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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Jacob Rudhe

An increasing demand for wood products in China has resulted in large areas invested for 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 nutrients are accumulated in the ecosystem a more sustainable forest management could be achieved. In this study, a nutrient budget was created for all biomass and soil components in a fertilization experiment with *Eucalyptus urophylla* for the nutrients; nitrogen, phosphorus and potassium. The nutrient budget was estimated 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 years. Fertilization had contributed to a 20% significantly larger tree biomass in the fertilized treatment. Additionally, the results indicated higher nutrient content in the fertilized treatment than in the control. The understory vegetation accounted for 11-17 % of the total amount of nutrients in the biomass, depending on nutrient and treatment. Most of the nutrients in the eucalypt ecosystem were found in the mineral soil (85-97%). Over time nutrients decreased in the soil and were instead accumulated in the biomass. Furthermore, the results indicated that significant amounts of nitrogen and phosphorus from the fertilized treatment had been leached out from the system. Phosphorus had instead been accumulated in the soil. As a result of larger nutrient cycling and more biomass in the fertilized treatment, the results also indicated more organic matter and available nutrients in the soil. This could thus 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 ecosystem through increased productivity.

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

Sammanfattning

Ett ökat behov av trävåvara in Kina har lett till att stora arealer avsatts för plantageskogsbruk med snabbväxande eukalyptus. Plantageskogsbruk med eukalyptus är ofta förknippat med en intensiv skötsel med bl.a. gödsling. Genom en ökad förståelse av 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* för en kontroll och en gödslad behandling. 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. Gödslingen visade sig ha bidragit med en 20% signifikant större trädbiomassa i den gödslade behandlingen. Dessutom indikerade resultaten på ett högre näringsinnehåll i den gödslade behandlingen jämfört med kontrollen. Undervegetationen stod för 11-17% av den totala mängden näring i biomassan. Den största delen av näringen i eukalyptus-ekosystemet fanns i mineraljorden, 85-97% beroende på näringsämne och behandling. Resultaten indikerade på att mängden av näringsämnena i marken hade minskat och istället ackumulerats i biomassa. Vidare indikerade resultaten att signifikanta mängder av kväve och kalium hade lakats ut ur systemet i den gödslade behandlingen. Fosfor hade istället ackumulerats i marken. Som ett resultat av mer näringsämnen och mer biomassa i den gödslade behandlingen antydde resultaten på en ökning i mängden organiskt material och växt tillgängliga näringsämnen i marken. Detta skulle på sikt kunna leda till förbättrade markförhållanden med högre vattenhållande förmåga och ökat näringshållande kapacitet. På lång sikt skulle gödsling därmed kunna bidra positivt till ekosystemet genom en ökad produktivitet.

Nyckelord: Eukalyptus, gödsling, näringsinnehåll, undervegetation, biomassa

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1. Introduction

1.1 Planted forest and fast-growing tree plantations

The demand for wood products worldwide is steadily increasing as an effect of growing populations and better living conditions (Turnbull, 2007). Additionally, 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 the problem 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 cover over 264 million hectares (2010) with an annually increase of 5 million hectares (FAO, 2010). Of the total area planted forest 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 being 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 9-18 m^3 ha^{-1} $year^{-1}$ for eucalypt species (Turnbull, 2007). Even though there are many advantages with fast-growing tree plantations, short-rotation periods often associated with whole-tree harvesting result in large exports 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 harvesting and through site management. They estimated the costs of compensating the management dependent nutrient losses with fertilization and showed that the costs to compensate the total nutrient losses would be unprofitable large. To increase the profitability, Mackensen & Fölster (2000) 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 through avoiding native pests and diseases the result is often a higher yield in quantity and/or quality. Although there are several thousand tree species in the world only around thirty species are extensively utilized 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 used widely 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 wide use in plantation forestry. Extensive development programs in forms of selected species and tree breeding programs, modern nursery techniques and efficient plantation management have also increased the productivity (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 saw 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 found in the southern parts. Plantations of eucalyptus 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-/grassland where the human impact for centuries through activities such as clearing and fuel gathering have affected the soils negatively (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). For most soils in southern China, phosphorus is the most limiting nutrient to biomass production (Xu et al., 2002). Long period of weathering and mainly found in unavailable forms with aluminum and iron have resulted in a low availability (Brady & Weil, 2007). Most of the plant available phosphorus is often associated to the residues of organic matter. With significant land degradation in many soils, availability of phosphorus can therefore be very limited. (Brady & Weil, 2007; UNDP, 2006) After phosphorus, the most common limiting nutrient in these soils is nitrogen (Xu et al., 2002). Nitrogen is mainly associated with the quality and amount of the litter and as for phosphorus the land use history has a large influence on the availability of nitrogen (Gundersen et al., 2006).

As 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). Nutrient content in trees increases rapidly in the early stages of stand development as a result of rapid growth of nutrient demanding parts of the tree such as; foliage, young branches and fine roots. 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) as 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 amount 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 thus contributing to the availability of nutrients in the soil (Qui et al., 2011; Carneiro et al., 2009, Turner, 1975). The understory vegetation has therefore an important role in conserving nutrients in the system before the trees have fully developed their 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 with less light to 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 growth, while in older stands, where the trees have a closed canopy with a high shading effect, the impact on understory vegetation depends on how the trees respond to the fertilizer (Smethurst et al., 2003, Turner, 1975). 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). However, the response time of the trees may lead to increased understory vegetation for shorter periods and thereby increased nutrient accumulation. The understory vegetation has many other positive effects to the forest ecosystem besides retaining nutrients and contributing to the available amount of nutrients in the soil (Carneiro et al., 2009). As the understory vegetation continuously contributes to the accumulation of organic matter it thereby improves the aggregation of soil and 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 very 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 nutrient cycling 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 for a more long-term sustainable management. Several studies have addressed the importance for 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 nutrients 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 mainly very mountainous with a 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, 2011).

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

The soil type at the site is ferric acrisol with a sandy texture of reddish color (FAO-Unesco, 1978). Andersson (2007) investigated 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 from the start of the experiment in 2006. The experiment was divided in two compartments, plot 1-30 and 31-41. Soil properties investigated; 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 from Andersson (2007).

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