the temperature and the effluent irrigation rate (Figures 7.9 - 7.10). The recovery rates were only closely correlated to temperature (Figure 7.20). Effluent irrigation rate, which gave various levels of nutrient input, had only a small effect on the recovery rates, especially for nitrogen. The most successful nutrient recovery occurred at the 15°C temperature. Least nutrients were recovered at the 5°C temperature. More nitrogen was recovered than phosphorus. Therefore, the ability to recover the nutrients which originate from the effluent is mainly dependent on temperature and hence season in the field. This also suggests that little or no effluent should be irrigated to the land treatment systems during winter if crop uptake is the key nutrient recovery mechanism since at this time the trees can play only a minor role in nutrient recovery.

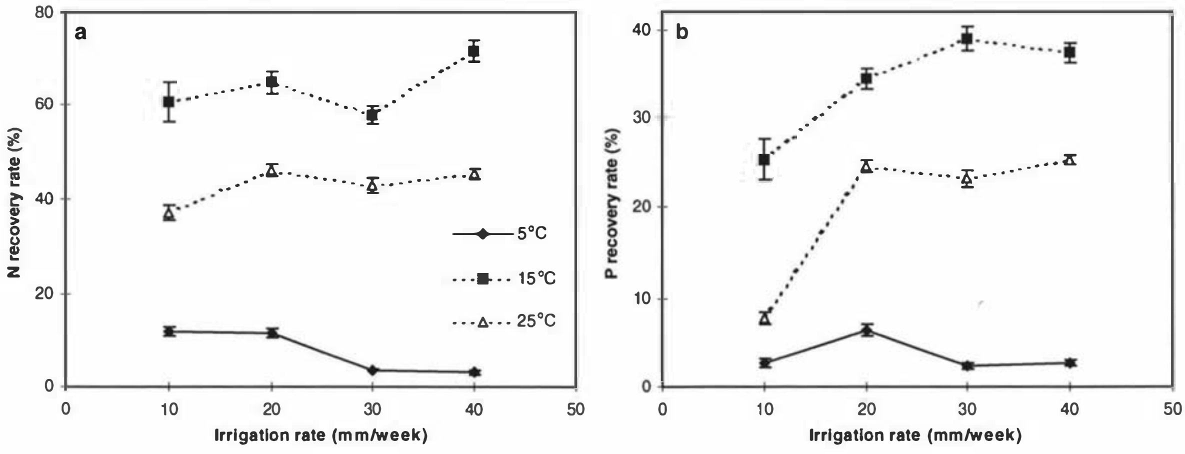

Figure 7.20 Tree nutrient recovery rate from effluent irrigation under the three temperature regimes: (a) nitrogen, and (b) phosphorus (Vertical bars indicate s.e.m.).

Biomass and nutrient distribution in the trees

Different physiological activities characterise the root and shoot development with respect to the life history of these structures of terrestrial plants. The root develops in the soil and thus becomes fully dependent on assimilates and energy produced by the shoot in the course of photosynthesis (Eshel & Waisel 1996). By contrast, the shoot growing in air and light is dependent on water and mineral nutrients taken up by the root from the soil. These activities ensure the weight and volume increments of both roots and shoots. The relationship of root and shoot growth can most simply be expressed by the dry weight root:shoot or shoot:root ratio (Jesko 1991). At certain limits, an equilibrium must exist between the functions of the root and those of the shoot. Therefore, the ratio of shoot and root is usually the index to compare plant growth equilibrium.

In the current study, higher shoot:root ratios were found in the trees irrigated with effluent than in the trees irrigated with water, except in the lowest temperature regime where there was no difference (Figure 7.14, Table 7.10).

Roots usually are not harvestable parts of trees. In this pot trial, less than 25% of the total biomass, nitrogen and phosphorus were accumulated in the root system after the 13 week period of growth (Figures 7.11 - 7.13, Tables 7.7 - 7.9). A greater root weight ratio (RWR) was found in the trees irrigated with water, especially at the 15°C temperature, when the trees produced most biomass. Without sufficient nutrient supply under the water irrigation, more roots may be developed to provide the required nutrient uptake. On the contrary, fewer roots were produced under effluent irrigation as sufficient nutrients were more readily supplied. Less biomass and less nutrient accumulation in these non-harvestable parts are preferable for biomass production in an effluent land treatment system, where as much nutrient removal as possible is required. However, fewer roots may cause tree windblow in the field, which should be considered when selecting a site for effluent land treatment.

Stems are usually the main tree parts to be harvested in forests. In this pot trial, there was no significant difference in branch weight ratio (BWR) between water and effluent irrigation, and between the irrigation rate except for the trees at 0 mm/week as control (Table 7.7). BWR was lower at the 5°C temperature than at the other two higher temperatures. The overall average BWR was 34.7%. With regards to nutrient contents in stem, the average branch nitrogen ratio (BNR) and branch phosphorus ratio (BPR) were even lower than the BWR, being 19.4% and 28.5%, respectively. Hence, only the stem should be harvested if minimum nutrient removal is desirable in forest management. On the contrary, the whole tree should be harvested to maximize nutrient removal in a land treatment system (also see section 5.3.5.1).

Leaves are harvestable tree parts, but they usually have a relatively shorter life than the other above ground tree components. Only a portion of the total foliage produced could be removed at harvest since leaf litter falls consistently throughout the whole life of most trees. In this pot trial, about 50% of biomass, 60% of nitrogen, and 50% of phosphorus were found in the leaves of the young tree (Figures 7.11 - 7.13, Tables 7.7 - 7.9). In addition, the main difference between shoot:root ratios was contributed by differences in leaf mass.

Pereira et al. (1989) indicated that improving the nutrient and water availability in the soil would enhance foliage growth which included larger leaves as well as more leaves per plants. Effluent irrigation not only enhanced foliage growth, but also significantly increased the leaf weight ratio (LWR), especially at the 15°C temperature (Figure 7.11). The first response to effluent irrigation was to produce more leaves. This resulted in more photosynthesis and hence in more total biomass production. However, the more leaves produced will result in more leaf litter fall in the future. This could explain the higher production of biomass, and higher litter fall in the plantation irrigated with effluent than without irrigation (section 5.3.4.1). As most nutrients are concentrated in the leaves, it is important to manage the leaves properly to maintain the nutrient balance to give sustainable land use.

Sufficient water and nutrient supplies significantly increased tree growth, and at same time sped up the nutrient cycling. Even though less leaf mass was found on the trees irrigated with effluent than on the trees without irrigation, the total leaf mass produced (litter leaves + living leaves) during a whole rotation of the plantation was greater (section 5.3.5.1). Sopper (1980) reported that municipal wastewater irrigation more than tripled the potential biomass production of poplar trees, more than doubled the foliar biomass, and the amounts of nutrients recycled in the wastewater irrigated plantations were three times faster than in the unirrigated plantations. In this pot trial, a similar trend (more biomass and more foliar biomass) was found in the trees irrigated with effluent. The potential for faster nutrient recycling might have existed if the experiment had lasted longer. Pereira & Chaves (1993) found that the growth of *E. globulus* was negatively correlated with the root:shoot ratio and specific leaf area (SLA) in their study on plant water deficits. There was no such relationship in this present study as the nutrient availability in the effluent played an important role (Figure 7.14, Tables 7.10 - 7.11).

In their study on water supply to young *E. globulus*, Borralho et al. (1989) reported that irrigation resulted in a 3.3-fold increase of biomass production and a 2.3-fold increase in leaf area index, the leaves in the irrigated plants having a greater surface area per unit of biomass (leaf area ratio -- LAR) than those of the non-irrigated plants. Pereira & Chaves (1993) concluded that a major reduction in leaf area took place in *E. globulus* grown with a limited water supply which resulted in less radiation being absorbed by the foliage. This was the major cause of reduced tree growth. White et al. (1994) found that the leaf area index was significantly increased by irrigation. In the current study water irrigation only resulted in a small increase of biomass and leaf area (Figures 7.5, 7.7, 7.15). The LAR and SLA also showed little difference between the various irrigation rates (Table 7.11). These results were evidently influenced by nutrient availability as effluent irrigation not only increased biomass production and leaf area, but also increased the LAR and SLA.

Overall, the nutrients in the effluent played a special role in enhancing tree growth and increasing the rate of nutrient cycling.

7.4.3 Litter decomposition

Litter decomposition can be controlled by internal factors (the physico-chemical properties of the substrate) and external or environmental factors under which decay takes place (Williams & Gray 1974; Gillon et al. 1994). In the current study, the litter bag experiment was designed to test the effects of four external factors (temperature, light condition, irrigation type, and irrigation rate) on *E. globulus* fresh leaf litter which was collected from trees irrigated with effluent. By using only one litter type, the effects of internal factors were excluded since it was assumed these would be constant for all treatments.

Consideration of environmental factors must include those which may be regarded as "external" to the decomposition process, e.g. moisture, temperature and humidity (Jensen 1974; Nagy & Macauley 1982; Woods & Raison 1983; Attiwill & Adams 1993). Effluent irrigation not only influenced the soil moisture, but also changed the nutrient balance. Light intensity may also have had some effects on microbe activities, which would affect the rate of litter decomposition.

In litter decomposition studies, the annual instantaneous decay constant (*k*) is widely used to compare litter decomposition rates between species or environments. A large range of the *k* values from 0.01 to 1.34 was determined in this pot trial study (Table 7.13) giving an average of

0.36. These were comparable with results from other studies on eucalypt litter decomposition in the field (Table 7.14). The highest value from the pot trial (k = 1.34, L15E30 in Table 7.2) was lower than for the same species litter (k = 1.81) in the field experiment (section 6.4.1).

Table 7.14 Instantaneous decay constants (k) for the eucalypt leaf litter decomposition in various field studies.

Species	k	Reference
E. botryoides	0.24 - 0.37	section 4.3.2.1
E. obliqua	0.39	Baker & Attiwill (1985)
E. dives	0.47	Woods & Raison (1983)
E. ovata	0.52	section 6.4.1
E. pauciflora	0.53	Woods & Raison (1983)
E. diversicolor	0.54	O'Connell (1987)
E. obliqua	0.59	Baker & Attiwill (1985)
E. delegatensis	0.68	Woods & Raison (1983)
E. brookerana	0.76 - 0.94	section 4.3.2.1
E. botryoides	0.80	section 6.4.1
E. globulus	1.81	section 6.4.1

Temperature significantly influenced litter decomposition with the lowest rate of decomposition found under the highest temperature (Tables 7.12 - 7.13). Gunadi et al. (1998) reported that variations in water content appeared to affect decomposition more than temperature in pine litter decomposition. However, the temperature was more or less stable in their study. Factors that retard decomposition include low temperatures and lack of atmospheric moisture (Miller 1989). Thus, the low humidity (data not shown) in the highest temperature regime of the current study could have resulted in the low decomposition rate. The lower dry weight loss from litter in the field during summer time (section 4.3.2.1) may also be attributed to the higher temperature and lower humidity for that season.

In general, litter tissues decay under abiotic conditions of high temperature and high moisture (Bloomfield et al. 1993). In the current study, the irrigation rate also had a significant influence on the litter decomposition (Figure 7.18, Tables 7.12 - 7.13). The higher the irrigation rate, the faster the litter dry weight loss. However, usually the effect of either temperature or moisture is not constant and they interact in a more complicated way (Gunadi et al. 1998).

Irrigation with effluent significantly increased the rate of loss of organic matter and nutrients from *Pinus radiata* needle litter (Baker et al. 1990). Similarly, effluent irrigation increased the litter decomposition in this pot trial, which was attributed to the nutrient contents in the effluent. The key difference was mainly found at the 5°C temperature (Figure 7.16). The nutrient contents in the effluent possibly enhanced microbe activity in the litter layer to consume litter even at the low temperature regime. This may also be the case in the field during winter time.

More dry weight loss was found from the bagged litter exposed to light than from the shaded litter (Figure 7.18). Effluent irrigation hardly influenced litter decomposition under shaded conditions, but did when exposed to light (Figure 7.17). Nutrients in the effluent could only enhance microbe activity to consume more litter under light conditions. A similar situation may occur on the forest floor before full canopy closure, such as under one year old trees or after harvesting a coppice crop rotation. This also partly explains the reasons for more litter accumulation under 6 year old *E. botryoides* stands irrigated with effluent (section 3.3.3) and the slow litter decomposition under 3 year old *E. globulus* stands when irrigated with effluent (section 6.3.1).

Prescott (1996) reported that the apparent differences in soil fauna activities on the forest floor may influence litter decomposition rate. Soil fauna activities were not monitored in the current study, but it was likely that the effects of effluent irrigation and light condition would increase these activities. Further work is required to confirm whether or not this is indeed the case from the results of this pot trial.

In summary, from the results of this pot trial, litter decomposition can be accelerated while the litter is on the forest floor at moderate temperatures around 15°C and in non shaded conditions particularly if receiving irrigation and especially effluent irrigation.

7.5 CONCLUSIONS

Effluent irrigation influenced soil properties. It reduced the soil pH, and increased soil nutrient concentrations. At the same time, it enhanced tree biomass production, increased nutrient cycling via more leaf mass resulting in more litter fall, and gave faster litter decomposition. However, the temperature and irrigation rates significantly influenced the effects of effluent irrigation. How successful nutrients originating from the effluent were recovered by the trees was highly dependent on the temperature, but not on the increase in effluent irrigation rate. All these factors should be considered when managing forest systems linked with effluent land treatment systems.

In the litter decomposition process, temperature, water or effluent irrigation, irrigation rate and light condition had significant effects on the litter decomposition. In addition, they interacted with each other. More dry weight loss was found from the bagged litter under light conditions than under shaded conditions. Effluent irrigation hardly influenced litter decomposition under shaded conditions, but did under light conditions. Differences between water and effluent irrigation occurred mainly at the lowest temperature (5°C). The higher the irrigation rate applied, the faster the litter dry weight loss.

8. GENERAL DISCUSSION AND CONCLUSION

8.1 INTRODUCTION

Short rotation forests have good potential as a renewable energy source. In New Zealand, eucalypts are particularly good candidate species to be used due to their rapid growth. Several species have shown excellent growth characteristics in the study area, with *Eucalyptus globulus* being one of the more outstanding.

In a land treatment system, effluent irrigation increases the soil nutrient levels and soil moisture, hence enhancing the crop production. Effluent irrigation also changes the nutrient concentrations and ash content of the crop, whether pasture or forest, and may influence the quality of the end products. Such changes are possibly less important in short rotation forests as the products from the system are out of the human food chain.

Short rotation forests can be linked with effluent land treatment systems and function as purification plants (vegetation filter stands), while at the same time producing biomass for energy conversion. This system has good potential because sufficient water and nutrients can increase tree growth to give high biomass production. The fast growing young trees quickly consume water and take up nutrients, so high levels of nutrient removal from the site can be obtained by frequently harvesting the young trees. These can then be coppiced or replanted. Hence, there exist the potential for environmental benefits (less air pollution from biomass compared with fossil fuels and reduced water pollution from effluent disposal) and economic benefits (combined wastewater treatment and fuel biomass production).

Litter fall plays a special role in the overall forest system for it transfers energy and nutrients from above-ground components of forest to the soil surface (Bray & Gorham 1964). The litter accumulated on the soil surface intercepts incident light and rain on the soil surface, and changes the soil surface structure, affecting the transfer of heat and water (and probably gases) between the soil and the atmosphere (Facelli & Pickett 1991).

The management of short rotation forests should be based on the knowledge of nutrient cycling to give sustainable renewable energy biomass production and land use system. The management decisions depend on the main objective of growing the plantations.

The overall objective of the current study was to identify the key role of nutrient cycling within a short rotation forest linked with effluent land treatment system in order that management decisions can be made to obtain maximum economic benefit with minimum environmental impact.

8.2 NUTRIENT CYCLING IN SHORT ROTATION FORESTS

Soil response

Tree planting into pasture increased organic matter and nutrient levels of the top soil, and reduced the infiltration rate (sections 3.3.1 and 5.3.1). Effluent irrigation further increased the organic matter and nutrient levels, but had little effect on infiltration rate. Gilmour et al. (1977) concluded that a side effect of the application of sewage effluents to soil was the production of acid from the nitrification reactions. This varies case by case (section 5.4.1). Even though the soil pH in the current study was reduced down to 3.8 in some treatments following effluent irrigation, eucalypt trees still grew much better than trees without irrigation. This demonstrated that planting selected species of eucalypts in effluent land treatment systems can be a good choice.

Tree nutrient uptake

Short rotation forests take up a large amount of nutrients due to their fast growth. Ericsson (1994) found that the annual nitrogen uptake in managed eucalypt stands was between 26 and 130 kg/ha/y. In the current study, the total above biomass production in the first three year rotation was from 36.1 to 89.8 OD t/ha and the total nitrogen uptake over the 3 year period ranged between 265.5 and 859.0 kg/ha (section 5.4.2.2). This gave a mean annual nutrient net uptake ranging from 88.5 to 286.3 kg/ha/y over the 3 year period, and the current annual nutrient uptake at the end of the three year rotation was 104.4 to 479.6 kg/ha. Nutrient supply and water from the effluent increased biomass production and nutrient uptake significantly. It also showed the potential nutrient demand of the fast growing young eucalypt trees in the short rotation forests. Following effluent irrigation, nutrient recovery rate by the trees depended on the ambient temperature rather than the amount of nutrient input from the effluent (section 7.4.2).

Nutrient return via litter fall

As trees grow, some components (mainly leaf in short rotation forests) of the biomass produced are shed from the trees as litter. In the current study, this process starts reasonably soon after tree planting, being less than one year. Over the 3 year period, 10% to 20% of the total above ground biomass produced fell from the trees as litter (section 5.4.4). Annual litter fall increased with age and reached up to 13.4 OD t/ha/y by year 3. About 8 - 24% of the total nitrogen uptake was returned to soil surface via the litter fall in the three years giving an annual nitrogen return up to 140 kg/ha/y. Similar nutrient returns in natural or plantation forests were also reported in other studies (Table 4.1). Therefore, nutrient return via litter fall is one of the main characteristics of forests. Effluent irrigation in the current study increased the biomass production, the total leaf biomass (including living and litter leaves), and also increased nutrient cycling. There were some special relationships between nutrient uptake and nutrient return (section 5.3.5.2).

Being evergreen trees, eucalypts return nutrients via litter fall all year around, but with a peak in the summer (Penfold & Willis 1961; Bray & Gorham 1964; Ashton 1975; Attiwill et al. 1978; Baker 1983; Frederick et al. 1985b; Toky & Singh 1993; Lisanework & Michelsen 1994; Hart 1995; Specht 1996). This was confirmed by the current study (sections 4.3.1.4 and 5.3.4.3). Effluent irrigation had little effect on this trend.

Nutrient accumulation in the litter layer

The build-up of litter is rapid: 17.0 OD t/ha in a 4 year old stand and 21.6 OD t/ha in an 8 year old stands of *E. tereticornis* (Toky & Singh 1993). The predicted equilibrium mass of the forest floor (annual litterfall balanced against decomposition rate) is approximately 40 OD t/ha (O'Connell & Grove 1996). The litter accumulation in the forest floor under *E. regnans* forests was 44 and 47.5 OD t/ha (Feller 1978; Feller 1980). In the current study, the litter accumulation on the forest floor under 6 year old *E. botryoides* was 14.7 OD t/ha in the stand without irrigation and 38.8 OD t/ha in the stands irrigated with effluent (section 3.3.3).

The litter layer can store relatively large amount of nutrients, e.g. 233 kg N/ha and 22 kg P/ha under the *E. botryoides* plantation without irrigation, but 969 kg N/ha and 95 kg P/ha under the plantation irrigated with effluent (Table 3.4). Therefore, the litter layer on the soil surface acts as a nutrient pool in the system. If it is collected and removed from the site, a significant nutrient output from the system can be achieved, which is particularly important in the land treatment system before harvesting.

Nutrient release via litter decomposition

In general, litter tissues under abiotic conditions of high temperature and high moisture, and having substrate quality of low carbon, low lignin and high nitrogen, tend to decay rapidly (Bloomfield et al. 1993). In the current study, litter decomposition and subsequent nutrient release were significantly influenced by both internal factors (i.e. species, source of the litter), and external factors (i.e. tree density, effluent application and plantation age) (sections 4.3.2 and 6.3).

In the litter decomposition process, temperature, irrigation with water or effluent, the irrigation rate and light penetration all had significant effects on the rate of litter decomposition. In addition, they interacted with each other (section 7.3.3). More dry weight loss was found from the bagged litter exposed to light than the shaded litter. Effluent irrigation hardly influenced litter decomposition under shaded conditions, but did so where the litter was exposed to light. The difference between water and effluent irrigation was mainly at the lowest temperature (5°C). The higher the irrigation rate applied, the faster the litter dry weight loss.

8.3 MANAGING SHORT ROTATION FORESTS

According to the objective of growing a short rotation forest and nutrient cycling, the nutrient balance in the system can be controlled through well designed and implemented management. This will help make this land use more sustainable (Figure 8.1).

A sustainable short rotation forest is likely if the following guidelines are followed:

i) A well-designed system, involving selection of suitable species and rotation length; appropriate soil type and climate; adequate area to supply biomass for energy conversion, and to treat the expected volume of liquid or solid waste.

ii) Successful crop management including time of harvest, fertilization, irrigation (water or effluent), tree components to be removed from the site, biomass yield optimisation, a market for the biomass harvested, and control of nutrient removal from the site.

iii) Positive soil changes (physical, chemical and biological) to give sustainable land use and future productivity, no matter how many crop rotations in the short or long term.

iv) Negligible environmental pollution, including avoidance of nutrient runoff and leaching to groundwater.

v) A program to monitor the system to ensure correct management in order to avoid soil degradation, and environment pollution whilst optimising crop production.

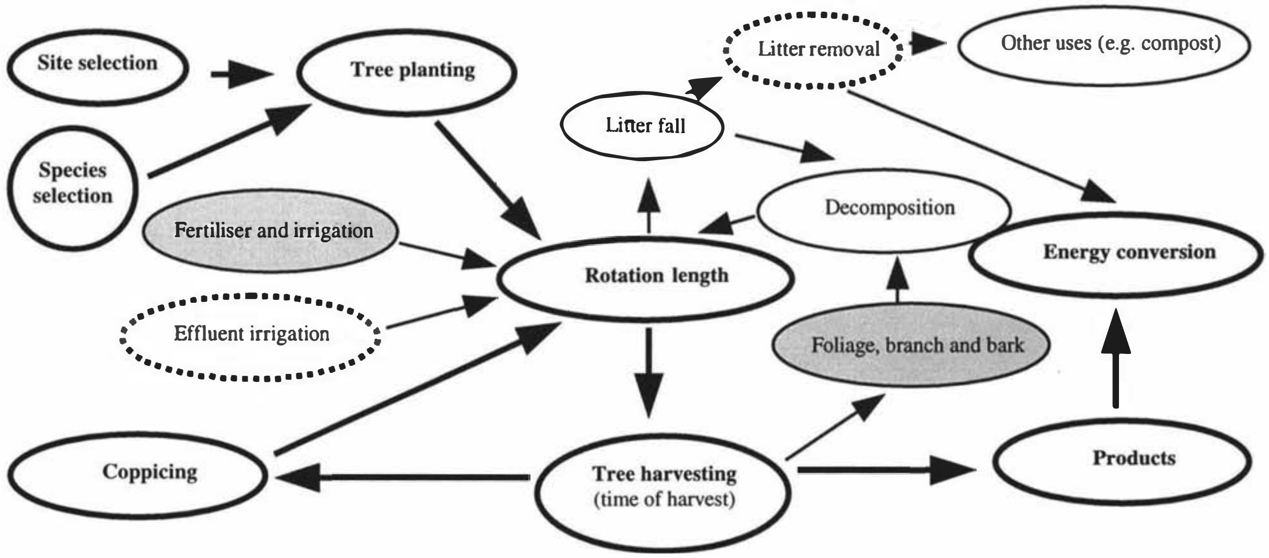

Figure 8.1 Decision chart for managing short rotation forests

▨ not linking with effluent land treatment. ◌ linking with effluent land treatment.

8.3.1 Species

If short rotation forests are grown primarily for energy biomass production, the species, variety, family and clone giving the fastest growth and **highest** nutrient use efficiency should be selected. Thus, less nutrients will need to be added from commercial fertilizer. When short rotation forests are grown in a land treatment system and designed to strip nutrients, the species, variety, family and clone with the fastest growth, but **lowest** nutrient use efficiency should be selected, which is a new challenge to tree breeders.

Many highly productive tree species can be used in short rotation forests for biomass production, e.g. *Populus*, *Salix*, *Robinia*, *Acacia*, and *Eucalyptus*. For effluent land treatment systems, deciduous trees with a dormant period each year and N-fixation trees with extra nitrogen input are less suitable. Coppicing is recommended in most short rotation forests though replanting is an acceptable alternative. Eucalypt species are often preferred in suitable climates because of their fast early growth, coppicing ability and high wood density leading to high levels of MJ/ha/y.

A significant goal of on-going tree improvement is to identify clones with high nutrient-use efficiency (White et al. 1996). For the special purpose of effluent land treatment, fast water consumption and nutrient uptake, and less nutrient-use efficiency in the harvested biomass should be added into the species selection criteria. In the current study, *E. globulus* showed the best performance over *E. botryoides* and *E. ovata*, either with or without effluent irrigation (section 5.3.2).

8.3.2 Rotation length

Usually, the crop rotation length is determined by the interaction of mean annual increment and current annual increment (Figure 8.2).

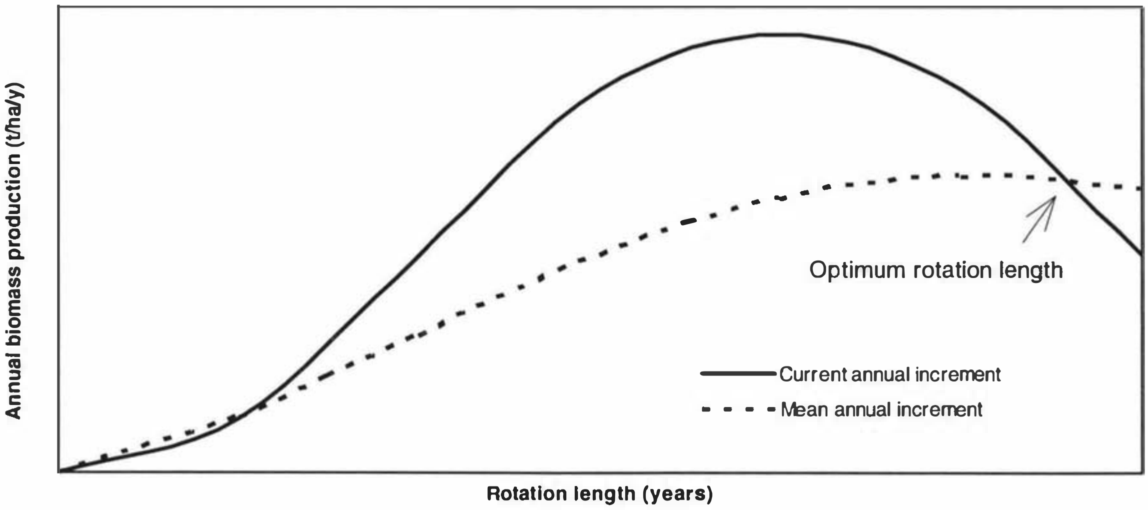

Figure 8.2 Yield pattern for determining optimum rotation length.

Similar thinking is useful for correctly managing the nutrient balance of plantation forests. Annual total nutrient uptake is a key factor. However, net nutrient uptake is more important as some part of the total uptake will be returned via litter fall.

According to the nutrient flow in plantation forests, four stages can be identified (Figure 8.3):

i) Stage I -- establishment period: one way nutrient flow (uptake); no nutrient return, or perhaps a little via litter fall towards the end of this stage.

ii) Stage II -- peak nutrient demand period: nutrient uptake is dominant; at the same time there is significant return via litter fall, but which is much less than the uptake.

iii) Stage III -- self-sufficient period: two way (uptake and return) flows occur simultaneously though the return is still less than uptake.

iv) Stage IV -- over-mature period: nutrient return is dominant though some uptake still occurs.

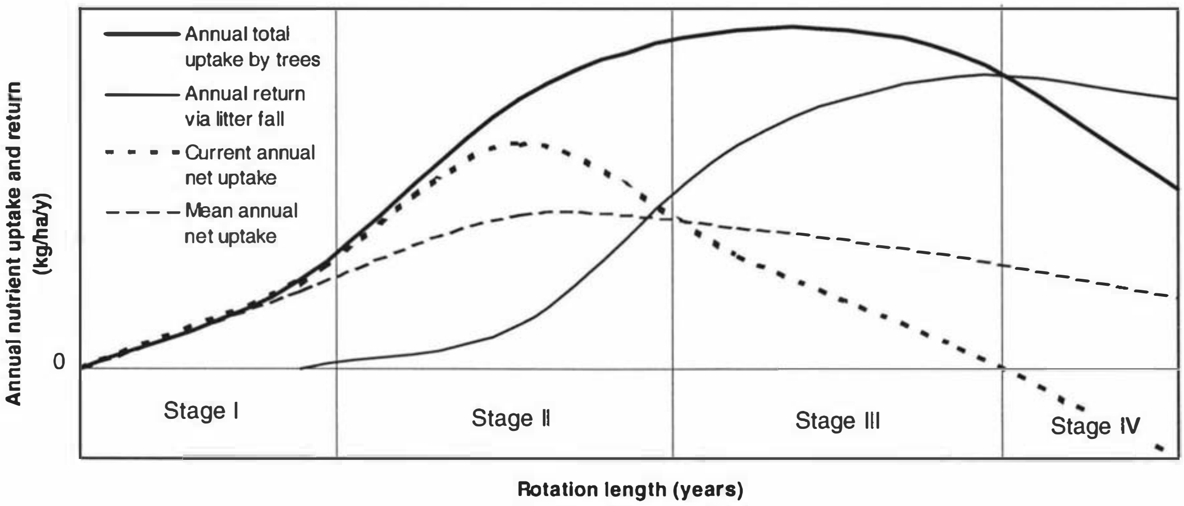

Figure 8.3 Nutrient uptake pattern for determining optimum rotation length in a plantation forest: Stage I -- establishing period, Stage II -- peak nutrient demand period, Stage III -- self-sufficient period, and Stage IV -- over-mature period.

O'Connell & Grave (1996) found that the annual rate of accumulation of nutrients in the above-ground components of vegetation in *E. diversicolor* forest decreased as the forest aged. Kreutzer (1990) indicated that the yearly uptake of nitrogen by forest stands ranged between

30 and 90 kg/ha/y. About 10% was stored up in the growing biomass, the rest returned to the soil mainly by litter fall. These cases most likely occur in Stage III. The annual uptake may be equal to the annual return in a mature forest or even lower than the return in an over-mature forest (Stage IV). Plantation forests should be harvested before the end of Stage III as the annual production rate should decline at that time. The end of Stage III may be correlated with the optimum rotation length based on yield. Over mature natural and plantation forests should occur in the Stage IV.

In short rotation forests not linked with effluent land treatment, the optimum rotation length should be up to Stage III. Any harvesting before Stage III would be inefficient from a nutrient status view. Fertilization would normally be recommended during Stage I, and even Stage II.

In short rotation forests linked with effluent land treatment, less effluent should be irrigated during Stage I since the trees do not fully occupy the site and play a limited role in nutrient recovery. Trees start to play a full role at the end of Stage I. Stage II is the period when trees efficiently recover nutrients from effluent in a land treatment system. The trees should be harvested at the end of that stage as after that their nutrient recovery ability declines. Alternatively, less or no effluent should be irrigated to the trees at this stage. However, effluent irrigation can be prolonged to Stage III or even Stage IV if the nutrient containing litter is to be collected and removed from the site.

How long each stage lasts depends on the tree planting density and tree growth rate. The higher the density and the faster the tree growth, the shorter the stages last, especially the first two stages. Coppiced stands may reach these stages even quicker due to the multi-stem characteristics. Evergreen conifer trees, such as *P. radiata*, would normally have longer Stages I and II than eucalypts because of their leaf and growth rate characteristics.

8.3.3 Harvesting parts

Which tree parts are to be harvested and removed from the site should be determined according to the end use for the biomass and the requirements of sustainable land use. To minimize nutrient removal from the site, leaves, branches and even bark should be kept on the site. By contrast, to strip maximum nutrients, all tree parts, even including the litter accumulated on the forest floor, should be removed from the site.

If short rotation forests are grown for energy biomass production without effluent irrigation, only the tree components with high nutrient use efficiency (e.g. the wood) should be removed from the site. Foliage especially should be kept on the site for it is the largest component of nutrient storage in trees (Bargali et al. 1992b, section 5.3.2.3). The nutrient "cost" of energy can be defined as the amount of nutrient removed in the crop per unit of energy harvested. Leaving foliage in the eucalypt forest would decrease the nutrient costs by about 10% for calcium and almost 50% for nitrogen (Madgwick et al. 1981). Thus, less nutrient loss would need to be remedied through application of commercial fertilizer.

For greater nutrient removal from short rotation forests grown to strip nutrients in a land treatment system, all the above ground tree parts, especially the leaves (including both living and litter leaves) should be harvested and removed from the site. Therefore, how to successfully convert the whole biomass, not just the stem wood, into energy should be considered since all tree parts contribute a significant portion of the harvestable biomass (section 5.3.2).

8.3.4 Time of harvest

Nutrients are more concentrated in the foliage than in the other tree parts. Leaves usually have the shortest life of tree parts in the above ground biomass. Therefore, the harvesting time and season of the year will significantly influence the quantity of nutrient removal from the site.

Deciduous trees can be harvested either in the dormant period for less nutrient removal or in the growing season before litter fall in the autumn to give greater nutrient removal.

Harvesting evergreen trees at any season will inevitably include living leaves and result in a substantial nutrient removal. The leaf litter contributes a major part of the total nutrient return. For eucalypts, litter fall occurs all year around but there is a summer peak (sections 4.3.1.4 and 5.4.4). Hence, the time of harvest is important to control the amount of nutrient removal from the site. As nutrient removal is one of the main objectives of an effluent land treatment system, all above ground biomass of eucalypt trees should be harvested before the peak leaf fall. If grown without effluent irrigation, the trees should be harvested after summer to minimise depletion of nutrients from the site.

8.3.5 Litter decomposition

As litter fall returns a large amount of nutrients to the soil surface under the plantation forests (sections 4.3.1 and 5.3.4), it is important to manage the litter to obtain nutrient balance in the systems. Litter decomposition and nutrient release could be successfully controlled through correct species selection, irrigation management and silvicultural regime (fertilizer, thinning and harvesting).

Briones & Ineson (1996) suggested that mixtures of eucalypt litter with other species litter (e.g. *Fraxinus excelsior*) could be one mechanism by which the high productivity rates of eucalypt plantations could be maintained. Manipulation of the leaf litter mixtures could then make an important contribution to synchronising nutrient release to plant uptake. Species with fast leaf litter decomposition rate, such as *E. globulus* as identified in the current study, should be selected in short rotation energy forests. Other species may be introduced for longer rotations, at least as some understorey species to maintain nutrient cycling. In land treatment systems, a species with slow leaf litter decomposition rate, such as *E. ovata* as shown in the current study, should be selected if the litter is also collected to maximize nutrient removal. Depending on the main purpose for growing a short rotation forest, the species should be selected partly by the content of the cellulose or lignin in the fallen leaf as this controls the decomposition rates (section 6.3.4).

If the plantation is to be managed to remove nutrients in an effluent land treatment system, the litter accumulated on the forest floor should be removed from the site since the layer accumulates a large amount of nutrients (section 3.3.3). Nutrients stored in this layer could be released in a short period after some major environmental change, for instance, tree harvesting. Soon after summer would be the best time to remove the litter from a site.

Effluent irrigation increased the litter decomposition rate until canopy closure occurred (section 6.3.1). Once a fully closed canopy was formed, effluent irrigation retarded the litter decomposition rates. Light penetration played a key role in that and interacted with temperature, irrigation type, and irrigation rate (section 7.3.3). The resulting increased accumulation of litter is good for collection and nutrient removal. Litter can accumulate nitrogen and phosphorus during its initial decomposition (section 6.3.2), which could be important for nutrient removal.

Overall, effluent application can significantly increase biomass production in short rotation forests. When harvested the biomass removed from the site will contain nutrients which originated from the effluent. Therefore, the concept of short rotation energy forests linked with effluent disposal has good potential as both a sustainable and renewable energy source and a sustainable effluent treatment system to protect the environment if designed and managed rationally and based on a good knowledge of nutrient cycling in the system.

Key factors to provide the most suitable system design and management include species selection (which affects nutrient uptake, biomass production, and nutrient release via litter decomposition), tree planting density, irrigation with water or effluent, fertilization, rotation length, time of harvest, and litter management.

Decomposition and nutrient cycling in terrestrial ecosystems involve complex and long-term processes which cannot be quantified by short-term studies. The results from the current study, however, provide a basis for comparing nutrient cycling processes in different short rotation forest systems, especially when linked with the land treatment of meatworks effluent. The operation at the ecosystem level of organization can now be better described than was possible before the work began.

Further studies are suggested for more successful management of short rotation forest:

i) Litter accumulation on the soil surface is a special phenomenon in a forest ecosystem. It may play a greater role than providing energy and nutrients to soil fauna and micro-organisms in the system, particularly with effluent land treatment. The litter provides sufficient organic carbon, and irrigation with effluent reduces the soil oxygen level intermittently. Nitrates can be formed by nitrification from other nitrogen forms. Hence, denitrification in a forest land treatment system should be evaluated.

ii) A significant goal of on-going tree improvement efforts is to identify the species, families or clones with high nutrient-use efficiency. However, species, families or clones giving high biomass production but low nutrient-use efficiency should be sought for land treatment purposes.

iii) Litter accumulated on the soil surface and non-wood components contribute significant portion of the total biomass produced in short rotation forests. How to convert them to useful energy in adequately designed combustion or gasification equipment needs to be evaluated.

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