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# Closing the nutrient budget for a eucalyptus fertilization experiment in southern China

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# Foreword

This master thesis comprises 30 ECTS credits and is part of the Swedish forestry program at the Swedish University of Agricultural Sciences. The thesis has been carried out at the department of Southern Swedish Forest Research Centre, Alnarp. The fertilization experiment is a collaboration between the department of Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences and the Research and Development department at Stora Enso Guangxi.

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Abstract

An increasing demand for wood products in China has resulted in large areas invested in fast-growing tree plantations of eucalyptus. Eucalyptus plantations are often associated with an intensive management including fertilization. By understanding the effects of fertilization and where in the ecosystem nutrients are accumulated a more sustainable forest management could be achieved. In this study, a nutrient budget including all biomass and soil components was created for *Eucalyptus urophylla*. The examined nutrients were nitrogen, phosphorus and potassium. The nutrient budget was created for a control and a fertilized treatment which had been fertilized with; 830 kg $ha^{-1}$ nitrogen, 408 kg $ha^{-1}$ phosphorus and 736 kg $ha^{-1}$ potassium as NPK fertilizer during six consecutive years. Results showed that fertilization had contributed to a 20% significantly larger tree biomass. The results also indicated a higher nutrient content in the fertilized treatment than in the control. Depending on nutrient and treatment, the nutrients in understory vegetation accounted for 11-17 % of the total amount of nutrients in the biomass. The main part of the nutrients in the eucalypt ecosystem was found in the mineral soil (85-97%). Over time nutrients decreased in the soil and instead accumulated in the biomass. Furthermore, the results indicated that significant amounts of nitrogen and potassium in the fertilized treatment had leached out. Phosphorus had instead accumulated in the soil. The results also indicated more organic matter and available nutrients in the soil probably due to higher amounts of nutrients and biomass in the fertilized treatment. More organic matter and available nutrients in the soil could lead to improved soil conditions with higher water holding capacity and increased nutrient retention. Fertilization could therefore have a long-term positive effect on the soil leading to a higher productivity.

Keywords: Eucalyptus, fertilization, nutrient content, China, understory vegetation, biomass

# Sammanfattning

Ett ökat behov av träråvara i Kina har lett till att stora arealer avsatts för plantager med snabbväxande eukalyptus. Plantageskogsbruk med eukalyptus är ofta förknippat med en intensiv skötsel med bland annat gödsling. Genom en ökad förståelse för gödslingens effekter och var näringsämnena ackumuleras skulle ett mer hållbart skogsbruk kunna uppnås. I denna studie skapades en näringsbudget för alla biomassa- och markkomponenter i ett gödslingsförsök med *Eucalyptus urophylla*. De inkluderade näringsämnena var kväve, fosfor och kalium. Näringsbudgeten skapades för en kontroll och en gödslad behandling där den gödslade behandlingen hade mottagit; 830 kg $ha^{-1}$ kväve, 408 kg $ha^{-1}$, fosfor och 736 kg $ha^{-1}$ kalium i form av NPK-gödsel under en sexårsperiod. Resultaten visade att gödslingen hade bidragit till en 20% signifikant större mängd trädbiomassa. Dessutom indikerade resultaten att den gödslade behandlingen hade ett högre näringsinnehåll jämfört med kontrollen. Beroende på näringsämne och behandling stod näringsämnena i undervegetationen för 11-17% av den totala mängden näringsämnen i biomassan. Huvuddelen av näringsämnena i eukalyptus-ekosystemet återfanns i mineraljorden, (85-97%). Resultaten indikerade på att mängden näringsämnena i marken sedan försökets start hade minskat och istället ackumulerats i biomassan. Vidare indikerade resultaten att signifikanta mängder kväve och kalium i den gödslade behandlingen hade lakats ut. Fosfor hade istället ackumulerats i marken. Resultaten indikerade även på en ökning av mängden organiskt material och växttillgängliga näringsämnen i marken, antagligen till följd av mer näringsämnen och biomassa i den gödslade behandlingen. En ökad mängd organiskt material och växttillgängliga näringsämnen skulle kunna leda till förbättrade markförhållanden med högre vattenhållande förmåga och ökad näringshållande kapacitet. Gödsling skulle därmed kunna ha en långsiktigt positiv effekt på marken vilket skulle kunna leda till en högre produktivitet.

Nyckelord: Eukalyptus, gödsling, näringsinnehåll, Kina, undervegetation, biomassa

# 摘要

中国日益增长的木材产品需求，促成了对速生桉树人工林的大面积投入；而桉树人工林经营往往采用集约的形式，其中包括施肥措施。因此，实现桉树人工林的可持续经营需要对施肥的效果及养分在生态系统中的积累进行深入了解。本文在尾叶桉施肥试验上对所有生物量和土壤成分组成的养分（氮、磷、钾）收支状况进行研究。该养分收支是通过施肥试验的一个对照处理和一个施肥处理（六年里每公顷总共施入830Kg氮，408Kg磷和736Kg钾）进行估计的。在施肥处理中，施肥使木材生物量显著提高了20%。另外，在施肥处理的养分含量比对照处理的较高。林下植被占生物量总养分的11-17%，取决于养分和处理。桉树生态系统里绝大部分的养分（85-97%）都在矿质土壤。随时间的推移养分在土壤里减少，但积累到生物量里。而且，结果表明来自施肥处理的大量的氮和钾被淋洗到此系统之外，而磷已积累到土壤里。在施肥处理中，由于更多的养分进入循环和更多的生物量，试验还显示了在土壤中有更多的有机物和有效养分存在。这增加了持水量和营养利用从而改善土壤状况。因此，施肥措施将通过提高林地生产力而对生态系统带来长期而积极的影响。

关键字：桉树，施肥，养分含量，林下植被，生物量

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# 1. Introduction

## 1.1 Planted forest and fast-growing tree plantations

The worldwide demand for wood products is steadily increasing as an effect of growing populations and better living conditions (Turnbull, 2007). At the same time, wood supplies from natural forest and the area of available land for forest plantations are steadily decreasing (Cossalter & Pye-Smith, 2003; Mackensen & Fölster, 2000). Plantations with fast-growing tree species may reduce this problem by using less land to produce a higher yield on a shorter period than many semi-natural forests (Cossalter & Pye-Smith, 2003). In recent decades there has been a large increase in the area of planted forest, including fast-growing tree plantations, in many parts of the world (FAO, 2009; Evans, 1992). In total, planted forest covers over 264 million hectares (estimated in 2010) with an annual increase of 5 million hectares (FAO, 2010). Of the total planted forest area FAO (2010) estimates that 76% have wood production as their main purpose.

Fast-growing tree plantations are one of the most intensive forms of plantation forestry and has been defined by Cossalter & Pye-Smith (2003) as plantations which are; "intensively managed for commercial plantation, set in blocks of a single species, which produce industrial round wood at high growth rates (mean annual increment of no less than 15 $m^3$ $ha^{-1}$ $year^{-1}$) and which are harvested in less than 20-years". However, many plantations are grown as fast-growing plantations without reaching the limit for mean annual increment. In China for example, estimations show that the mean annual increment for plantations ranges from 9 to 18 $m^3$ $ha^{-1}$ $year^{-1}$ for eucalyptus species (Turnbull, 2007). Even though there are many advantages with fast-growing tree plantations, short-rotation periods often associated with whole-tree harvesting results in large removals of biomass and nutrients (Guo et al., 2002). On nutrient poor and degraded soils this may lead to nutrient depletion and in the long-term decreased stand productivity (Turnbull, 2007; UNDP, 2006; Guo et al., 2002). This has raised several concerns regarding the sustainability of fast-growing plantations (Guo et al., 2002; Mackensen & Fölster, 2000). Mackensen & Fölster (2000) concluded that most plantations in the tropics suffer significant nutrient losses due to removal of biomass at harvest and through site management. The authors suggested that management dependent nutrient losses had to be reduced through a more sustainable forest management.

The majority of tree species used in fast-growing plantations are exotic species (FAO, 2009; Zobel, 1988). Exotic species are used to replace or supplement native ones which for some reasons do not fulfill the demands or when the local forests have been destroyed (Zobel, 1988). By carefully matching species to site and by avoiding native pests and diseases the result is often a higher yield in quantity and/or quality. Although there are several thousand of tree species in the world only around thirty are extensively used in plantation forests (FAO, 2009; Zobel, 1988). The limited number of species have resulted in considerable knowledge and understanding about the productivity and requirements for the specific species (Zobel, 1988). The most commonly used exotic tree species can be found in the genus; *Acacia, Eucalyptus, Pinus* and *Populus* (FAO, 2009).

## 1.2 Eucalyptus plantations

*Eucalyptus* is a widespread genus with over 700 species mostly native to Australia (Coppen, 2002). It is the most represented genus in tropical plantation forests and have been widely used in the last thirty to forty years (Laclau et al., 2005; Cossalter & Pye-Smith, 2003). Eucalypts have a wide range of end uses from energy (fuel and charcoal) to raw material for pulp production and sawn wood (White, 1993). Many favorable properties such as high production capacity, high adaptability to a wide range of sites and easy management, including straight stems and limited amount of branches, have resulted in the high use in plantation forestry. Extensive development programs such as selected species and tree breeding programs, modern nursery techniques and efficient plantation management have also led to an increased productivity of the species (Turnbull, 2007; White, 1993). Despite the large number of species, only a few are used in commercial production (White, 1993). According to Eldridge et al. (1993) the five most important eucalyptus species in terms of current annual increment of wood are; *E. grandis*, *E. camaldulensis*, *E. tereticornis*, *E. globulus* and *E. urophylla*.

## 1.3 Eucalyptus in China

China is one of the largest growing economies with an increasing demand for wood products (Turnbull et al., 2007; UNDP, 2006). As a result, China has invested in large areas for fast-growing tree plantations, mainly for pulp-wood and to some extent sawn timber production (Turnbull et al., 2007). Eucalypts have been planted in China for over 100 years and have a higher productivity than most native species. In 2007 there were about 1.5 million hectares of eucalyptus plantations in China with the majority in the southern parts. Eucalyptus plantations are therefore a significant part of the rural landscape in southern China affecting the ecosystem in many ways.

## 1.4 Fertilization of eucalyptus

Much of the eucalyptus in southern China is planted on old scrub- or grassland where the human impact for centuries have affected the soils negatively through activities such as clearing and fuel gathering (Turnbull, 2007). Consequently the soils, which are mostly acidic and highly weathered, are often low in organic matter with depletion of many nutrients resulting in low nutrient availability and unfavorable soil conditions (Xu et al., 2002; UDPN, 2006). Even though the potential productivity of eucalyptus plantations is high in the tropical and subtropical regions it is often not achieved without fertilizer (Qui et al., 2011; Smethurst et al., 2003). Hence, nutrient fertilization is a common practice in most commercial eucalyptus plantations in southern China (Bai & Gan, 1996). Several studies have shown the positive effect on tree growth with fertilizer (Andersson, 2007; Graciano et al., 2006; Xu et al., 2002). Phosphorus is the most limiting nutrient to biomass production for the majority of the soils in southern China (Xu et al., 2002). This can be explained by the highly weathered soils where the main part of the phosphorus is bound in unavailable forms for plants (Brady & Weil, 2007). Most of the phosphorus available for plant is therefore often associated with residues of organic matter. After phosphorus, nitrogen is the most commonly limiting nutrient in these soils (Xu et al., 2002). Nitrogen is mainly associated with the quality and amount of litter and like phosphorus the land use history has a large influence on the availability (Gundersen et al., 2006).

Since the fertilization often is a minor input of the total nutrient demand of the tree, timing of the fertilizer can influence the stand growth considerably (Cromer & Williams, 1982). The demand for nutrients, especially nitrogen and phosphorus is highest in the early ages of the stand and decreases with age (Groove & Malajczuk, 1985). In the beginning of the rotation period nutrient demanding parts of the tree such as; foliage, young branches and fine roots needs large amounts of nutrients. When the canopy later closes, nutrient demand decreases with heartwood development.

## 1.5 Understory vegetation

Understory vegetation is an important part of the forest ecosystem (Turner, 1975) since it constitutes a significant part of the total biomass, especially in early stages of the rotation period (Carneiro et al., 2009; Fabião et al., 2002). By accumulating large amounts of nutrients, understory vegetation play a significant role in the conservation and cycling of nutrients. Carneiro et al. (2009) could in an 11 month year old *E. grandis* stand determine that the nutrient accumulation in the understory vegetation was at the same magnitude or even higher than in the trees. Understory vegetation may affect the tree productivity negatively, especially in the beginning of the rotation period, by competing for resources such as water, nutrients and light (Carneiro et al., 2009; Turner, 1975). However, as the understory vegetation biomass turns into litter it provides the soil with increased amounts of nutrients and organic matter (Qui et al., 2011; Carneiro et al., 2009, Turner, 1975). The understory vegetation therefore has an important role in conserving nutrients in the system when trees are young and have a minor nutrient uptake. As the stand increase in age most studies have shown that the amount of understory vegetation generally decreases (Fabião et al., 2002; Cromer & Williams, 1982). This is often explained by a closed tree canopy resulting in less light reaching the ground floor and higher competition from the trees (Michelsen et al., 1996).

Fertilization affects the understory vegetation in various ways depending on the age of the stand (Turner, 1975). In young stands it will mainly result in increased biomass (Smethurst et al., 2003, Turner, 1975). In older stands where the trees have a closed canopy with a high shading effect the impact on understory vegetation will depend on how the trees respond to the fertilizer. If the trees respond with increased foliar biomass leading to increased shading effect on the ground, the amount of understory vegetation biomass will most likely decrease (VanderSchaaf et al., 2010; Turner, 1975).

The understory vegetation has many other positive effects on the forest ecosystem. By continuously contributing with organic matter it improves the aggregation of the soil which in turn increases the water holding capacity (Groove & Malajczuk, 1985). By improving the soil conditions a long-term effect may result in a higher productivity which can lead to less need of fertilization (Fabião et al., 2002).

## 1.6 Objectives and research questions

Eucalyptus plantations are often associated with a highly intensive management including short-rotation periods often with fertilization, whole tree harvesting, scarification and heavy machinery during forest operations (Fabião et al., 2002; Guo et al., 2002). By understanding the effects and quantities of nutrients in a forest stand a more sustainable forest management could be achieved. Depending on how management is performed nutrients may cycle differently in the system which will affect the productivity. By understanding the whole or at least part of the nutrient budget in a stand, decisions can be made towards a more long-term sustainable management. Several studies have addressed the importance of studying complete nutrient budgets and how they may be affected by changes in soil fertility (Laclau et al., 2005; Groove & Malajczuk, 1985).

In this study, I will set up a nutrient budget for all biomass and soil components in a previously established fertilization experiment with eucalyptus. I will investigate if there are any differences to where nutrients have been accumulated in a fertilized and a non-fertilized treatment. I will also investigate how the understory vegetation is affected by fertilization in terms of biomass- and nutrient accumulation and if there are any differences between different fertilization regimes. To find answer to this, four questions were formulated:

1) Are there any differences in the amount (t $ha^{-1}$) of understory vegetation biomass between three fertilization treatments?

2) Which component of the biomass (tree and understory vegetation) contains the highest amount (kg $ha^{-1}$) of nitrogen, phosphorus and potassium?

3) How much of the nutrients in the soil are available for the trees and understory vegetation?

4) How much of the added fertilizer has been accumulated in the biomass?

# 2. Material and Methods

## 2.1 Study area

The study was performed in southern People's Republic of China, 90 kilometers northeast of the town Beihai, in Baisha. The area is part of Guangxi Zuang autonomous region (fig. 1) and is characterized by a very mountainous and karst landscape (UNDP, 2006). The southern parts, however, provide a more flat and undulating landscape. Forests are originally tropical forest in valleys and seasonal dry rainforest on slopes below 500 meters. However, much of the formerly forested land has during the last century been converted to different forms of agriculture land and scrubland.

Fig. 1. Map over People´s Republic of China with Guangxi Zuang autonomous region highlighted (Wikimedia Commons, 2005).

The area has a semi hot tropical/subtropical monsoon climate (UNDP, 2006). The mean annual temperature is 23 °C with hot humid summers and cooler dryer winters (FAO, 1987). At the experiment site the average annual rainfall exceeds 2000 mm per year (FAO, 1987) with the main part falling during the summer rain period from May to September (Xu et al., 2002).

The soil type at the experiment site is ferric acrisol with a sandy texture of reddish color (FAO-Unesco, 1978). Andersson (2007) determined the soil properties at the experiment site (table 1) showing the relatively low pH values which are characteristic for the soil type (FAO-Unesco, 1978).

Table 1. Soil properties recorded at the start of the experiment in 2006 (Andersson, 2007). The experiment is divided in two compartments, plot 1-30 and 31-41 (see map fig. 2). Soil properties recorded; pH, organic material (g $kg^{-1}$), total amount (g $kg^{-1}$) of N, P and K and available amount (mg $kg^{-1}$) of N, P and K on two depths 0-20 cm and 20-40 cm.

| Plot | pH | Organic matter (g $kg^{-1}$) | Total amount of nutrient (g $kg^{-1}$) | | | Available nutrients (mg $kg^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|
| 1-30 | | | N | P | K | N | P | K |
| 0-20 cm | 4.8 | 13.57 | 0.50 | 0.13 | 1.32 | 39.87 | 0.81 | 12.33 |
| 20-40 cm | 4.95 | 11.84 | 0.46 | 0.12 | 0.69 | 31.85 | 0.52 | 14.24 |
| 31-41 | | | | | | | | |
| 0-20 cm | 4.73 | 14.21 | 0.58 | 0.13 | 0.81 | 32.85 | 1.02 | 16.69 |
| 20-40 cm | 4.88 | 10.71 | 0.44 | 0.12 | 1.36 | 31.52 | 0.91 | 8.06 |

## 2.2 Trial establishment and treatments

The study was conducted in a fertilization experiment established in year 2005. Soil preparation was done with a bulldozer in January preparing rows 0.5 meter deep and 0.6 meter wide with the distance of four meters between the rows (Andersson, 2007). In February the entire experiment site was base fertilized with 187.5 kg ha$^{-1}$ CMP-fertilizer with 18% phosphorus ($P_2O_5$) and 125 kg ha$^{-1}$ NPK-fertilizer with 16% nitrogen (N), 3.6% phosphorus ($P_2O_5$) and 12% potassium ($K_2O$) (table 2). Plantation was performed with 1250 seedlings per hectare of two different *Eucalyptus urophylla x grandis* clones, DH 32-29 and GL-GU9 with the spacing; 2 x 4 meter. In July the site was treated with a herbicide treatment using Round-up and in August there was a second fertilization adding 375 kg ha$^{-1}$ NPK-fertilizer with the same proportions as earlier.

In the beginning of March 2006, 12 months after planting, plots where laid out and fertilization treatments were decided (Andersson, 2007). The experiment was divided into four blocks to take initial differences into account. In each block treatments were randomly assigned to plots with a size of 32 x 32 meter. Measurements were done in an inner plot consisting of four rows with ten trees in each, covering an area of 300 m$^2$ to exclude edge effects from neighboring plots. A total of seven treatments with different amounts of fertilizer and one control treatment were established (fig. 2).

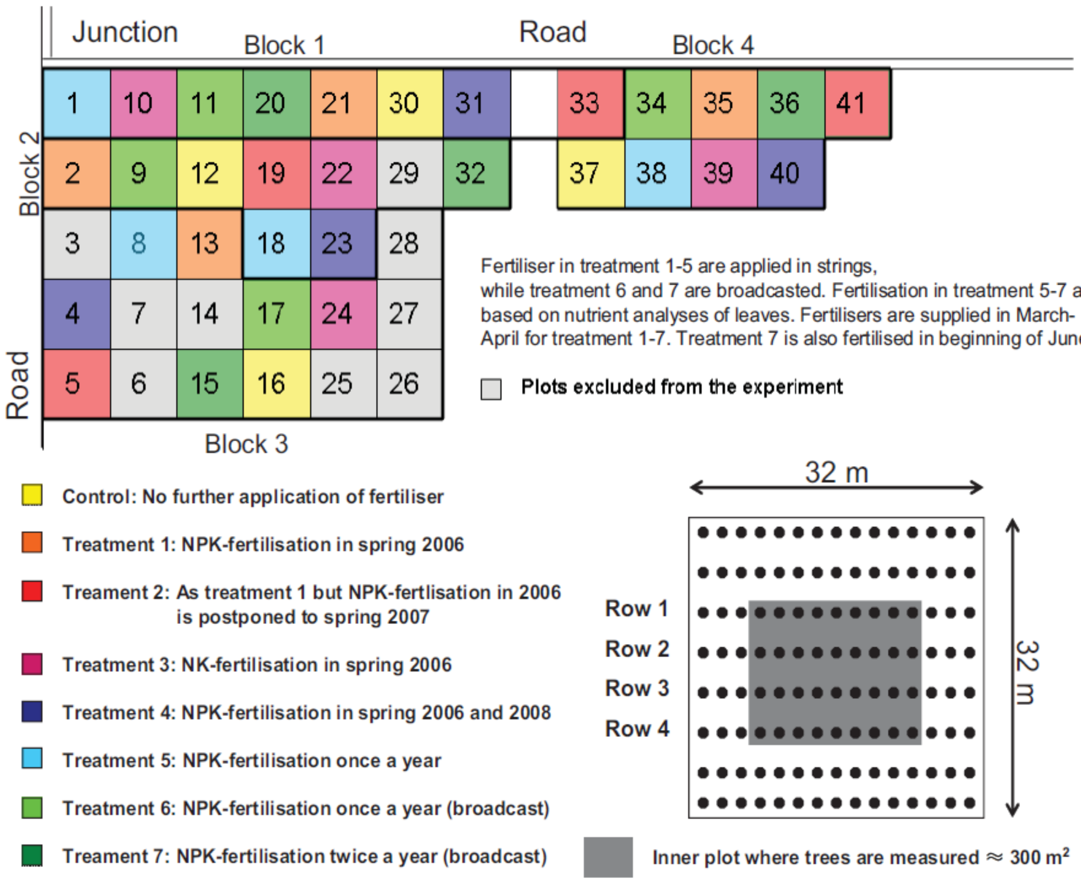


Fig. 2. Map over the fertilization experiment in Baisha from Andersson (2007). In the present study, measurements were done in plot; 16, 30, 37 for control treatment, 4, 23, 31 for moderately fertilized treatment (4) and 1, 18, 38 for intensively fertilized treatment (5).

Three of the treatments were used in the present study, a control, a moderately fertilized and an intensively fertilized treatment (table 2). The control treatment had received no fertilization after the experiment start (Timander, 2011). The moderately fertilized treatment, *NPK-100-2* had been fertilized twice, first in year 2007 with; 625 kg $ha^{-1}$ NPK (16%, 3.6%, 12%) consisting of 100 kg $ha^{-1}$ N, 22.5 kg $ha^{-1}$ P and 75 kg $ha^{-1}$ K. The second fertilization had been done one year later with the same amount as the previous year but with changed proportions of the NPK fertilization (16%, 6%, 16%) consisting of 100 kg $ha^{-1}$ N, 37.5 kg $ha^{-1}$ P and 100 kg $ha^{-1}$ K. Fertilizer had been applied in strings meaning that it was buried between every tree (Andersson, 2007). The intensively fertilized treatment *NPK 150-S* had been fertilized every year until 2010 with 938 kg $ha^{-1}$ NPK (16%, 3.6%, 12%). In 2008, an extra amount of 120 kg $ha^{-1}$ P was added. The proportions of NPK-fertilization was also changed for the last three years to the proportions 16% N, 6% P, 16% K and 0.3% boron, still as NPK 938 kg $ha^{-1}$. Changes in proportions of phosphorus and potassium were made due to insufficient levels of phosphorus in the first used fertilizer. See table 2 for detailed description of fertilization scheme and total amounts of nutrients.

Table 2. Total amount of nutrients (kg $ha^{-1}$) fertilized for the three treatments from Timander (2011).

| Year | Control | | | Moderately fertilized *NPK-100-2* | | | Intensively fertilized *NPK-150-S* | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | N | P | K |
| 2005, March | 20 | 38 | 15 | 20 | 38 | 15 | 20 | 38 | 15 |
| 2005, August | 60 | 14 | 45 | 60 | 14 | 45 | 60 | 14 | 45 |
| 2006 | | | | | | | 150 | 34 | 113 |
| 2007 | | | | 100 | 22,5 | 75 | 150 | 34 | 113 |
| 2008 | | | | 100 | 37.5 | 100 | 150 | 176 | 150 |
| 2009 | | | | | | | 150 | 56 | 150 |
| 2010 | | | | | | | 150 | 56 | 150 |
| Total | 80 | 52 | 60 | 280 | 112 | 235 | 830 | 408 | 736 |

## 2.3 Tree biomass estimations and nutrient content

In this study, a nutrient budget was constructed for the control and the intensively fertilized treatment. Data was collected for the tree, understory vegetation and soil in three different plots for each treatment resulting in a sample of 3 (n=3). In all plots tree diameter was calipered in centimeters at 1.3 meters height (diameter at breast height, DBH). The diameters were used in biomass functions to determine the dry weight for the trees on five different parts; leaves, branches, stem, bark and roots. Biomass functions were created from previously estimated dry weights and volumes derived from sixteen trees (n=16) at the experiment site (Timander, 2011). A more detailed description of the procedure can be found in Timander (2011). A regression model for each tree part with DBH as explaining variable were created in the SAS software version 9.2 (2009). Functions for leaves and branches was given directly in dry weight (kg) but for the stem two volume functions, over bark and under bark were created. Bark volume was obtained by subtracting the stem volume under bark from the stem volume over bark. The stem volume under bark was multiplied with the mean basic density value 483.5 kg $m^{-3}$, previously estimated for the eucalyptus trees in the experiment (Timander, 2011) resulting in dry weight for stem under bark (kg). The bark volume was also multiplied with a mean basic density value for eucalyptus bark. Bark density was obtained from two previously done studies. Foelkel & De Assis (1995) estimated bark density for seven years old *E. salinga* to 0.23-0.28 g $cm^{-3}$ and Wang et al. (1984) estimated bark density for twenty progenies of 1.4 years old *E. grandis* to 0.258 g $cm^{-3}$. A mean from both studies resulted in the mean bark density value used in the present study; 0.257 g $cm^{-3}$. The stem volume functions over and under bark had high adjusted $r^2$-values, both 0.96. The functions for leaves and branches had a higher variance and lower adjusted $r^2$-values; (0.59; 0.65).

To determine the dry weight of roots two functions created by Xu et al. (2002) were used, one function for large roots (> 2 cm in diameter) and one for small roots (< 2 cm in diameter). Both had been created from measurements done in a 75 month year old clonal stand of *E. grandis* x *E. urophylla* in southern China. In the functions, diameter was used as predictor variable.

Large root (> 2cm in diameter): $\ln(Dry\ matter) = -2.797 + 2.102 * \ln(DBH)$ $r^2$: 0.862

Small root (< 2cm in diameter): $\ln(Dry\ matter) = -2.383 + 0.783 * \ln(DBH)$ $r^2$: 0.640

The functions from Xu et al. (2002) were validated by comparing the function for stem under bark from Xu et al. (2002) with the functions for stem under bark applied here, resulting in a difference less than one percent. The two root biomasses were combined to obtain a total root biomass for each tree. Finally, all biomasses where summed up and displayed per hectare for each treatment.

For both the control and the intensively fertilized treatment, nutrient concentrations for the parts; stem, bark and branches were used from previously analyzed nutrient concentrations (Timander, 2011). The nutrient concentrations used for the intensively fertilized treatment were from an even more fertilized treatment, *NPK-300-B*, in the same experiment. Nutrient samples for the parts; leaves and roots, were collected in field in both treatments. In each of the plots, one tree was randomly selected for destructive harvesting. Leaves were randomly collected from the whole crown. Roots were collected from one tree in each plot with a mixture of different thick parts. The leaves were dried in an oven at 85 ºC for 48 hours and the roots at 105 ºC for four days. The samples were sent to the Tropical Forestry Research Institute in Nanning for nutrient analysis. The analyzed nutrient concentrations were multiplied with the dry weight to obtain the nutrient content for the specific part.

## 2.4 Understory vegetation biomass and nutrient content

Understory vegetation biomass was beside the control and intensively fertilized treatment, also estimated for the moderately fertilized treatment. This was done in order to more distinctively see how the fertilizer affected the understory vegetation. In each plot, biomass was collected in four subplots with a radius of one meter, resulting in a sample of 12 for each treatment (n=12).

The subplots were systematically placed along diagonals in the plot with one subplot on the first quartile from each corner. All understory vegetation, which consisted of herbs and woody plants, were harvested. Leaves from woody plants were analyzed separately resulting in three understory vegetation groups; leaves, woody stems and herbs. Additionally, litter including all dead biomass on the ground, was collected (fig. 3). All parts were weighed at place with an *ATZ-10* scale with capacity 0-10 kg and an accuracy of 25 g. A small amount of each part with the approximate proportions as in the plot was collected and weighed again at Stora Enso's laboratory in Shankou with a *G&G-TC4K* scale with capacity 0-6 kg and an accuracy of 0.1 g. All parts, except woody stems, were dried in an oven at 85 ºC for 48 hours. The woody stems were dried at 105 ºC for four days to be sure that all water had disappeared. After the samples had been dried they were weighed again and a dry weight ratio was calculated for each part by dividing the dry weight with the fresh weight. The ratios were then multiplied with the total fresh weight for each part to get the total dry biomass for each plot.

Fig. 3. Harvested and separated understory vegetation as litter (two piles), woody plants (divided on leaves and stems) and herbs.

The understory vegetation root biomass was estimated in a 30 x 30 centimeter and 20 centimeter deep area with the same center as the subplot. Soils and roots were separated. Roots were weighed at the laboratory with a *G&G-TC4K* scale with capacity 0-6 kg and an accuracy of 0.1 g. As for the aboveground biomass, some of the roots were dried to get a dry weight ratio to calculate the dry root biomass.

For each plot, nutrient analyses were done on all understory vegetation parts and litter by collecting a small sample with the approximate proportions between the species and the litter origin as in the plots. The samples were dried in an oven with the same temperature and time as for the other biomasses. Samples were sent to the Tropical Forestry Research Institute in Nanning for nutrient analyses. Both understory vegetation and tree parts were analyzed for total nitrogen with Kjeldahl analysis method. Total phosphorus and potassium was analyzed with $HNO_3/HClO_4$ digestion and colorimetry for phosphorus and $HNO_3/HClO_4$ digestion determined flame photometrical for potassium (Matusiewicz, 2003).

## 2.5 Soil analyses

Soil analyses were performed for the control and intensively fertilized treatment. Five subsamples were taken on two depths; 0-20 centimeters and 20-40 centimeters in every plot. The subsamples from the same depth were aggregated and sent to the laboratory in Nanning for analyses. Bulk density was determined for two different depths (0-20, 20-40 cm) with three measure points in the experiment site. The value for the upper layer (0-20 cm) was; 1.53 g $cm^{-3}$ and 1.61 g $cm^{-3}$ for the deeper layer (20-40 cm). Determination of organic matter was done using $K_2Cr_2O_7$ oxidation and external heating method (Schulte & Hoskins, 2011). Total nitrogen was determined by Kjeldahl digestion and diffusion. Total phosphorus was analyzed with NaOH melting and colorimetry. Total potassium was analyzed with NaOH melting and flame photometry. Plant available amounts of nitrogen, phosphorus and potassium were determined using alkaline hydrolysis diffusion for nitrogen, 0.005 mol $L^{-1}$ HCL 0.025mol $L^{-1}$ $1/2H_2SO_4$ extraction and colorimetry for phosphorus and 1 mol $L^{-1}$ $NH_4AC$ extraction and flame photometry for potassium. Nutrient concentrations from the soil were multiplied with the bulk density to obtain the amount of total and available nutrients (kg $ha^{-1}$) in the two layers of the soil.

To observe differences in nutrient content over time comparisons between previously done soil measurements (Andersson, 2007) were made by multiplying concentrations (g $kg^{-1}$; mg $kg^{-1}$) from Andersson (2007) with the bulk density from the present study.

## 2.6 Statistical analyses

Statistical analyses were done on biomasses, nutrient content and nutrient concentrations using general linear model (ANOVA) between the treatments. For the understory vegetation root biomass, analyses were made with means per plot (n=3) instead of on subplot level because of non-independent values.

# 3. Results

## 3.1 Understory vegetation

The mean amount of understory vegetation biomass (t $ha^{-1}$) above ground was 5.52 t $ha^{-1}$ in the intensively fertilized treatment (fig. 4). In the control and the moderately fertilized treatment, the biomass amount were 3.84 t $ha^{-1}$ and 4.42 t $ha^{-1}$ respectively, indicating an increase in biomass with fertilization intensity. However, no significant difference could be found between the treatments ($P = 0.616$).

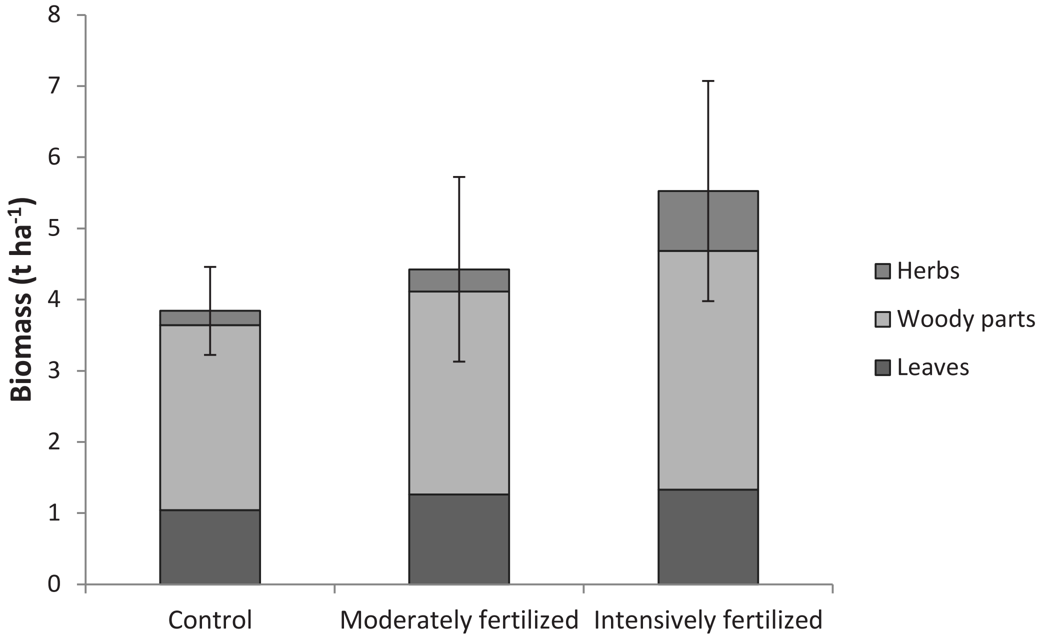


Fig. 4. Aboveground understory vegetation biomass (t $ha^{-1}$) for treatments; control, moderately and intensively fertilized divided on: leaves, woody stems and herbs. Error bars show standard error for total aboveground understory biomass (n = 12).

The mean herb vegetation biomass (t $ha^{-1}$) was significantly larger ($P = 0.018$) with 0.84 t $ha^{-1}$ in the intensively fertilized treatment compared to the control with 0.31 t $ha^{-1}$ and the moderately fertilized treatment with 0.20 t $ha^{-1}$. Regarding parts of woody plants: leaves ($P = 0.824$) and woody stems ($P = 0.852$), no significant difference was found between the treatments. However, both parts indicated an increase in biomass with fertilization intensity.

The mean understory vegetation root biomass ($t\ ha^{-1}$) was 5.99 $t\ ha^{-1}$ for the control (fig. 5). Corresponding values were 5.22 $t\ ha^{-1}$ and 4.56 $t\ ha^{-1}$ for the moderately fertilized and intensively fertilized treatment respectively ($P = 0.922$), indicating a decrease in biomass with fertilization intensity.

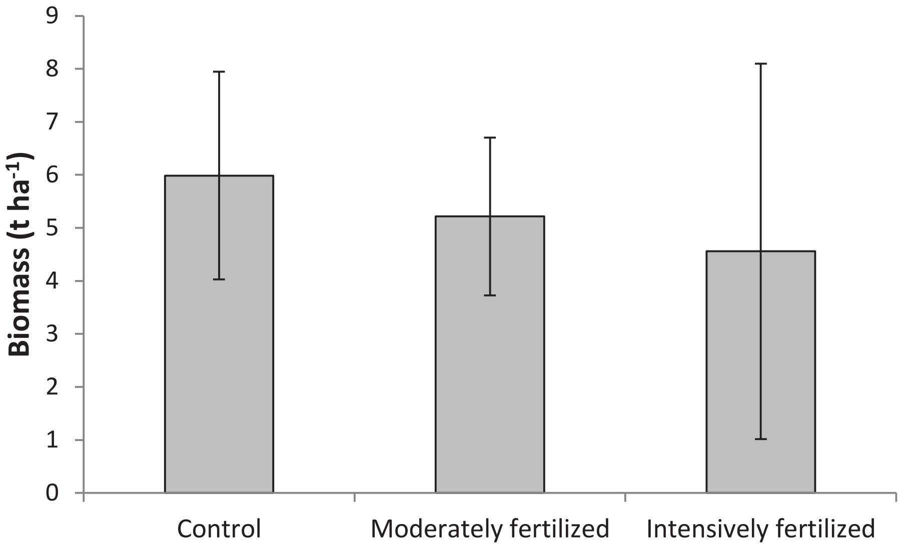


Fig. 5. Understory vegetation roots biomass ($t\ ha^{-1}$) for the treatments, control, moderately and intensively fertilized with error bars showing standard error ($n = 3$).

No significant difference in nutrient concentrations could be found between the control and the intensively fertilized treatment (appendix). However, most parts of understory vegetation indicated higher nutrient concentrations in the intensively fertilized treatment compared to the control. Only phosphorus and potassium concentrations in roots were higher in the control treatment. Leaves from woody plants contained the highest concentrations of nitrogen and phosphorus except in the intensively fertilized treatment where phosphorus concentration was highest in the herbs. For both treatments, highest concentrations of potassium were found in the herb vegetation.

## 3.2 Tree biomass and nutrient concentrations

The total tree biomass ($t\ ha^{-1}$) was significantly larger ($P = 0.018$) in the intensively fertilized treatment compared to the control (fig. 6). The amount of biomass was 181 $t\ ha^{-1}$ in the intensively fertilized treatment and 150 $t\ ha^{-1}$ in the control treatment. The result was equivalent to a 21% increase of biomass in the intensively fertilized treatment.

For both treatments, 70% of the total biomass was found in the stem; 104 $t\ ha^{-1}$ in the control and 127 $t\ ha^{-1}$ in the fertilized treatment (fig. 6). Roots (sum of small roots < 2 cm and large roots > 2 cm biomass) accounted for 17% of the total biomass in the control and 18% in the intensively fertilized treatment. Of the total aboveground biomass, leaves were only a small part with less than two percent in both treatments.

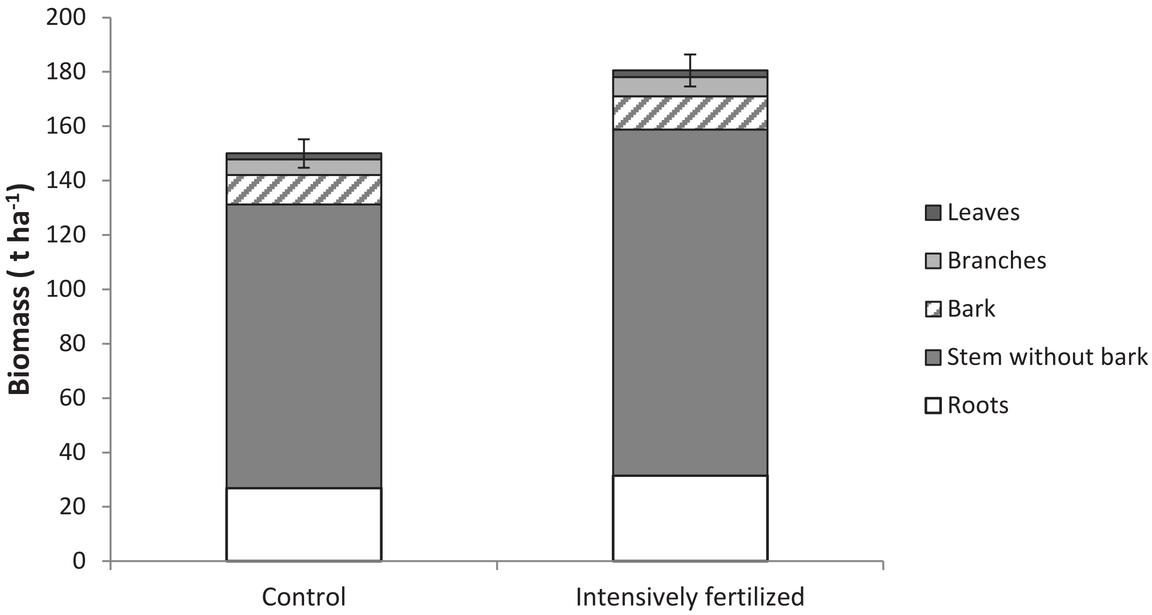


Fig. 6. Amount of tree biomass (t $ha^{-1}$) shown for the components; leaves, branches, bark, stem without bark and roots for the treatments; control and intensively fertilized. Error bars show standard error for the total tree biomass (n = 3).

As for the understory vegetation, no significant difference in nutrient concentrations between the control and the intensively fertilized treatment could be found (appendix). For the parts branches, bark and stem without bark, no statistical analysis could be done because of only one nutrient concentration value. However, nutrient concentrations of phosphorus and potassium indicated to be higher in the intensively fertilized treatment for all parts except leaves. Nitrogen concentrations were instead higher in the control for all parts except the bark. For both treatments, leaves were the tree part that contained the highest nutrient concentrations.

## 3.3 Nutrient content and distribution in biomass

In the living biomass, highest amounts of nutrients (kg $ha^{-1}$) were found in the trees (table 3). This applied to all nutrients in both the control and the intensively fertilized treatment. Depending on nutrient and treatment, the nutrients in understory vegetation accounted for 11-17% of the total amount of nutrients in the biomass. The intensively fertilized treatment had higher amounts of nutrients in all biomass parts compared to the control except for understory vegetation roots. The litter showed the opposite pattern with highest amounts of nutrients in the control. Of the total biomass, phosphorous showed the highest relative increase from 31 kg $ha^{-1}$ in the control to 65 kg $ha^{-1}$ in the intensively fertilized treatment. All differences between the treatments were insignificant with P-values varying from 0.11 to 0.9 depending on nutrient and biomass part.

Table 3. Estimated nutrient content (kg $ha^{-1}$) for nitrogen, phosphorus, and potassium for all biomass components (including litter) for the two treatments, control and intensively fertilized.

| Biomass parts (kg $ha^{-1}$) | Control | | | Intensively fertilized | | |
|---|---|---|---|---|---|---|
| | N | P | K | N | P | K |
| Tree | | | | | | |
| Leaves | 32.18 | 2.59 | 15.04 | 33.60 | 2.84 | 13.57 |
| Branches* | 19.14 | 4.06 | 18.54 | 19.31 | 6.10 | 27.24 |
| Stem without bark* | 110.79 | 7.31 | 42.76 | 126.70 | 13.11 | 65.00 |
| Bark* | 37.10 | 5.57 | 26.02 | 56.96 | 27.00 | 48.38 |
| Roots | 58.43 | 6.40 | 25.96 | 66.72 | 9.28 | 37.52 |
| **Total tree** | **257.64** | **25.93** | **128.32** | **303.29** | **58.33** | **191.71** |
| Understory vegetation | | | | | | |
| Leaves | 10.04 | 0.94 | 5.78 | 14.74 | 1.57 | 8.66 |
| Woody stems | 10.32 | 1.42 | 8.46 | 15.49 | 1.90 | 9.88 |
| Herbs | 1.78 | 0.19 | 1.92 | 10.04 | 1.54 | 9.38 |
| Roots | 28.32 | 2.99 | 11.72 | 20.43 | 2.40 | 10.59 |
| **Total understory veg.** | **50.46** | **5.54** | **27.88** | **60.70** | **7.41** | **38.51** |
| **Total biomass** | **308.10** | **31.47** | **156.20** | **363.99** | **65.74** | **230.22** |
| **Litter** | **111.11** | **7.24** | **22.10** | **90.18** | **7.08** | **18.05** |

*For the parts branches, stem without bark and bark there was only one value on nutrient concentration per nutrient, resulting in no possible statistical analyses.

## 3.4 Nutrient content and distribution in the soil

The amount of nutrients (kg $ha^{-1}$) available for plants was a minor part of the total nutrient content in the soil varying from 0.5 to 5.7% depending on nutrient and treatment, see table 4 for the specific values. The total amount (kg $ha^{-1}$) of phosphorus and potassium was greatest in the deeper layer of the soil whereas the total amount of nitrogen was highest in the upper layer. Significant difference between depths was only found for available amount of phosphorus in the control treatment ($P = 0.017$) and available amount of potassium in the intensively fertilized treatment ($P = 0.014$) where values were larger in the upper layer. However, the amounts of available nutrients tended to be higher in the upper layer (0-20 cm) for all nutrients and treatments.

All nutrients indicated higher content in the intensively fertilized treatment (table 4). Significant difference in nutrient content (kg $ha^{-1}$) between treatments was only found for two variables; available amount of phosphorus in the upper layer ($P = 0.047$) and available amount of potassium in the deeper layer ($P = 0.048$) which both were larger in the intensively fertilized treatment. Phosphorus showed the largest relative difference between the treatments with almost 50% higher values of total amounts in the intensively fertilized treatment and over 100% higher values of available amounts. This indicated that phosphorus had accumulated in the soil.

Table 4. Nutrient content (kg ha$^{-1}$) in the soil divided on two depths (0-20, 20-40 cm) for the control and the intensively fertilized treatment. Values with letters in the same row are significantly different. Bold values in same column are significantly different at 0.05 level.

| | Control | | | Intensively fertilized | | |
|---|---|---|---|---|---|---|
| Depth (cm) | Total N | Total P | Total K | Total N | Total P | Total K |
| 0-20 | 1291.2 | 393.5 | 2733.8 | 1616.5 | 580.5 | 3197.4 |
| 20-40 | 1094.1 | 419.4 | 3123.6 | 1149.9 | 624.3 | 3368.2 |
| **0-40 cm total** | **2385.3** | **812.9** | **5857.4** | **2766.4** | **1204.8** | **6565.6** |
| | **Control** | | | **Intensively fertilized** | | |
| | Available | Available | Available | Available | Available | Available |
| Depth (cm) | N | P | K | N | P | K |
| 0-20 | 68.9 | **2.3a** | 86.2 | 79.6 | 4.5b | **112.4** |
| 20-40 | 51.4 | **1.5** | 55.2a | 77.8 | 3.7 | **80.7b** |
| **0-40 cm total** | **120.3** | **3.8** | **141.4** | **157.4** | **8.2** | **193.1** |

The nutrient content in the soil at the experiment start was determined for the two compartments using values from Andersson (2007). Since the nutrient content was similar for both compartments values were averaged and shown in table 5. Comparisons between the measurements done by Andersson (2007) and the measurements done in the present study indicated that both total and available amounts of nitrogen had decreased. For potassium, the total amounts were similar but available amounts were higher in the present study. Phosphorus showed the largest difference with higher amounts in the intensively fertilized treatment in the present study, supporting the indication that phosphorus from the fertilization had accumulated in the soil.

Table 5. Mean nutrient content (kg ha$^{-1}$) in the soil divided on two depths (0-20, 20-40 cm) from year 2007 determined by Andersson (2007).

| Depth (cm) | Total N | Total P | Total K |
|---|---|---|---|
| 0-20 | 1657.7 | 382.8 | 3248.6 |
| 20-40 | 1436.8 | 389.4 | 3304.9 |
| **0-40 cm total** | **3094.5** | **772.2** | **6553.5** |
| | Available | Available | Available |
| | N | P | K |
| 0-20 | 110.9 | 2.8 | 44.3 |
| 20-40 | 102.0 | 2.3 | 35.9 |
| **0-40 cm total** | **212.9** | **5.1** | **80.2** |

The litter mainly consisted of tree bark and foliage detritus in different stages of decomposition. The mean amount of litter (t ha$^{-1}$) was 17.35 t ha$^{-1}$ in the control (fig. 7). In the moderately and intensively fertilized treatment, mean amounts were 16.53 t ha$^{-1}$and 13.33 t ha$^{-1}$, indicating a decrease in litter with fertilization intensity. No significant difference could be found between the treatments (P = 0.11).

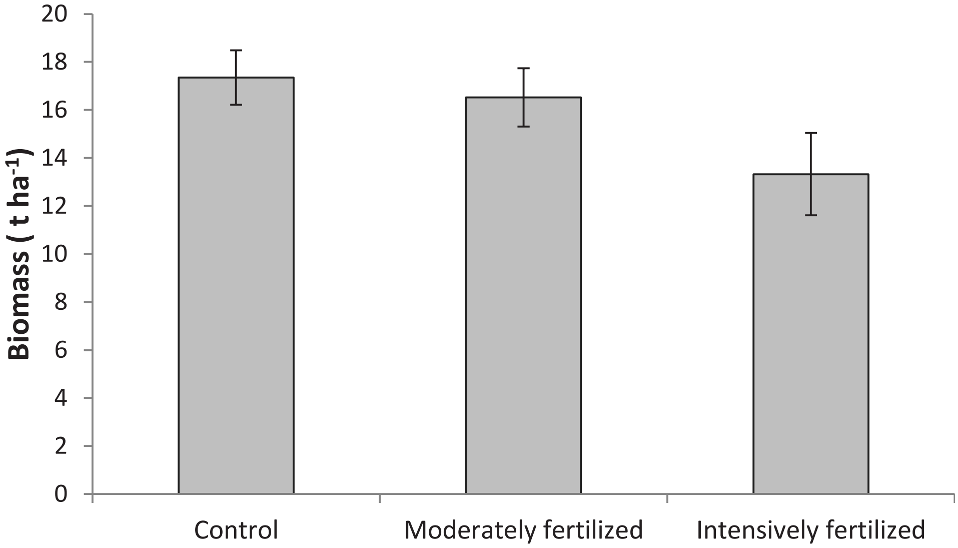


Fig. 7. Litter biomass (t ha$^{-1}$) for the treatments, control, moderately and intensively fertilized. Error bars indicate standard error (n = 12).

The mean amount (t ha$^{-1}$) of organic matter was 108.5 t ha$^{-1}$ in the intensively fertilized treatment and 95.4 t ha$^{-1}$ in the control, indicating increased organic matter in the soil with fertilization (P = 0.633) (fig. 8). Both treatments indicated larger amounts of organic matter in the upper layer of the soil (P = 0.76 for control; 0.56 for intensively fertilized). A comparison with the measurements from the experiment start (Andersson, 2007) indicated that the amount of organic matter had increased since the experiment start.

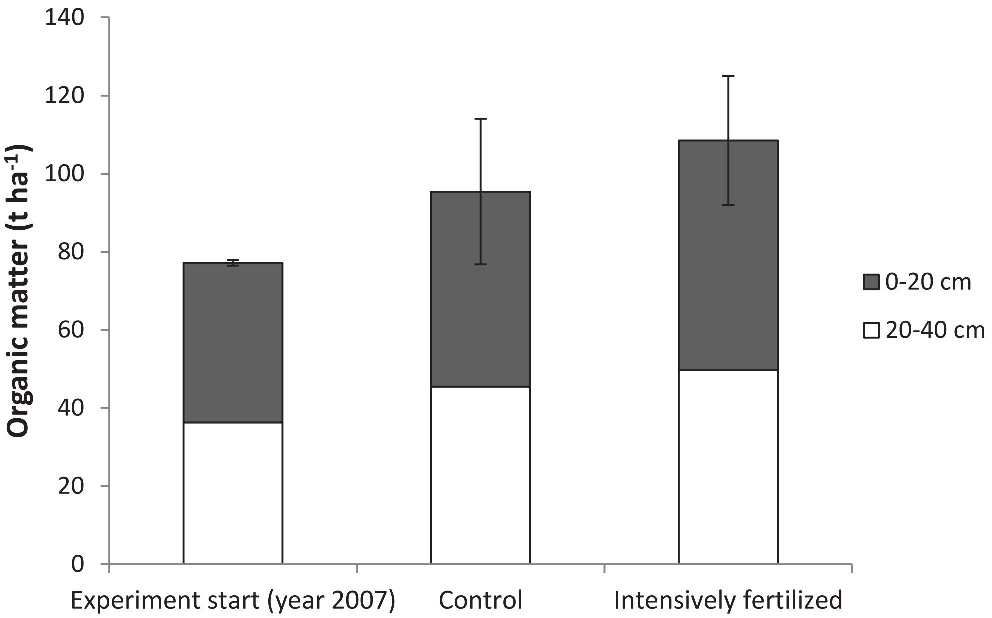


Fig. 8. Organic matter (t ha$^{-1}$) in the soil divided on two depths (0-20, 20-40 cm) for the two treatments; control and intensively fertilized (n = 3) and measurements of organic matter by Andersson (2007) (n = 2). Error bars show standard error for the total amount of organic matter.

## 3.5 Total budget and nutrient recovery

The mineral soil contained the largest part of nutrients in the eucalypt ecosystem in both the control and intensively fertilized treatment (fig. 9). For the overall nutrient budget, the intensively fertilized treatment contained higher amounts of nutrients for all nutrients; nitrogen: 3221 kg $ha^{-1}$, phosphorus: 1278 kg $ha^{-1}$, potassium: 6814 kg $ha^{-1}$ in the ecosystem compared to the control with; nitrogen: 2805 kg $ha^{-1}$, phosphorus: 852 kg $ha^{-1}$and potassium: 6036 kg $ha^{-1}$.

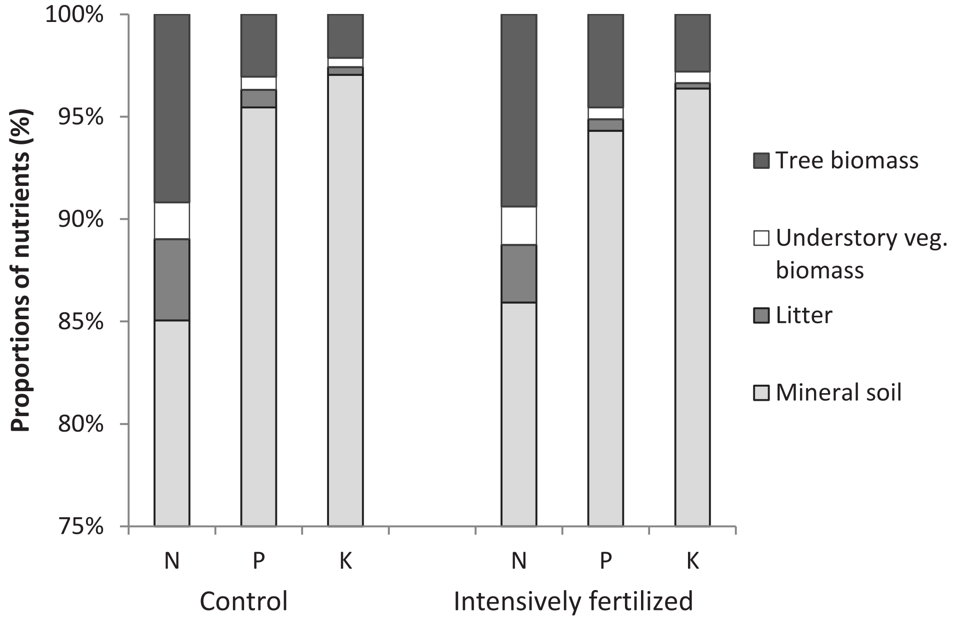


Fig. 9. Proportions of the total amounts of nitrogen, phosphorus and potassium divided in tree biomass, understory vegetation, litter and mineral soil (0 to 40 cm depth) for the control and the intensively fertilized treatment.

For both the tree and understory vegetation biomass, nutrient recovery was used as a measure to observe the relative amount of added fertilizer recovered in the biomass. This was done by subtracting the nutrient content from the control with the intensively fertilized treatment and then dividing the amount of nutrient content left with the total amount of added fertilizer.

The results showed that 5.9% of the nitrogen, 9.1% of the phosphorus and 9.2% of the added potassium had been taken up and accumulated in the tree biomass (fig. 10). The proportion of accumulated nutrients from the fertilizer found in the understory vegetation was less than in the tree biomass. The results showed that 1.4% of nitrogen, 0.5% of phosphorus and 1.6% of potassium had been accumulated in the understory vegetation biomass.

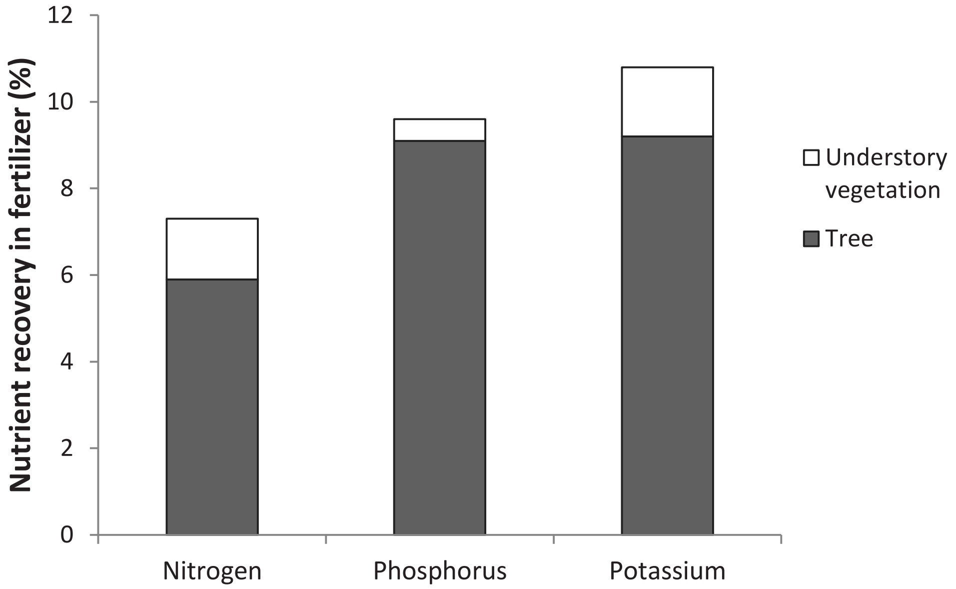


Fig. 10. Nitrogen, phosphorus and potassium accumulated in the tree biomass and understory vegetation in relation to the added fertilizer in the intensively fertilized treatment.

# 4. Discussion

## 4.1 Understory vegetation biomass

Even though no significant difference in understory vegetation biomass could be found between the three treatments, understory vegetation biomass showed a trend towards more aboveground biomass with increased amount of fertilization. This is in agreement with several previous studies which also have shown increased amount of understory vegetation biomass in fertilized stands compared to non-fertilized (VanderSchaaf et al., 2010; Bauhaus et al., 2001; Turner, 1975). Compared to the aboveground understory vegetation biomass, understory vegetation root biomass showed an opposite trend with decreased amount of biomass with increasing fertilization, however with a very high p-value ($P = 0.922$). A decreased need for the plants to expand the root system could be associated to the increased availability of nutrients. With more nutrients in the soil, plants can allocate more carbon to the aboveground parts resulting in an increased aboveground biomass (Harris, 1992) which the results in my study also support.

According to Turner (1975), the understory vegetation is constantly changing in composition and mass with stand age. Previous studies have shown that the understory biomass often increases until canopy closure and then start to decrease as an effect of reduced availability of mainly light (VanderSchaaf et al., 2010; Carneiro et al., 2008; Turner, 1975) but also competition for nutrients (VanderSchaaf et al., 2010). With only one measurement occasion in my study, it is difficult to know if the understory vegetation is changing. However, since the trees have closed canopies and have not been fertilized in two years it is reasonable to assume that the amount of biomass is stable.

A small sample with only twelve plots per treatment ($n = 12$) and large variation among these could explain the lack of statistical significance between the treatments. Within the fertilization experiment some of the variation in vegetation seemed to be related to the water availability since lower situated areas at end of slopes often had more vegetation (personal observation). The experiment has since the start also been affected by several disturbances; burning, typhoons, grazing by livestock and herbicide treatments[1] which in different ways probably have influenced the understory vegetation growing there today. Understory vegetation roots showed an even higher variation than aboveground parts probably related to differences in soil properties, plant species as well as the smaller sampled area.

[1] Jiang, Hu, Personal conversation at Stora Enso office in Hepu. 2012-12-05

## 4.2 Distribution of nutrients in biomass

The tree biomass contained the highest amount of all nutrients for both the control and intensively fertilized treatment. The amount of nutrients in the understory vegetation was just a small part (11-17%) of the total amount estimated in the biomass (tree and understory vegetation). Of the total biomass in the eucalypt ecosystem, trees accounted for over 90%. This also resulted in large amounts of nutrients accumulated there even though the nutrient concentrations tended to be lower in the trees than in the understory vegetation. Consequently, the majority of the nitrogen, phosphorus and potassium were found in the eucalypt trees.

Although understory vegetation did not account for much of the total nutrient content in this study, the understory vegetation often accounts for a larger part in the early stages of the rotation period when the trees are younger (Carneiro et al., 2009; Fabião et al., 2002). When the trees are harvested and removed at the end of the rotation period, understory vegetation will again account for a major part of the nutrients in the biomass contributing with nutrients to the soil. Laclau et al. (2000) showed that more than half of the nitrogen and 35% of the potassium in a stand of *E. alba* hybrids had accumulated in the tree biomass by the time the stand reached two years. Recommendations should therefore be to keep the understory layer as intact as possible to retain the nutrients in the soil and limit leaching in the beginning of the rotation period. However, the retention of understory vegetation has to be balanced against the risk of competition with the tree seedlings and a potential decrease in tree growth.

## 4.3 Differences in nutrient content between the treatments

Comparisons between the control and the intensively fertilized treatment showed no significant difference in nutrient content. However, the result indicated that more nutrients had accumulated in the intensively fertilized treatment. This applied to all parts except the litter which showed the opposite pattern with highest nutrient content in the control. As an effect of fertilization, the tree biomass was significantly larger with 21% more biomass in the intensively fertilized treatment compared to the control. Compared to other studies (Xu et al., 2002; Cromer & Williams, 1982) the effect of fertilization in my study was quite small. Larger effects with less fertilization have been observed in the neighboring Guangdong province with a four-fold increase in biomass with only 312 kg $ha^{-1}$ superphosphate after 75 months (Xu et al., 2002).

Even though no significant difference was found in nutrient concentrations between the two treatments, the concentrations for phosphorus and potassium tended to be higher in the intensively fertilized treatment. This indicated that the trees and the understory vegetation had increased their uptake of nutrients as a result of fertilization. With more available nutrients in the soil, trees respond with an increased uptake of nutrients in the biomass (Xu et al., 2002; Bauhaus et al., 2001). However, nitrogen concentrations in the trees showed higher values in the control compared to the intensively fertilized treatment. This was unexpected since the intensively fertilized treatment had been fertilized the same year (in 2010) as the nutrient concentrations for; stem, bark and branches were estimated. The fact that the nitrogen concentrations were lower in the intensively fertilized treatment could be explained by dilution of nitrogen as the biomass increases. Nitrogen is also mainly accumulated in green parts such as leaves (Brady & Weil, 2007) which are regularly replaced. Since the last fertilization in the intensively fertilized treatment, the trees have replaced their leaves several times and the effect of fertilization could therefore have disappeared with time. It can also not be ignored that large parts of the nitrogen probably has been leached out of ecosystem. The difference between the total amounts of nitrogen in all components at the experiment start compared to the amounts at the present measurement (after 81 months) for the intensively fertilized treatment showed that 704 kg $ha^{-1}$ nitrogen had disappeared from the ecosystem (fig.11). This indicated that a significant part of the added fertilizer could have leached out. Due to a coarse soil structure and a low content of organic matter resulting in a low cation exchange capacity the soil probably has a low ability of retaining nitrogen. Potassium which also has a tendency to leach out because of weak bonds (Brady & Weil, 2007) showed the same pattern, with 474 kg $ha^{-1}$ potassium less at the present measurement compared to the amounts at the experiment start.

Large amounts of fertilizer were applied in the intensively fertilized treatment. However, the growth of biomass only seemed to have responded moderately to the input of nutrients. This indicated that something more than the nutrients were limiting the growth at the experiment site, most likely the water availability. During parts of the year, precipitation is lower than the potential evapotranspiration which means that the trees will be water-limited for shorter periods (FAO, 1987). Besides the climatic factors, unfavorable soil properties such as low content of organic matter and sandy soil could result in low water retention capacity affecting the water availability for the trees. The results, however, indicated that the amount of organic matter had increased since the establishment of the experiment. This could lead to improved water holding capacity if the input of biomass (litter) is maintained.

The biomass functions used to estimate the tree biomass were derived from a limited number of trees (n = 16) with a smaller mean diameter than the trees in the present study. With more updated functions including a potential fertilization effect on tree morphology more pronounced differences between the treatments might be observed. The root functions obtained by Xu et al. (2002) were well suited for this study. They were both based on trees with the same age as in my study. However, the functions did not consider if the roots had been fertilized or not. According to Fabião et al. (1995) differences in growth pattern between fertilized and non-fertilized eucalyptus roots are insignificant for trees older than six years and possible differences were therefore neglected in the study.

Nutrient concentrations for the tree parts; stem, branches and bark had been obtained from Timander (2011). The nutrient concentrations for the parts in the intensively fertilized treatment were, however, from a more intensively fertilized treatment in the same experiment which had been fertilized twice a year instead of once. Even though there were differences in the amount of added fertilizer, previous studies in the same experiment have not shown any major differences in nutrient concentrations between the most fertilized treatments (Genfors, 2008; Andersson, 2007). For that reason it was reasonable to draw the conclusion that the nutrient concentrations from Timander (2011) could be used in my study. Since only one value on nutrient concentration per biomass part was available, statistical analyses were not possible. For the parts leaves and roots where more values (n=3) were available, nutrient concentrations did not show any significant difference, probably due to a too small sample with only three values for each biomass part and treatment. With a larger sample, significant results could probably have been found for both nutrient concentrations and nutrient content.

## 4.4 Nutrient recovery in the biomass

The relationship between accumulated nutrients in the biomass and the added fertilizer showed that only a small part of the added fertilizer was accumulated in the tree biomass at the measurement occasion (5.9% in nitrogen, 9.1% in phosphorus and 9.2% in potassium). This could partly be explained by too excessive amounts for the plants to take up, mainly in the beginning of the rotation period. As the results indicated, much of the phosphorus had instead been accumulated in the soil. Nitrogen and potassium on the other hand indicated to have leached out from the system. Previous studies in fertilization experiments (Xu et al., 2002; Cromer & Williams, 1982) have shown similar proportions of phosphorus recovery where Xu et al. (2002) could show that the recovery started to decrease when fertilizer exceeded as low amounts as 13 kg $ha^{-1}$ phosphorus.

## 4.5 Distribution of nutrients in the soil

The plant available amounts of nitrogen, phosphorus and potassium were just a small fraction (0.5-5.6%) of the total nutrient content in the soil. Highest amounts of available nutrients were found in the upper layer of the soil indicating that the availability of nutrients was related to the mineralization of biomass. In these highly weathered soils, organic sources of especially phosphorus can be a significant part of the available amounts for plants and trees (Brady & Weil, 2007). In both treatments, the total and available amounts of nitrogen also tended to be higher in the upper layer of the soil. The amount of nitrogen in the soil is mainly associated to the organic matter which depends on the amount and quality of the litter (Gundersen et al., 2006) and probably also the land-use history.

The results showed that the control contained the highest amount of litter (kg $ha^{-1}$) and thereby the highest total amount of nutrients. However, the nutrient concentrations tended to be lower in the control compared to the two fertilized treatments. The lower nutrient concentration in the control probably resulted in a lower rate of mineralization (Brady & Weil, 2007) and thereby more litter than in the two fertilized treatments.

The higher amounts of nutrients found in the intensively fertilized treatment, compared to the control, indicated that nutrients from the fertilizer had accumulated in the soil. The largest relative increase was observed for the total amount of phosphorus which was 48% higher in the intensively fertilized treatment. This indicated the high ability of phosphorus to bind in the soil mainly in unavailable forms with iron and aluminum (Brady & Weil, 2007). In my study, less than 1% of phosphorus was found in forms available for the trees and plants. The relationship between the added amount of fertilizer and the increase of nutrient content in the intensively fertilized treatment indicated that the main part of the added phosphorus had accumulated in the soil. The soil measurements from the experiment start also confirmed that the increased accumulation of phosphorus in the soil could be an effect of fertilization. Nitrogen and to some extent also potassium had instead decreased since the experiment start. This was probably an effect of increased uptake in the biomass and a low retention capacity of the soil.

## 4.6 Nutrient removal by harvesting

The proposed rotation period for eucalyptus plantations according to Stora Enso is seven years (UNDP, 2006) meaning that the trees at the experiment site would be ready to harvest. Stem harvest with de-barking in the intensively fertilized treatment would result in removal of 127 kg ha$^{-1}$ nitrogen, 13 kg ha$^{-1}$ phosphorus and 65 kg ha$^{-1}$ potassium (fig. 11). Similar values have been estimated by Laclau et al. (2000) where stem harvest with de-barking of *E. alba* hybrids for pulpwood resulted in exports of 82 kg ha$^{-1}$ nitrogen, 23 kg ha$^{-1}$ phosphorus and 31 kg ha$^{-1}$ potassium. Harvesting with whole-tree method, including all aboveground parts of the tree, would increase the removal of nutrients with more than 100% compared to only stem harvest (fig. 11).

Without knowing all sources of nutrient input to the ecosystem it is difficult to know if the removal will result in a depletion of nutrients in the long-term. However, as previous studies have shown (Qui et al., 2011; Carnerio et al., 2008; Brady & Weil, 2007; Gonçalves et al., 2006) keeping as much biomass as possible at the site could be important to sustain the productivity. As the result indicates, much of the plant available nutrients are received from the litter and the biomass and if too large amounts of nutrients are removed from the ecosystem depletion of nutrients in the soil could be expected.

## 4.7 Conclusions

Based on the results in the study, fertilization increased the growth of *Eucalyptus urophylla* and probably also the amount of understory vegetation. A higher input of organic matter and available nutrients seems to be beneficial for these often degraded soils by improving the soil conditions with higher water holding capacity and increased nutrient retention. The recommended amount of fertilizer should, however, be lowered as the ecosystem indicated leakage of especially nitrogen and potassium. As understory vegetation contributed to a significant part of the nutrients in the biomass it will be important to keep the understory layer as intact as possible to prevent leaching and to retain nutrients in the ecosystem, especially in the beginning of the rotation period. Maintaining as much biomass and thereby nutrients to the site could probably result in improved soil conditions and thereby maintained or even higher long-term productivity.

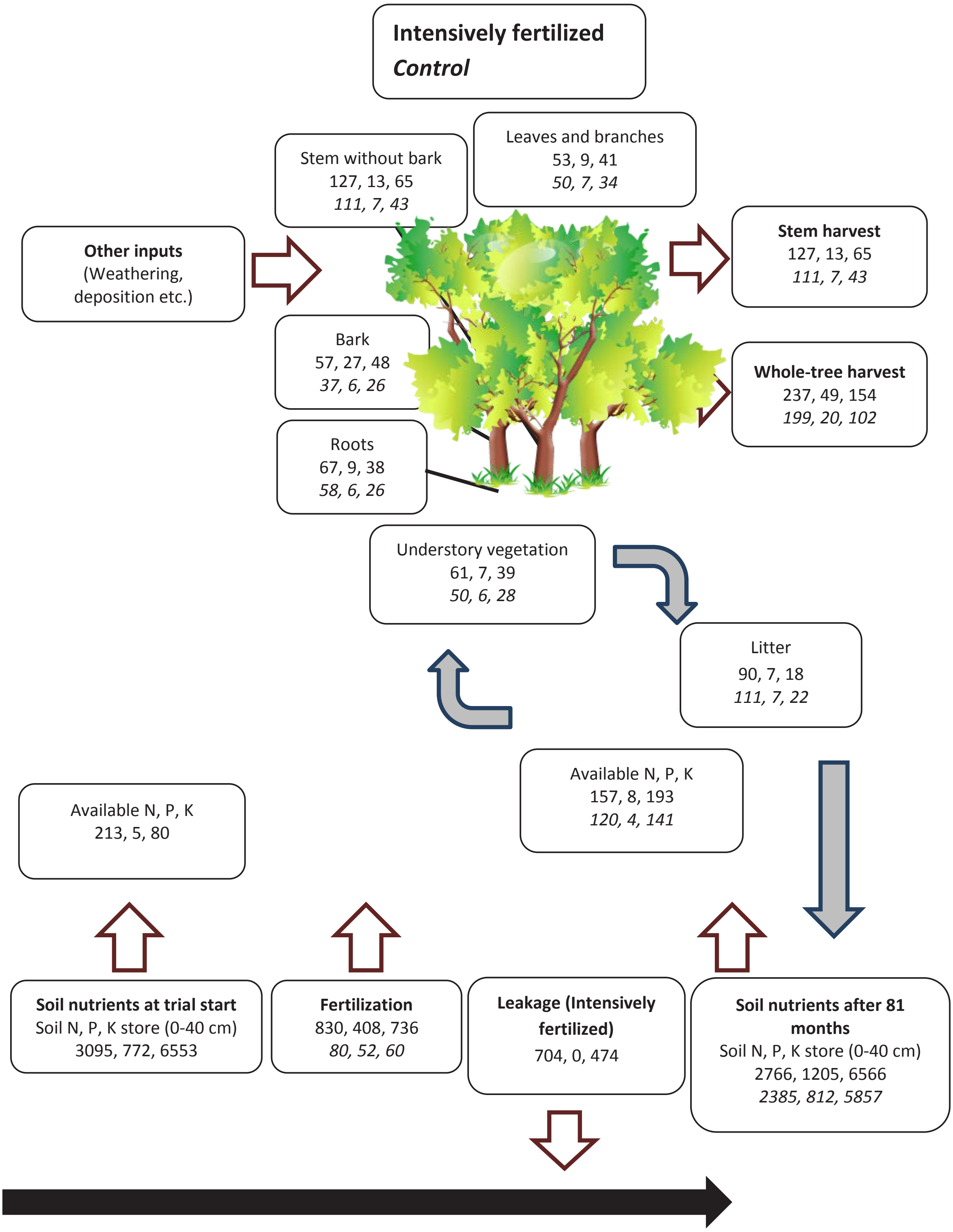


Fig. 11. Summarizing model of nutrient content for nitrogen (N), phosphorus (P), potassium (K) and flows (kg ha$^{-1}$) between the different parts in the ecosystem for both the intensively fertilized treatment and the control, (in *italic*). Dark arrow indicate shift over time (from trial start to 81 months later), grey arrows indicate flows between parts and hollow arrows indicate in-/output of nutrients from the ecosystem. Other inputs are all sources increasing the amounts of nutrients in the ecosystem. The leakage frame is the difference in total amount of the nutrient from the experiment start and after 81 months and should therefore be interpreted cautiously.

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# Appendix

Table 6. Mean concentrations (g kg$^{-1}$) for the biomass parts for the two treatments; control and intensively fertilized

| Biomass parts (kg ha$^{-1}$) | Control N | Control P | Control K | Intensively fertilized N | Intensively fertilized P | Intensively fertilized K |
|---|---|---|---|---|---|---|
| Tree | | | | | | |
| Leaves | 14.78 | 1.19 | 6.91 | 13.05 | 1.11 | 5.28 |
| Branches* | 3.32 | 0.70 | 3.31 | 2.77 | 0.88 | 3.91 |
| Stem without bark* | 1.06 | 0.07 | 0.41 | 1.00 | 0.10 | 0.51 |
| Bark* | 3.41 | 0.51 | 2.39 | 4.63 | 2.19 | 3.93 |
| Roots | 2.18 | 0.24 | 0.96 | 2.13 | 0.30 | 1.19 |
| Understory vegetation | | | | | | |
| Leaves | 9.69 | 0.91 | 5.57 | 12.44 | 1.51 | 9.19 |
| Woody parts | 4.01 | 0.54 | 3.15 | 4.32 | 0.72 | 4.80 |
| Herbs | 8.98 | 0.83 | 9.04 | 11.19 | 1.64 | 9.92 |
| Roots | 4.56 | 0.51 | 1.93 | 4.34 | 0.45 | 1.99 |

*For the parts branches, stem without bark and bark there was only one value on nutrient concentration per nutrient, resulting in no possible statistical analyses.

Table 7. Compilation of all biomass compartments (t ha$^{-1}$) for the two treatments control and intensively fertilized.

| **Biomass parts (t ha$^{-1}$)** | **Control** | **Intensively fertilized** |
|---|---|---|
| Tree | | |
| Leaves | 2.18 | 2.57 |
| Branches | 5.77 | 6.97 |
| Stem without bark | 104.30 | 127.29 |
| Bark | 10.87 | 12.31 |
| Roots | 26.89 | 31.42 |
| **Total tree biomass** | **150.01** | **180.56** |
| Understory vegetation | | |
| Leaves | 1.04 | 1.33 |
| Woody parts | 2.60 | 3.36 |
| Herbs | 0.20 | 0.84 |
| Roots | 5.99 | 4.56 |
| **Total understory vegetation** | **9.83** | **10.09** |
| Litter | 17.35 | 13.33 |
| **Total biomass** | **177.19** | **203.98** |