Biomass and Nutrient Studies of Selected Tree Species of Natural and Plantation Forests: Implications for a Sustainable Management of the Munessa-Shashemene Forest, Ethiopia

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Dedicated
to my mother
the late Bekeleche Kebede
with a lot of love

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asl	Above see level
ANOVA	Analysis of variance
BBD	Basal branch diameter
BDW	Branch dry weight
CEC	Cation exchange capacity
DDW	Dry disk weight
DBH	Diameter at breast height
DSH	Diameter at stump height
FDW	Fresh disk weight
FoDW	Foliage dry weight
ha	Hectare
hPa	Hecto pascal
ICP-AES	Inductively coupled plasma atomic emission spectrometry
LFR	Live fine root
LFW	Log fresh weight
pH	Negative decadic logarithmic of the proton activity
R^2	coefficient of determination
SFM	Sustainable forest management
UNCED	United Nations Conference on Environment and Development

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Summary

Over 90% of the population in Ethiopia depends on firewood and charcoal to meet their energy needs, of which wood from forests contributes significantly. In addition, many rural people living in the surroundings of forested area depend on forest resources for constructing houses and for making different household and farm utensils. Forests are also important in watershed management, soil protection and biodiversity conservation. The multiple uses of forests are now endangered because of the high rate of deforestation in the country. It has been estimated that 100,000–200,000 ha land is deforested annually.

Plantation forests with exotic tree species have been introduced to alleviate the problems of deforestation. In the future, more plantation forests with fast growing species should be grown for coping with the ever-increasing demands for fuelwood and other forest products. However, it is not known whether plantation forests are sustainable or not. For the sustainability of plantation forests with exotic tree species, it is of paramount importance to thoroughly understand their ecological and social attributes through a holistic approach. For this reason, a multidisciplinary project was initiated in the Munessa-Shashemene Forest. Such an approach gives valuable information about the sustainability of plantation forests when the basic ecological features of the natural forests are compared with plantation forests.

As an integral part of the multidisciplinary project, the objectives of this study are to: i) quantify the fine roots and aboveground biomass of selected tree species in both natural and plantation forests; ii) quantify the macronutrient stocks of the fine roots and aboveground components of selected trees species in both natural and plantation forests; and iii) evaluate the implication of the changes in the biomass and macronutrient stocks for a sustainable management of forests.

The study focused on four tree species, *Podocarpus falcatus* (Thunb.) Mirb., Podocarpaceae and *Croton macrostachys* Hochst. ex Del. Euphorbiaceae, were selected from a natural forest. *Cupressus lusitanica* Miller, Cupressaceae and *Eucalyptus globulus* Labill. Myrtaceae were selected from plantation forests.

Root architectures of the study trees were studied by excavation. The live fine root biomass (<2 mm in diameter) of the dry and wet seasons was determined from samples collected at the distances of 1, 2 and 3 meters from the bole of the study trees. At each of the distances, root cores were taken at the depth intervals 0-10, 10-35, 35-60, 60-85 and 85-100 cm using a hand auger. Linear regression equations were used to estimate the aboveground biomass on the basis of the relation between DBH and dry weights of the aboveground plant components. Macronutrient concentrations were determined following a standard laboratory procedure.

Studies on the root architecture revealed that *C. lusitanica* has a shallow root and is more susceptible to windthrow compared to *E. globulus*. With the exception of *E. globulus*, the dry season live fine root (LFR) biomass was higher for all trees studied. The change in soils moisture of the study area attributed to the seasonal variation in the fine root biomass. For all trees investigated, the mean annual LFR biomass was highest at the depth interval 0-10 cm at all distances. The favorable soil texture, pH and organic matter content at the depth interval 0-10 cm might be responsible for higher LFR biomass.

The significantly higher LFR biomass of *P. falcatus* (1.34 kg m^{-2}) coupled with its higher macronutrient stocks compared to *C. macrostachys* (0.32 kg m^{-2}) suggest the importance of *P. falcatus* in the sustainability of the natural forest by transferring more macronutrients to the soil through its fine roots. Similarly, the significantly higher total LFR biomass of *C. lusitanica* (0.88 kg m^{-2}) coupled with its higher macronutrient stock compared to *E. globulus* (0.27 kg m^{-2}) indicated less depletion of soil nutrients by the former.

The stand structure of the natural and plantation forests differed largely. In the natural forest, the density of *C. macrostachys* was much higher (143 ± 72 trees ha^{-1}) than the density of *P. falcatus* (73 ± 39 trees ha^{-1}). Generally, the structural change of the natural forest due to selective cutting of *P. falcatus* was found to have negative implications on the sustainability of the natural forest. The differences in the structure of *C. lusitanica* and *E. globulus*, despite their similar densities, resulted in a significantly lower understory ground cover by herbaceous and shrub species in the former. The effect of a poor understory growth on the floor litter thickness and thereby on nutrient capital of the soil may negatively affect the sustainability of *C. lusitanica* plantation.

The harvesting of the stemwood of *C. lusitanica* and *E. globulus* removes a substantial amount of nutrients from the plantation sites. Furthermore, the current practice of collecting foliage, twigs and branches for firewood by the local people results in a higher depletion of nutrients. In order to make the plantation forests sustainable, the silvicultural practice in the future should consider on site conservation of foliage and bark.

It is recommended that more studies on aboveground and belowground biomass, fine root turnover, and nutrient concentrations of the plantation forests should be carried out in a chronosequence in order to gain more insight on their sustainability.

Ausführliche Zusammenfassung

A. Einleitung

Über 90% der äthiopischen Bevölkerung hängt bei der Energieversorgung von Feuerholz und Holzkohle ab, die in immer kleiner werdenden Wald- und Gehölzflächen produziert werden (WBISPP 1997). 83% der Bevölkerung lebt im ländlichen Raum von den Erzeugnissen von Ackerbau und Viehzucht. Insbesondere die Menschen, die in der Nachbarschaft der verbliebenen Wälder leben, sind zur Befriedigung ihrer täglichen Bedürfnisse auf die Ressourcen der Wälder angewiesen. Sie brauchen Bauholz für ihre Hütten, weiteres Nutzholz zur Herstellung von Geräten für die Landwirtschaft und den Haushalt. Die restlichen Wälder sind schließlich auch bedeutsam für den Wasserhaushalt in ihren Einzugsgebieten, für den Bodenschutz und die Erhaltung der Artenvielfalt.

Hoher Bevölkerungsdruck (fast 3% Bevölkerungswachstum) hat zu wachsender Nachfrage nach agrarischen Landnutzungsflächen und gleichzeitig zu einer hohen Entwaldungsrate geführt. Nach de Vletter (1991) gehen in jedem Jahr 100.000 bis 200.000 ha Waldfläche durch Rodung verloren.

Um dieser Entwicklung zu begegnen sind in verschiedenen Teilen des Landes Forstpflanzungen angelegt worden (Stiles 1991), stark degradierte Gebiete wurden aufgeforstet (EFAP 1994; Hvidberg-Hansen 1977) und Prioritäten für zukünftige Waldflächen wurden festgelegt (EFAP 1994). Bisher haben jedoch diese Anstrengungen noch keine langfristige Lösung gebracht. Hierfür wird unter anderem das Fehlen von Forstmanagement, welches auf wissenschaftlichen Grundlagen aufbaut, verantwortlich gemacht (CSE 1997; EFAP 1994).

Es ist deshalb von höchster Dringlichkeit, nachhaltige Formen forstlichen Managements zu entwickeln und in den restlichen bestehenden und neu zu begründenden Waldgebieten Äthiopiens anzuwenden. Für degradierte Flächen wurde als eine Alternative bereits von Pohjonen und Pukkala (1990) der Anbau

schnellwüchsiger Arten vorgeschlagen. Noch immer aber ist nicht bekannt, ob Pflanzungen mit solchen Arten nachhaltig sind. Auch weiß man kaum etwas über ihre Akzeptanz bei der ländlichen Bevölkerung. Erst wenn die ökologischen, ökonomischen und sozio-kulturellen Grundlagen für das aufzuforstende und zu bewirtschaftende Gebiet bekannt sind, kann Nachhaltigkeit erreicht werden.

Aus diesem Grund hat eine aus Bodenkundlern, Pflanzenphysiologen und Biogeografen zusammengesetzte Forschergruppe ein Projekt im Munessa-Shashemene Wald begonnen, in welchem wichtige Ökosystemprozesse erforscht werden. Begleitet werden diese Studien von sozio-ökonomischen Untersuchungen bei der Bevölkerung im Untersuchungsgebiet, eingeschlossen örtliche Meinungsbildner und Entscheidungsträger. Die Erstellung eines für äthiopische Förster bestimmten Leitfadens zum nachhaltigen Management der Wälder und Aufforstungen ist ein gemeinsames Ziel der Forschergruppe.

Ein wichtiger Teil dieses multidisziplinären Projekts sind Untersuchungen zur ober- und unterirdischen Biomasse. Spezielle Ziele dieser hier vorliegenden Studie sind:

- Quantifizierung der Feinwurzelbiomasse ausgewählter Baumarten des Naturwaldes und der bestehenden Pflanzungen mit exotischen Arten.
- Quantifizierung der oberirdischen Biomasse derselben Arten.
- Analyse der Makronährstoffe in Feinwurzeln und oberirdischer Biomasse von Baumarten des Naturwaldes und der Pflanzungen.
- Beurteilung der Ergebnisse im Hinblick auf ein nachhaltiges Management der Naturwälder und der Pflanzungen.

B. Das Arbeitsgebiet

Der Munessa-Shashemene Wald liegt etwa 240 km süd-südöstlich von Addis Abeba auf der Ostabdachung des Rift Valley, östlich des Langanosees zwischen ca. 1900 m und 2700 m üNN. Das Gebiet gehört zur Arssi Zone des Oromia Regional State. Über tertiären Ignimbriten (Mohr 1971) sind verschiedene Bodentypen entwickelt, die einem Höhengradienten zugeordnet werden können und aus den tieferen Lagen nach oben folgend nach der World Reference Base als Mazic Vertisols, Mollic Nitisols, Humis Umbrisols und Mollic Cambisols klassifiziert werden.

Das Klima ist wechselfeucht-tropisch mit mittleren Jahresniederschlägen um 1000 mm und einer mittleren Jahrestemperatur von 16° C. Nach Friis (1992) und unseren Beobachtungen setzt sich die Kronenraumvegetation des Munessa-Shashamene Waldes aus *Podocarpus falcatus*, *Croton macrostachys* und in den höheren Lagen des Arbeitsgebietes aus *Hagenia abyssinica*, *Hypericum revolutum*, *Schefflera volkensii* und *Nuxia congesta* zusammen.

C. Material und Methoden

C.1 Ausgewählte Baumarten

Für die Biomassestudien wurden vier Baumarten ausgewählt: *Podocarpus falcatus* (Thunb.) Mirb. (Podocarpaceae), eine Schlussbaumart und *Croton macrostachys* Hochst. ex Del. (Euphorbiaceae), eine Pionierbaumart aus dem Naturwald, sowie *Cupressus lusitanica* Miller (Cupressaceae) und *Eucalyptus globulus* Labill. (Myrtaceae) als exotische Baumarten aus den Plantagen.

C.2 Unterirdische Biomasse

Von je einem Individuum der ausgewählten Baumarten wurden die Wurzeln freigelegt und danach die jeweilige Wurzelarchitektur auf der Basis von Länge und

Durchmesser lateraler Wurzeln und – so vorhanden – der Pfahlwurzel(n) beschrieben. Sodann wurden von jedem der ausgewählten Bäume (mit gleichem dbh) Wurzelproben in Abständen von einem, zwei und drei Metern vom Stamm aus fünf verschiedenen Bodentiefen (0-10, 10-35, 35-60, 60-85 und 85-100 cm) mit einem Bohrer je einmal in der Trocken- bzw. Regenzeit entnommen. Der Bohrer hatte einen inneren Durchmesser von 8 cm und konnte zylindrische Proben bis zu einer Länge von 25 cm bergen. Die Proben wurden gewaschen und nur die lebenden Feinwurzeln (LFR) wurden isoliert, getrocknet und gewogen (Böhm 1979).

C.3 Oberirdische Biomasse

Auf fünf Versuchsflächen (zwei je 20 m mal 30 m im Naturwald, drei je 20 m mal 20 m in den Aufforstungen) wurde der dbh der Versuchsbäume gemessen. Nach diesem Kriterium wurden sie in Klassen gruppiert und sodannje 6 Individuen einer Klasse von den Arten *Croton macrostachys*, *Cupressus lusitanica* und *Eucalyptus globulus* gefällt. *Podocarpus falcatus* wurde aus Schutzgründen nicht gefällt und konnte deshalb auch nicht auf der gleichen Berechnungsbasis mit in die Untersuchung einbezogen werden. Die oberirdische Biomasse wurde sodann aufgrund der Beziehungen von dbh und Trockengewicht für die einzelnen Pflanzenorgane (Stamm, Zweige, Blätter) über eine lineare Regression ermittelt.

C.4 Analyse der Makronährstoffe

Für die unterirdische Biomasse (Feinwurzeln) und die oberirdische Biomasse (getrennt nach den Kompartimenten Stamm, Borke, Zweige, Blätter) wurde der Gehalt folgender Makronährstoffe analysiert: C, N, P, K, Ca, Mg, Na und S. Der CNS-Analyzer „Elementar Vario EL“ wurde für die Ermittlung von Kohlenstoff, Stickstoff und Schwefel genutzt. Na, Ca, Mg, K und P wurden mit Hilfe den „inductively coupled plasma atomic emission spectrometry“ (ICP_AES) bestimmt.

C.5 Statistische Analysen

Eine Varianzanalyse (ANOVA) wurde mit der Software STATISTICA / Version 6.1 durchgeführt. Bei signifikanten Unterschieden der Varianz ($p<0,05$) wurde der Scheffé-Test durchgeführt, um diese genauer zu analysieren.

D. Ergebnisse und Diskussion

D.1 Wurzelarchitektur der untersuchten Baumarten.

Podocarpus falcatus und *Croton macrostachys* besitzen eine sehr ähnliche Wurzelarchitektur, die durch dicke laterale Wurzeln und eine oder mehrere Pfahlwurzeln (bei *Podocarpus* vor allem im jugendlichen Stadium) gekennzeichnet werden kann. Solche Wurzelsysteme tragen zum Erfolg beider Baumarten als dominante Arten im Naturwald bei.

Eucalyptus globulus hat im Vergleich zu *Cupressus lusitanica* tiefere Pfahlwurzeln und längere laterale Wurzeln. Deshalb kann *Eucalyptus globulus* aus größerer Tiefe und einer weiteren Umgebung Wasser und Nährstoffe aufnehmen und wächst aus diesem Grund auch relativ schnell. Außerdem ist diese Art wesentlich besser im Boden verankert und erweist sich im Gegensatz zur Zypresse resistent gegenüber starken Winden.

D.2 Biomasse und Makronährstoffgehalte der Feinwurzeln.

Die Feinwurzelbiomasse war für drei der vier Arten für alle Bodentiefen und alle Entfernungen vom Stamm in der Trockenzeit höher als in der Regenzeit (Tabelle 2-5). Da die Böden in der Trockenzeit ebenfalls trockener sind, kann diese intensivere Wurzelentwicklung hierauf zurückgeführt werden. Für die *Eucalyptus*-Pflanzung konnte dieser Unterschied allerdings nicht festgestellt werden.

Bei allen vier Baumarten war die Feinwurzelbiomasse in den ersten 10 cm Bodentiefe bei ebenfalls allen Entfernungen vom Stamm signifikant am höchsten (siehe Figs 13-16). Dies wird auf drei Ursachen zurückgeführt. In erster Linie wird der sehr hohe Tonanteil aller tieferen Bodenhorizonte und die damit schwierigere Durchwurzelung und schlechte Durchlüftung das Wurzelwachstum einschränken. Daneben begünstigt auch der niedrigere pH-Wert in größeren Tiefen das Wurzelwachstum nicht (Jentschke and Drexhage 2001). Schließlich wird oberflächennah das Wurzelwachstum durch relativ hohe Anteile organischer Substanz und hohe Stickstoffverfügbarkeit gefördert.

Die Feinwurzelbiomasse von *Podocarpus falcatus* war über vier Mal höher als die von *Croton macrostachys* (siehe Fig. 17). Dies bedeutet, dass im Fall einer intensiven forstlichen Nutzung von *Podocarpus fal*catus und dem darauf folgenden Ersatz der Schlussbaumart durch den Pionier *Croton macrostachys* auch die Feinwurzelmasse erheblich betroffen ist. Dies wirkt sich wegen weniger Nährstoffrückführung in den Boden negativ auf die Nachhaltigkeit aus. Auch die Feinwurzelmasse der Zypressen ist etwa drei mal höher als die der Eukalypten. In der Bilanz werden durch die langsam wüchsigere Zypressen die Nährstoffvorräte deshalb wahrscheinlich weniger stark in Anspruch genommen.

Ganz ähnlich wie bei der Feinwurzelmasse erweist sich auch die Konzentration der meisten Makronährstoffe in den obersten 10 cm des Bodens als deutlich höher als in allen anderen Bodentiefen (siehe Tabelle 9). Dabei waren die Konzentrationen der meisten Nährstoffe bei *Podocarpus falcatus* doppelt so hoch wie bei *Croton macrostachys*. Auch hieraus lässt sich wiederum für die Schlusswaldart – wie nicht anders zu erwarten – ein höherer Beitrag zur Nachhaltigkeit ableiten. Schließlich gab auch *Cupressus lusitanica* mehr Nährstoffe an den Boden zurück als *Eucalyptus globulus*. Somit wird auch unter diesem Aspekt belegt, dass Eucalypten für eine nachhaltige Forstwirtschaft besonders kritisch beurteilt werden müssen.

D.3 Oberirdische Biomasse

Für eine Abschätzung der oberirdischen Biomasse der untersuchten Bäume wurde eine lineare Regressions-Gleichung entwickelt, die auch von der Munessa-Shashemene Forest Company genutzt werden kann. Diese Abschätzung ist für Stämme, Zweige und Blätter allein aufgrund der dbh-Daten möglich (siehe Fig. 18-20).

Die Bestandesstruktur des Naturwaldes und die der Pflanzungen unterscheiden sich erheblich. Im Naturwald ist dabei *Croton* wesentlich häufiger als *Podocarpus*. Eine weitere selektive Nutzung von *Podocarpus* muss als besonders nachteilig für die geplante nachhaltige Nutzung der Naturwälder beurteilt werden. Die beiden eingeführten Holzarten wurden als Reinbestände gepflanzt, wobei sich die Dichte der Bestände nicht sonderlich unterscheidet. (siehe Tabelle 6). Die Unterschiede in der Bestandesstruktur, die sich bei diesen beiden ergeben, sind vor allem auf den Unterwuchs zurückzuführen. Das dichte Kronendach von *Cupressus* lässt kaum Licht auf den Boden fallen. Die wesentlich lichteren *Eucalyptus*-Pflanzungen besitzen dagegen einen oft relativ dichten Unterwuchs aus einheimischen Kräutern, Gräsern, Sträuchern und Bäumen, verhindern also die natürliche Regeneration nicht.

D.4 Makronährstoffkonzentrationen in der oberirdischen Biomasse.

Mit Ausnahme von Ca und Na waren die Nährstoffkonzentrationen am höchsten in den Blättern, gefolgt von Zweigen, Borke und Stammholz. Ca war bei allen untersuchten Bäumen am höchsten in der Borke. Diese Ergebnisse stimmen mit denen von Fölster und Khanna (1997) überein, die ebenfalls tropische Plantagen untersuchten, sowie denen von Drechsel und Zech (1993), welche tropische Koniferen und Laubhölzer analysierten.

Bei der Nutzung von Stammholz der Zypressen und Eucalypten gehen den Wuchsorten erhebliche Nährstoffmengen verloren (siehe Fig. 29). Es werden darüber hinaus aber auch Blätter und vor allem die Zweige für Feuerholz genutzt, was einem weiteren Export von Nährelementen entspricht. Deshalb müssen – um überhaupt in die Nähe nachhaltiger Nutzung zu kommen – zukünftig nach Möglichkeit Blätter, Borke und auch Äste am Wuchsort verbleiben. Es sollten schließlich auch Versuche gemischter Aufforstungen der heute vertretenen Arten mit solchen Arten unternommen werden, die Stickstoff fixieren können.

E. Fazit

Es kann gezeigt werden, dass die selektive Nutzung und Degradierung der Naturwaldreste im Untersuchungsgebiet v.a. mit Veränderungen des Nährstoffhaushalts verbunden sind, die im Hinblick auf eine nachhaltige Nutzung negativ zu beurteilen sind. Bei den Pflanzungen mit exotischen Arten konnte nachgewiesen werden, dass eine Verarmung an Nährstoffen bei *Cupressus lusitanica* geringer ist als bei *Eucalyptus globulus*. Allerdings haben die Zypressenpflanzungen weniger Unterwuchs und sind stärker durch Windwurf gefährdet. Dagegen besitzen die Pflanzungen mit Eukalypten ein höheres Regenerationspotential und lassen sich leicht mit einheimischen Arten mischen.

Vergleichbare Studien wie die hier vorliegende sollten – insbesondere den Nährstoffhaushalt und das Regenerationspotential betreffend – in regelmäßigen zeitlichen Abständen wiederholt werden, um Trends klarer zu erkennen und die Möglichkeiten einer nachhaltigen Waldbewirtschaftung sicherer abzuschätzen.

1. Introduction

1.1 The forest resource base

Owing to its wide range of climatic, geological and topographic factors, Ethiopia is endowed with a wide array of vegetation types. For example, Pichi-Sermolli (1957) classified the vegetation of Ethiopia into 21 types. Broadly classified, the forest vegetation types include montane dry evergreen forest, montane moist evergreen forest and high-level bamboo forest (Westphal 1975). More recently Friis (1992) categorized the forest vegetation of Ethiopia into seven types. These include dry peripheral-deciduous Guineo-Congolian, transitional rainforest, Afromontane and riverine forest types.

Estimates on Ethiopia's land area covered by natural forests in the past are extremely varied. Based on rainfall distribution and forest relic patches von Breitenbach (1962) estimated the extent of forest cover in the past to be 40% of the total land area. Mesfin (1972) stated that only 5% of the country was covered by forests. EMA (1988) stated that 30% of the entire country was covered by forest. Sayer et al. (1992) estimated that 87% of the highlands were covered by forests. According to EFAP (1994) over 66% of the country was covered by forests and woodlands.

Although estimates of the land area covered by forests in the past strongly vary, the remnant natural forest patches and the climatic conditions prevailing in the highlands suggest that these areas were once covered by much more forests (CSE 1997; Mesfin 1972). According to the estimate made by FAO in the year 2000, the area covered by natural and plantation forests was estimated to be 4.2% and 0.19% of the total land area, respectively (FAO 2003). Further information on the forest resource base of Ethiopia was published in Logan (1946), Vernede (1955), von Breitenbach (1962), Chaffey (1980), EFAP (1994) and Gebre Markos (1998).

1.2 Importance of forest resources

Over 90% of the population in Ethiopia depends on firewood and charcoal for energy supply, of which wood from forests contributes significantly (WBISPP 1997). Furthermore, 83% of the total population live in the rural area and depends on agriculture for survival. Thus, the rural people living in the surroundings of forested area rely on forests for their daily needs.

Forests provide materials for constructing houses and for making different kinds of household and farm utensils. The contribution of forest trees in traditional honey production is also substantial (Fichtl and Admasu 1994). They also provide products such as incense, myrrh and gums and grazing for livestock (Girma 1998). Additionally, the moist southwestern forests support the production of important spices such as ginger (*Zingiber officinale*), cinnamon (*Cinnamomum zeylanicum*) and cardamom (*Elettaria cardamomum*) (CSE 1997; Girma 1998).

Forests are also important in watershed management, soil protection and biodiversity conservation. Particularly the mountain forests in Ethiopia are situated for capturing and storing rainfall and moisture, maintaining water quality, regulating river flow and reducing soil erosion (FAO 2003). The importance of Ethiopian forests in the conservation of forest genetic resources has also been rated as one of the highest in Africa (de Vletter 1991).

Data on the potential of the forestry sector in generating employment for the rural households are scarce and outdated. In 1988/89, it was reported that the forest industry accounted for 2.8% of the employment in the agricultural sector (EFAP 1992). It is obvious, however, that many households in rural Ethiopia rely on the income generated from employment related to forest management. Typical employments in the forest sector include nursery management, afforestations, and construction and maintenance of roads in forests. For instance, in the Munessa-Shashemene Forest Enterprise it has been estimated that in seasons, when thinning and other similar activities are carried out in the plantation forests, the Enterprise

employs up to 12,000 people (Assefa 1996). The average contribution of forestry to the total GDP in the years between 1980-92 was 2.5% (EFAP 1994).

Forests within the tropics has the potential to sequester up to 80% of the total CO_2 emitted worldwide (Rotter and Danish 2000) and play a positive role in alleviating problems associated with climate change. On the other hand, if the forests are not properly managed, the concentration of CO_2 in the atmosphere might significantly increase. The potential of remnant forests in Ethiopia in contributing to carbon sequestration might be useful for alleviating global warming. Likewise, their poor management could result in increasing level of CO_2.

1.3 Deforestation: threat to survival

The population size in Ethiopia increased from 12.9 million in 1920 to 70 million in 2003 (CSA 2003). The current annual population growth rate is reported to be 2.9% (CSA 2003). The high population pressure has resulted in high demands for agricultural lands and this in turn has caused a rapid rate of deforestation in the country. For example, De Vletter (1991) estimated that 100,000-200,000 ha of forest disappear every year as a result of clearing for agriculture and pasture. Pohjonen and Pukkala (1990) estimated that with the present trend of deforestation, there would be no forest in Ethiopia by the year 2020.

Though high population pressure and high demands for agricultural lands are considered to be the main factors for the alarming rate of deforestation in Ethiopia, it should be noted that causes for deforestation are multiple and interlinked. For example, Terefe (2001) discussed the relationship among high population growth, land tenure, political instability and war, fuelwood demands and backward agricultural systems in causing deforestation and environmental degradation. Thus, combating the challenges of deforestation needs to address these social, economical and political problems in an integrated approach.

Measures taken so far to curb the impact of deforestation include the establishment of plantation forests in different parts of the country (Stiles 1991), afforestation of degraded areas (EFAP 1994; Hvidberg-Hansen 1977) and demarcation of priority forest areas (EFAP 1994). However, these and other environmental rehabilitation programs have not been able to bring about a long lasting solution. The lack of forest management plans based on the scientific understanding of forest ecosystems has been attributed as one of the many factors for the failure of such programs (CSE 1997; EFAP 1994).

Studies made on the forests of Ethiopia so far have focused on individual component of forest ecosystems. For example, several studies about the vegetation (Chaffey 1980), soils (Lundgren 1971), and regeneration aspects (Demel and Anders 1995; Feyera 1998) of the Munessa-Shashemene Forest have been conducted.

Given the negative impacts of deforestation on the livelihood of the rural population, on forest biodiversity and to the national economy, it is a top priority to develop and implement a sustainable forest management plan in Ethiopia. The rehabilitation of the degraded areas with fast growing species has been suggested as one of the few alternatives for coping with the ever-increasing demand for fuelwood and other forest products by the rural population (Pohjonen and Pukkala 1990).

So far it is not known whether plantation forests are sustainable or not. Also, the attitude of the rural people towards the plantation forests has not been studied. For the sustainability of plantation forests with exotic tree species, however, it is necessary to have a thorough understanding of their ecological requirements and evaluate the attitude of the rural people in adopting them.

1.4 Approach to sustainable forest management

Concerns about sustainability in natural resources management have started in Germany in the eighteenth century when the principle of sustained yield was applied to forest production (Lusigi 1995; Marell and Laroussinie 2002). In the past, however, sustainable forest management (hereafter referred as SFM) had been limited to continued production of wood products giving less attention to the full array of environmental services and non-timber products of the forests (Vogt et al. 1997).

In 1992, the United Nations Conference on Environment and Development (UNCED) emphasized the importance of SFM for sustainable development. Following the UNCED, many international organizations and countries developed criteria and indicators that reflect a more comprehensive approach to SFM (Marell and Laroussinie 2002; Richardson et al. 1999). The forest principle, an outcome of the UNCED, emphasized the need for an ecosystem-based approach for SFM (United Nation Conference on Environment and Development 1992). Vogt et al. (1997) also pointed out that the key for sustainable management of forests is to understand the principal processes and functioning of their ecosystems through a holistic approach.

However, an ecosystem-based approach for SFM does not imply that it is absolutely necessary to collect data on all the different components of ecosystems. This is an almost impossible task (Beck and Müller-Hohenstein 2001) and is not recommended (Vogt et al. 1997). Such an approach requires the selection of basic ecosystem characteristics.

Since ecosystem function is greatly influenced by both the structure and productive capacity of the ecosystem, it is important to understand which factors and components determine the present structure of a system and which may change its productive capacity. Disturbances caused by natural and anthropogenic factors can affect the productivity of an ecosystem in different ways by changing the spatial

and temporal patterns of nutrient availability and cycling and change in biomass. The assessment of these patterns is important for developing a SFM plan (Vogt et al. 1997). Forest ecosystem management, therefore, has to incorporate the fact that ecosystems are dynamic. In such a dynamic system, sustainability is ensured when the balance between nutrient and energy input and output is balanced over a certain period of time (Waring and S. 1985).

1.5 General objectives

The Munessa-Shashemene Forest, like the other montane forests in Ethiopia, has been affected by changes caused by anthropogenic factors. It is also one of the few forests where plantation forests with exotic trees have been introduced in a large scale. Thus, this forest was selected since it provides an ideal setting to compare natural forest with the plantation forests in terms of their sustainability. Furthermore, considering the possibility of rehabilitating degraded areas with fast growing exotic trees in the future and the need for understanding their ecology, the Munessa-Shashemene Forest is suitable to gauge changes in the basic components of ecosystems resulting from the conversion of natural forest into plantation.

For this reason, a multidisciplinary team consisting of soil scientists, plant physiologists and biogeographers initiated a project based on an ecosystem approach in the Munessa-Shashemene Forest with the following general objectives:

- to monitor the basic ecosystem processes in natural and plantation forest sites;
- to undertake a socioeconomic study to identify processes which have a positive or negative effect on sustainable forest utilization; and
- to develop a sustainable forest management manual on the basis of the information generated by the above studies.

In order to achieve these general objectives, data on the vegetation structure and composition, water relation, soil properties, water and element fluxes, aboveground and belowground biomass and socioeconomic aspects were collected in the Munessa-Shashemene Forest.

1.6 Specific objectives

As an integral part of the multidisciplinary project stated above, the specific objectives of this study on the above-and belowground biomass are to:

i. quantify the fine root biomass of selected tree species in both natural and plantation forests;

ii. quantify the aboveground biomass of selected tree species in the natural and plantation forests;

iii. analyse macronutrient contents in fine roots and aboveground plant components of selected tree species in the natural and plantation forests; and

iv. evaluate the implication of changes in belowground and aboveground biomass as well as macronutrient contents resulting from the conversion of the natural forests to plantation forests for SFM.

2 Description of the study area

2.1 Location

The study was conducted in the Munessa-Shashemene Forest, Ethiopia. This forest has an estimated area of 23,000 ha (Silvanova 1996) and is divided into three blocks; namely Gambo, Sole and Degaga. Plots for the present study were established in the Degaga block, which is located at 7° 27' N and 38° 53' E and in the Oromia Regional State, Arssi Zone, about 240 km south of Addis Ababa (Fig 1).

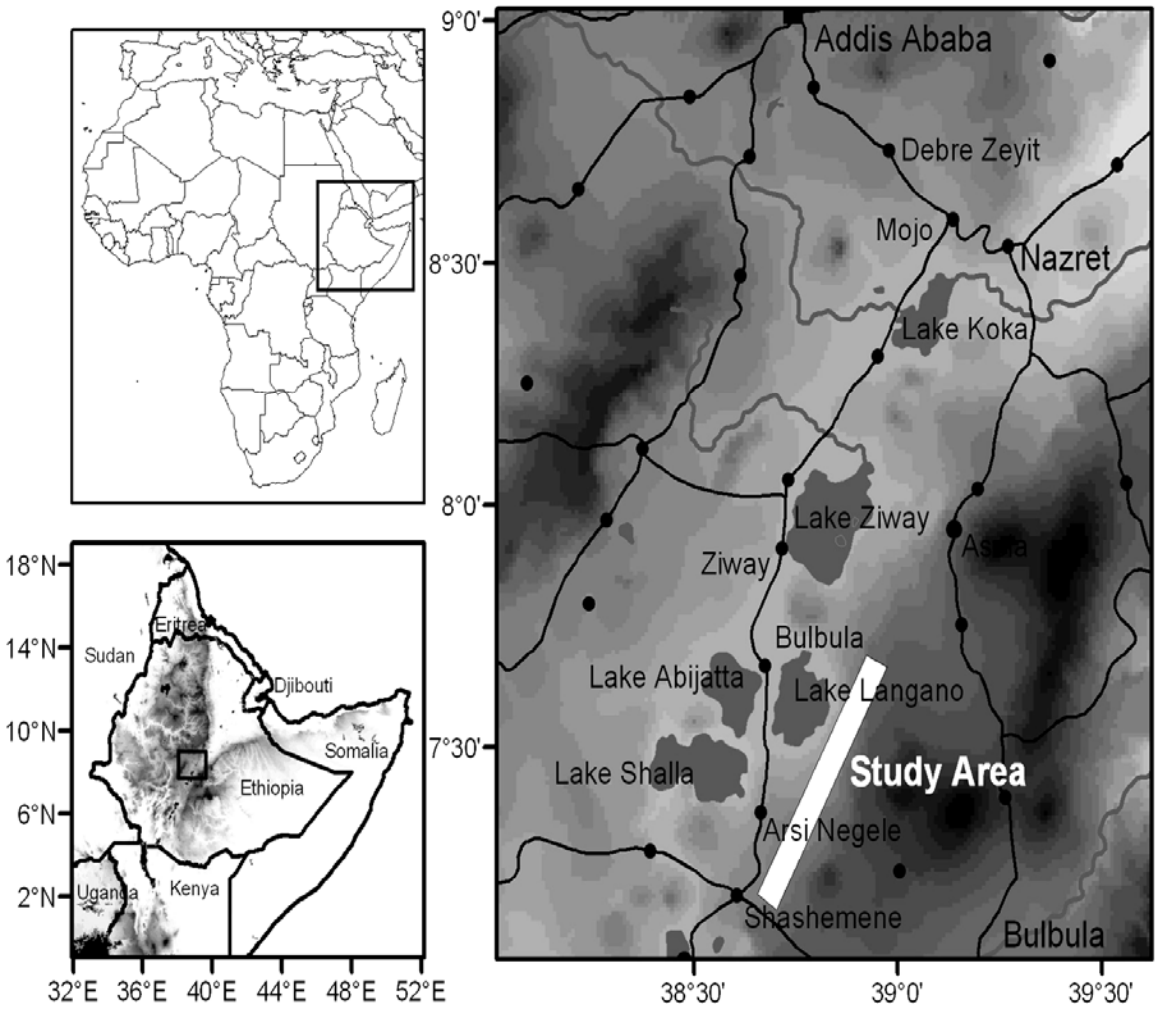


Fig. 1: Location of the study area, (Ormsby (2001), modified by Rückamp).

2.2 Geological basis, relief and soil characteristics

As in many other parts of Ethiopia, Precambrian rocks form the basement of the study area (Mesfin 1972; Mohr 1971). They consist of igneous and metamorphic rocks and are intensely folded. The Munessa-Shashemene Forest is largely associated with the Wonji belt of faults and craters. The basement complex is overlain with Tertiary Trappean Lava, principally consists of ignimbrite (Mohr 1971).

The altitude range extends from ca 1,900 m to 2,700 m asl. The plains descend gradually to the Langano, Abjata and Shalla Lakes that are situated at about 1,600 m asl. The Munessa forest is an important water catchment area for these lakes as surface streams and rivers drain into them (Lundgren 1971).

The soils are derived from weathered parent volcanic rocks, mainly reddish in color, freely draining and are of medium to heavy texture (Lundgren 1971). Only soils at lower slope positions are derived from debris and as well as from lacustrine sediments deposited during humid periods of the Quaternary (Gasse and Street 1978; Mohr 1971). According to the World Reference Base (WRB) soil taxonomic system, the soils of the study area are classified as Mazic Vertisols, Mollic Nitisol, Humic Umbrisol, Mollic Cambisol and Niti-Umbric-Alisol along altitudinal gradient (Fig. 2). The pH ($CaCl_2$) and cation exchange capacity (CEC) range 5.5-7 mmol($^+$) kg^{-1} and 30-100 mmol($^+$) kg^{-1}, respectively. Over 50% of the soil consists of clay (Fritzsche, unpublished)

2.3 Climate

General accounts on the climate of Ethiopia are given in Daniel (1977) and Mesfin (1972). According to the meteorological records at Degaga (altitude 2000 asl), the mean annual rainfall was 1,075 mm with a peak rainfall in July and the mean annual temperature was 16°C with the highest temperature in April (Fig. 3A). The annual rainfall and temperature at Kuke for the year 2002 (altitude 2300 asl), where plots for the present study were established, were 1,343 mm and 15°C, respectively, for the year 2002 (Fig. 3B).

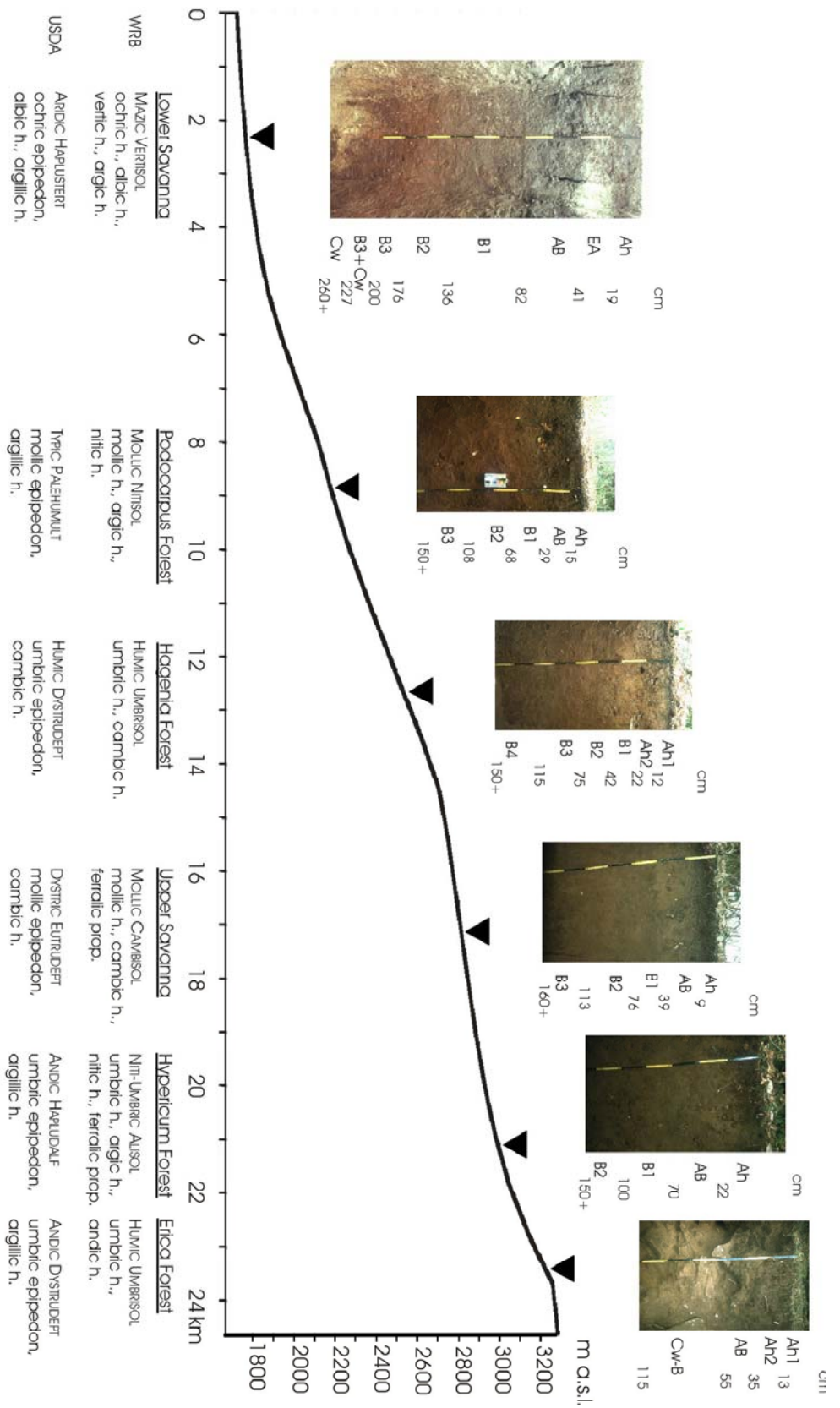


Fig. 2: Soils of the study area along an altitudinal gradient (Fritzsche, in preparation).

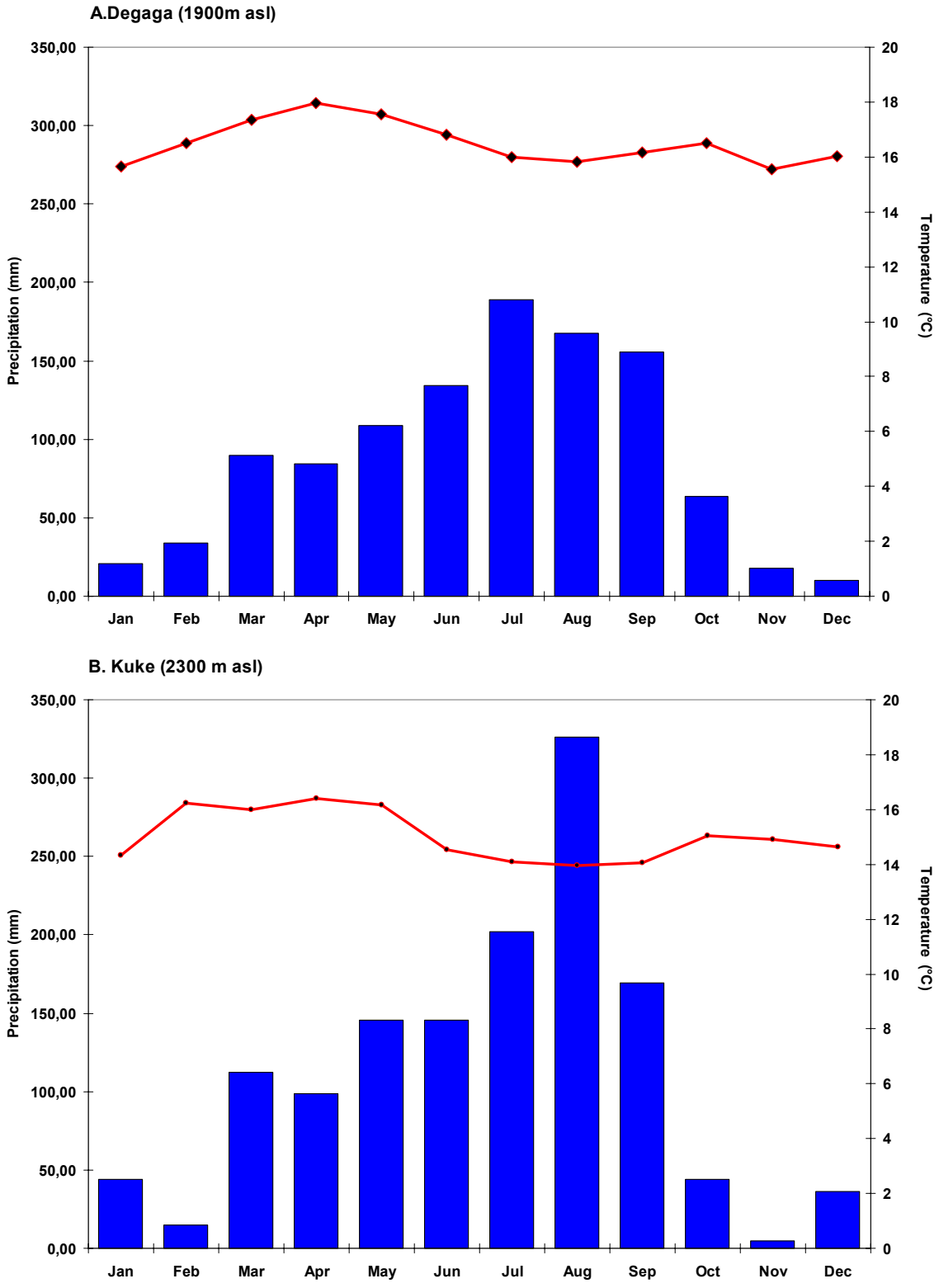


Fig. 3: Mean annual rainfall and mean annual temperature of the study area, A = Degaga, mean values averaged over 18 years for rainfall and 16 years for temperature (Source: Ethiopian Meteorological Service). B = Kuke, annual rainfall and temperature for the year 2002, recorded by a µMETOS weather station.

2.4 Vegetation

General classifications of the vegetation of the study area have been given in different forest and vegetation surveys (Chaffey 1979; Friis 1992; von Breitenbach 1962). According to Friis (1992) and own observation, the Munessa-Shashemene Forest contains a mixture of *Podocarpus falcatus* and broad-leaved species in the canopy at altitudes ranging from 2300-2500 m. Other medium sized canopy trees include *Croton macrostachys*, *Olea hochstetterii* and *Schefflera abyssinica*. Smaller trees and larger shrubs include *Allophylus abyssinicus*, *Bersama abyssinica*, *Brucea antidysenterica*, *Calpurnia aurea* and *Discopodium penninervium*.

At higher altitudes, between 2600-2800 m, the composition of the canopy altered and consists of mainly *Hagenia abyssinica*, *Hypericum revolutum*, *Schefflera volkensii*, *Nuxia congesta*, *Rapanea simensis* and *Arundinaria alpina*. Generally the epiphytes include orchids, ferns, mosses and lichens. *Urera hypselodendron* is the most common liana.

2.5 Human impact and history of the study area

Knowledge of the historical background of the Munessa-Shashemene Forest is useful in assessing the influence of forest conversion on the basic components of its ecosystem. Such information is also useful to indicate future directions for SFM. The following brief history focuses on changes that occurred in the Munessa-Shashemene Forest due to human influences.

The human interactions with the Munessa-Shashemene Forest, like the other forests in the highlands of Ethiopia, could have started thousands of years ago. For example, vegetation changes under human impact as early as 2000 years ago have been reported by Friis (1992) and Tamrat (1994). According to Assefa (1996), the Arssi Zone was inhabited by the Sidama state of Dawaro before the arrival of the Oromo in the area around the mid-sixteenth century. Between the sixteenth and

the nineteenth century, the Arissi Zone was dominated by nomadic Ormomo people, consisting of big Oromo tribes such as *Macca*, *Tulamma*, *Borana* and *Karayu* (Assefa 1996).

Following the conquest of the Arssi area by the Amhara in the nineteenth century, most of the land use system changed from nomadic to sedentary (Assefa 1996; Cohen 1987). The change in the land use habit might have been one of the factors that contributed to the deforestation of the Munessa-Shashemene Forest prior to 1930.

The heavy exploitation of the forest started after the 1930's with the establishment of sawmills in the forest. For example, von Breitenbach (1962) reported the presence of a sawmill in the Shashemene State Forest in 1946. This region suffered extensive deforestation after the Italian occupation, mainly because of the fuel and construction needs of northern immigrant settlers and the surrounding towns demand for charcoal (Assefa 1996). The exploitation was high because of its location at less than 250 Km from the major timber consumption center of Addis Ababa (Holmberg 1973).

Due to the high rate of deforestation in the Munessa-Shashemene Forest, the Chilalo Agricultural Development Unit (CADU) started large-scale plantations in 1968 as part of its rural integrated project (Hvidberg-Hansen 1977). The CADU's main objective was to find suitable tree species for the various ecological zones and expand forest areas to combat problems of land degradation through the protection of soil erosion (Cohen 1987). As a trial, many tree species of *Eucalyptus*, *Cupressus* and *Pinus* were planted between 1968 and 1970 in sites known as Degaga, Kuke and Gambo (Hvidberg-Hansen 1977). The plantations with exotic trees were established both by clearing the natural forest and in adjacent farmlands. In some areas the clearing of the natural forest was attained by burning. After burning the area was cultivated for three years before the plantation was established (Hvidberg-Hansen 1977). With the exception of *Eucalyptus globulus*, the introduction of exotic tree species in large-scale

plantations in the Munessa-Shashemene Forest was the first of its kind in Ethiopia (Hvidberg-Hansen 1977; von Breitenbach 1962).

As of 1987, the Munessa and Shashemene Forests were merged into one management system called the Munessa-Shashemene Integrated State Forestry Development and Utilization Project. According to Silvanova, (1996) the Project concession area is ca 98,000 ha out of which 17,000 ha was disturbed natural forest, 22,000 ha was bush, bamboo thicket and woodland; 6,000 ha was plantation and 53,000 ha was open land (agricultural and grassland). The objectives of this project were to conserve and wisely utilize the natural and the plantation forests (MoA 1990).

The economy of the people currently living around the Munessa-Shashemene Forest is based on livestock and crop productions. Livestock production includes cattle, goats, sheep, donkeys, horses and chickens. The major crops produced include different varieties of barley (*Hordeum vulgare*) wheat (*Triticum* sp.), millet (*Eleusine coracana*), maize (*Zea mays*), teff (*Eragrostis tef)*, sorghum (*Sorghum vulgare*), onion (*Allium cepa*), potato (*Solanum tuberosum*) and sugarcane (*Saccharum officinarum*). It is a common practice to use artificial fertilizer for crop production. The forest provides the local people with many resources that are essential for their livelihood (see section 1.2). More details on the socioeconomic aspects of the study area are given in Assefa (1996) and Müller-Hohenstein and Abate (2002).

3 Materials and Methods

3.1 Tree species studied

Four tree species (hereafter referred to as study trees) were selected for the present study. *Podocarpus falcatus* (Thunb.) Mirb., Podocarpaceae, which is a climax and highly demanded timber tree and *Croton macrostachys* Hochst. Del., Euphorbiaceae, which is the most common pioneer species, were selected from the natural forest. *Cupressus lusitanica* Miller, Cupressaceae and *Eucalyptus globulus* Labill., Myrtaceae were selected from the plantation forests. The *Cupressus lusitanica* plantation had the highest area coverage (62%) compared to the other plantation forests of the Munessa-Shashemene Forest (Silvanova 1996).

In order to facilitate the integration of the multidisciplinary research (soil science, ecophysiology and geobotany), all data required by the different disciplines were collected from similar plots established in the natural and plantation forests. The vegetation cover of these plots was estimated using the Braun-Blanquet method (Mueller-Dombois and Ellenberg 1974).

3.2 Belowground biomass sampling

3.2.1 Excavations

For a tree root, knowledge of the vertical and horizontal distribution of the root system is generally required before coring a particular portion of the root system using an auger (Böhm 1979; do Rosario et al. 2000). Therefore, the study trees were excavated before root coring by auger. The trees selected for excavation had similar DBH and were representative of the actual growth conditions.

3.2.2 Root system architecture

Root system architecture plays a major role in anchoring as well as in water and nutrient uptake of plants. Root architecture types can be determined and classified using branching patterns (Berntson 1997; Fitter 1991; Fitter and Stickland 1991; van Noordwijk and Muli 2002). Methods and justifications with regard to characterizing branching patterns are discussed in Berntson (1992), Berntson (1997), Fitter (1987) and Fitter and Stickland (1991). Such methods, however, require careful uprooting of all the root systems, mapping and analysis with a computer software designed for architectural analysis (Berntson 1992; Oppelt et al. 2001).

The most important root features that show systematic variation and that are useful to describe root systems are diameter, color and surface texture (Fitter 1991; Schroth 2003). Therefore, in the present study, observation of the general appearance of the root system and the diameters of tap and coarse lateral roots were used to characterize the root system of the study trees. It should be noted that the study trees excavated to determine the sampling design for root coring (section 3.2.1) were used to characterize the root system architecture of the study trees.

3.2.3 Sampling distance and depth

Following the excavations, the sampling distances and depths were determined. From each of the study trees, root samples were collected at the distance of 1, 2 and 3 meters from the bole of the trees. From each of the distances, samples were taken at the depth intervals 0-10 cm, 10-35 cm, 35-60 cm, 60-85 cm and 85-100 cm.

Samples were taken from six lines marked from the bole towards the canopy edge. These lines were marked by dividing the basal diameter into equal sections. The first three lines were sampled in April and the rest were sampled in August. According to the climatic condition of study area, the samples taken in April

represent the dry season and the samples taken in August represent the wet or rain season. Figure 4 shows a sketch of the sampling design for root coring.

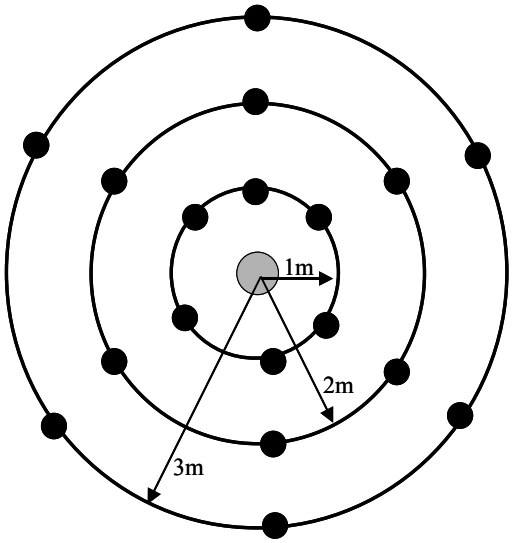


Fig. 4: Sketch of the fine root sampling design, the arrows show the distance from the bole, the bigger dot in the center and the dots on the circles indicate root coring spots.

3.2.4 Root coring

For complete quantitative information, auger sampling is the best technique (do Rosario et al. 2000). The core size of an auger is important in determining the quantity and quality of root samples to be collected. Generally, a small auger size is preferable when root densities are higher and many replicates are needed (Böhm 1979; do Rosario et al. 2000). The most commonly used core diameters range from 5 to 8 cm. For the present study, a hand auger with an inner diameter of 8 cm and a core length of 25 cm was used.

3.2.5 Sample storage

Information on methods for storing samples for short and long periods are given in Böhm (1979), Caldwell and Virginia (1989) and Schuurman and Goedewaagen (1971). Generally it is preferable to wash soil-root samples immediately after sampling in order to minimize weight losses by root respiration and microbial decomposition (Böhm 1979; do Rosario et al. 2000). Nevertheless, because of the

large size of the samples and lack of facilities in the proximity of the study site, root samples were stored for a period of 1-2 months before they were washed. As deep freeze is the best technique for long period storing (Böhm 1979), the root samples for this study were stored in a deep freeze. Even with the deep freezing technique it is possible that some root degradation occur before the samples attain the desired temperature (do Rosario et al. 2000).

3.2.6 Root washing and isolation

The root samples were washed following Böhm's method (1979). First, the samples were thawed for about 8 hours. Then the root samples were put in a bucket filled with water and left for overnight. The following day, the samples were stirred by hand until a homogenous suspension was formed. Then, the stirred solution was allowed to settle for 30 minutes and the suspension was poured onto 1 and 0.5 mm^2 meshes, which were placed upon each other. The remaining soil was half filled with water, stirred and poured until all roots were transferred onto the sieves. Live fine roots (hereafter referred to as LFR) < 2 mm in diameter were isolated using a 10x magnification lens. Color and structure were used to identify roots of the study trees from other species. Live roots were distinguished by their color and elasticity (Böhm 1979). The roots were dried at 85°C for 24 hrs. The weight was determined with a balance sensitive to 0.01 g.

3.2.7 Pit excavation and root mapping

Profile wall methods, in which roots on the exposed face of a soil trench are counted, are ideal for assessing spatial variation in the distribution of roots (Böhm 1979). The trench profile wall technique was used to map the root distribution of the study trees. At 1 m and 2 m distances from the bole of each of the study trees, 1 m^2 (1m deep and 1 m wide) soil pits were excavated. The profile was smoothed using a spade and the roots were exposed using a knapsack sprayer and knife. Then a plastic sheet was firmly placed on the profile wall and mapping was accomplished

with the aid of a wood frame. A 1.20 m x 1.20 m wood frame made out of wood and nylon was used to map the plots on a plastic sheet.

3.3 Aboveground biomass sampling

3.3.1 Stand Analysis

Due to the high heterogeneity in species composition in the natural forest compared to the plantation forests, a larger plot size was used in the natural forest for stand analysis. Thus, five plots with the size of 20 m x 30 m were established in the natural forests whereas five plots with a size of 20 m x 20 m were established in each of *C. lusitanica* and *E. globulus* forest. In each of the plots the DBH of the study trees was measured. The DBH data was used to determine the diameter class of trees to be felled. Six individuals from each of *C. macrostachys*, *C. lusitanica* and *E. globulus* species were felled. Felling *P. falcatus* was avoided because of conservation interest and not to cause additional disturbances to the natural forest ecosystem.

3.3.2 Field Sampling

After the trees were felled, they were separated into bole and branches. The bole was cut into 2 m logs, and disks about 5 cm long were cut from each of the logs. Then, the fresh weights of each of the logs were determined in the field. The basal diameter of each of the branches was recorded. Representative branches were sampled from the upper, medium and lower parts of the crown and their fresh weight was determined in the field. The disks and branches were oven dried at 105°C until they reached a constant weight. Foliage was sampled from representative branches and air-dried.

3.3.3 Establishment of allometric equation

Methods used to measure forest tree biomass include the mean tree method and direct measurements of photosynthesis and respiration. A detailed procedure on the methods for measuring aboveground biomass and productivity is given in Satoo and Madgwick (1982) and Brown (1997).

The most commonly used method in estimating the biomass of trees in a forest ecosystem is the allometric method in which biomass estimating equations are developed as a function of the DBH and/or height and dry weights of plant components. Different kinds of allometric equations can be used. Commonly used equations include linear, exponential and quadratic equations (Bonham 1989). In the present study, total aboveground biomass was determined using linear regression equations. The total foliage and total branch weights were determined on the basis of the allometric relation between basal branch diameter (BBD) and the dry foliage and branch weights, respectively (Bonham 1989). The total aboveground biomass was determined on the basis of the relation between DBH and dry weights of the aboveground plant components.

3.4 Macronutrient analyses

The macronutrients analysed from aboveground and belowground plant materials were carbon (C), nitrogen (N), phosphorus (P) potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) and sulphur (Smit et al.). CNS was analysed using CNS-Analyzer “Elementar Vario EL”. Inductively coupled plasma atomic emission spectrometry “(ICP-AES)” was used to analyse Na, Ca, Mg, K and P.

3.5 Statistical Analysis

Statistical analysis of the data was mainly carried out in replicates by one-way analysis of variance (ANOVA) using the software package STATISTICA: Release 6.1. If the main effects were significant at $P < 0.05$, a post hoc separation of means was done using Scheffé's test.

4 Results

4.1 Vegetation of the permanent plots

Figure 5 depicts the profile and canopy diagrams of the vegetation in the permanent plot of the natural forest. The important trees in this plot were *P. falcatus*, *Celtis africana*, *C. macrostachys*, *Syzygium guineense*, *Maytenus arbutifolia* and *Prunus africana*. Common shrub species include *Rubus steudneri* and Rytigynia *neglecta*. The most common herb species were *Oplismenus compositus*, *Hypoestes forskaolii* and *Bothriocline schimperi*. The lianas include *Urera hypselodendron, Jasminum abyssinicum and Acanthopale pubescens*. The names of the species in this plot are listed in Appendix 1.

Figure 6 and 7 show the profile and canopy diagrams of the *C. lusitanica* and *E. globulus* plantations, respectively. In the *C. lusitanica* plantation the most common herbs were *Hypoestes forskaolii* and *Carex spicato-paniculata* (Appendix 2) whereas in the *E. globulus* plantation, *C. macrostachys* was common and herbs that were also common in the natural forest were present (Appendix 3).

Though most of the shrub and herb species present in the *E. globulus* plantation were also present in the *C. lusitanica* plantation, there was a significant difference in their growth pattern. In the former, the plants were growing more lavishly and the ground was fully covered. Whereas in the latter, the growth of the species was poor and the ground was poorly covered.

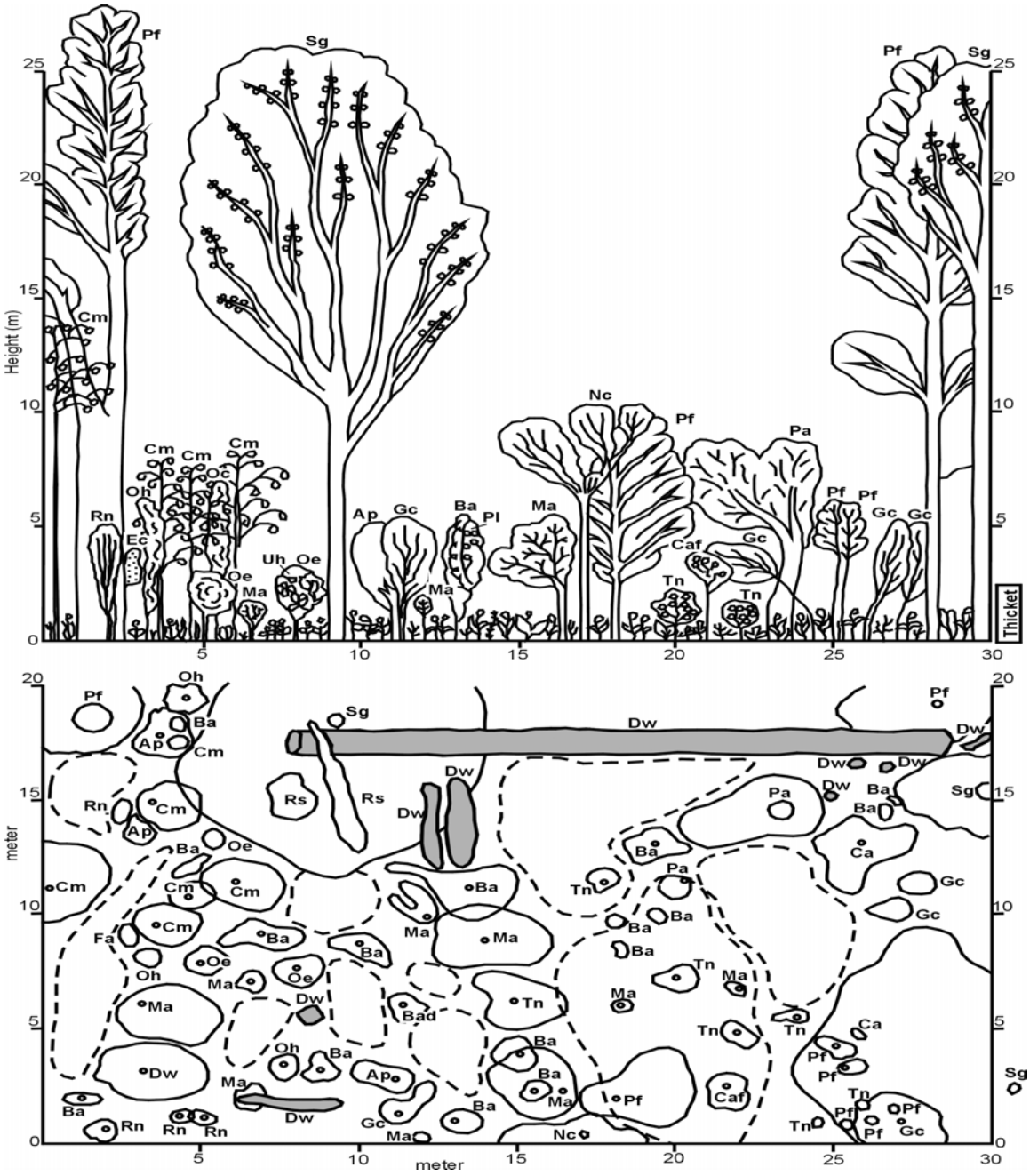


Fig. 5: Profile and canopy diagrams of the vegetation in one of the permanent plots of the natural forest. AP = *Acanthopale pubescens*, Ba = *Bersama abyssinica*, Bad = *Brucea antidysenterica*, Ca = *Calpurnia aurea*, Caf = *Celtis africana*, Cm = *Croton macrostachys*, Dw = dead wood, Fa = *Fagaropsis angolensis*, Gc = *Galiniera coffeoides*, Ma = *Maytenus arbutifolia*, Nc = *Nuxia congesta*, Oh = *Ochna holstii*, Oe = *Olea europaea* subsp. *cuspidata*, Pl =*Periploca linearifolia*, Pf = *Podocarpus falcatus*, Pa = *Prunus africana*, Rs = *Rubus steudneri*, Rn = *Rytigynia neglecta*, Sg = *Syzygium guineense*, Tn = *Teclea nobilis*, Uh = *Urera hypselodendron*. The thickets (also shown with broken lines in the canopy diagram) mainly include *Oplismenus compositus* and *Hypoestes forskaolii* (see Appendix 1 for the details).

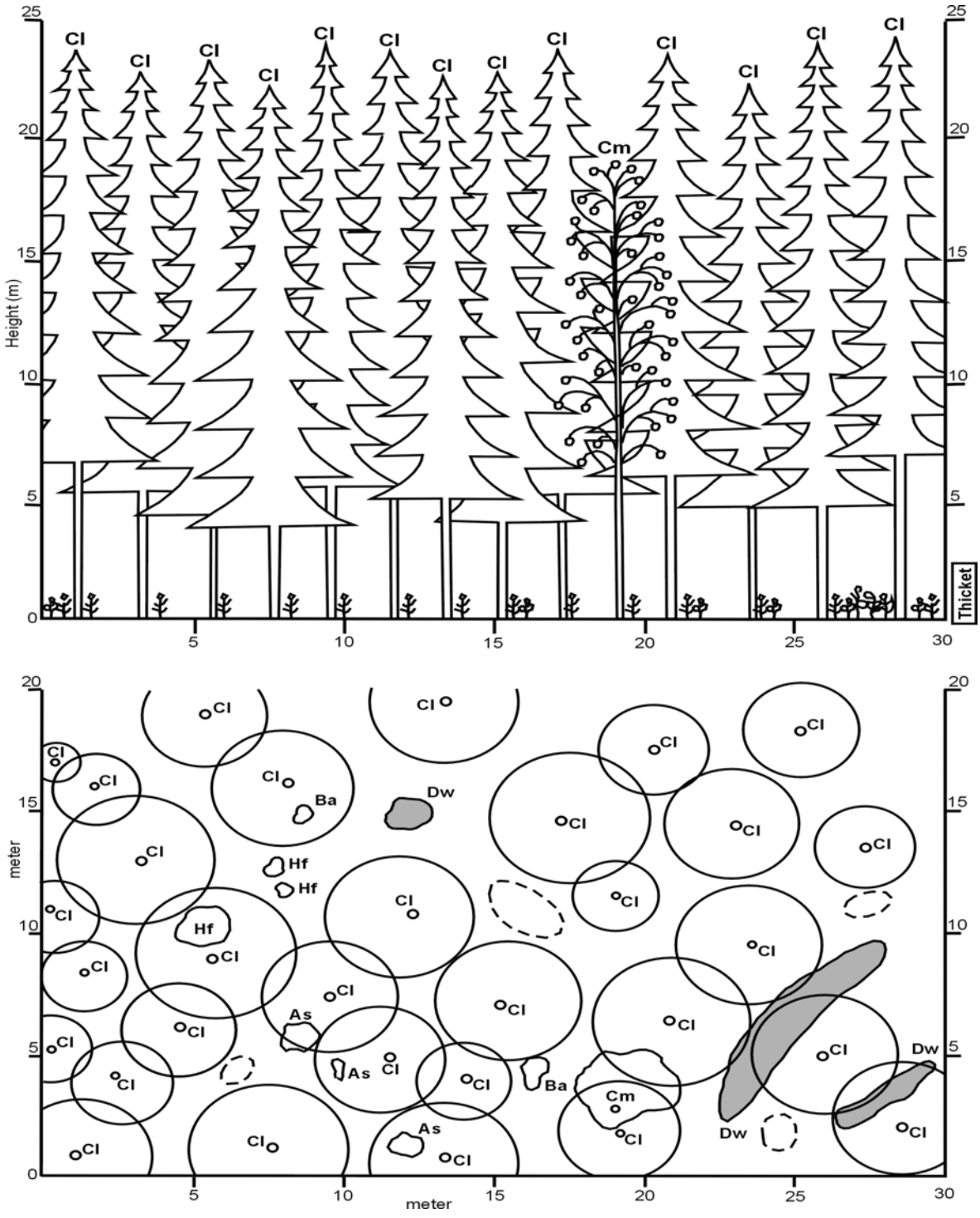


Fig. 6: Profile and canopy diagrams of the vegetation in *C. lusitanica* plantation. As = *Achyrospermum schimperi*, Ba = *Bersama abyssinica*, Cm = *Croton macrostachys*, Cl = *Cupressus lusitanica*, Dw = dead wood, The thickets (also indicated with broken lines in the canopy diagram) mainly include *Carex spicato-paniculata* and *Hypoestes forskaolii* (Hf) (see Appendix 2 for the details).

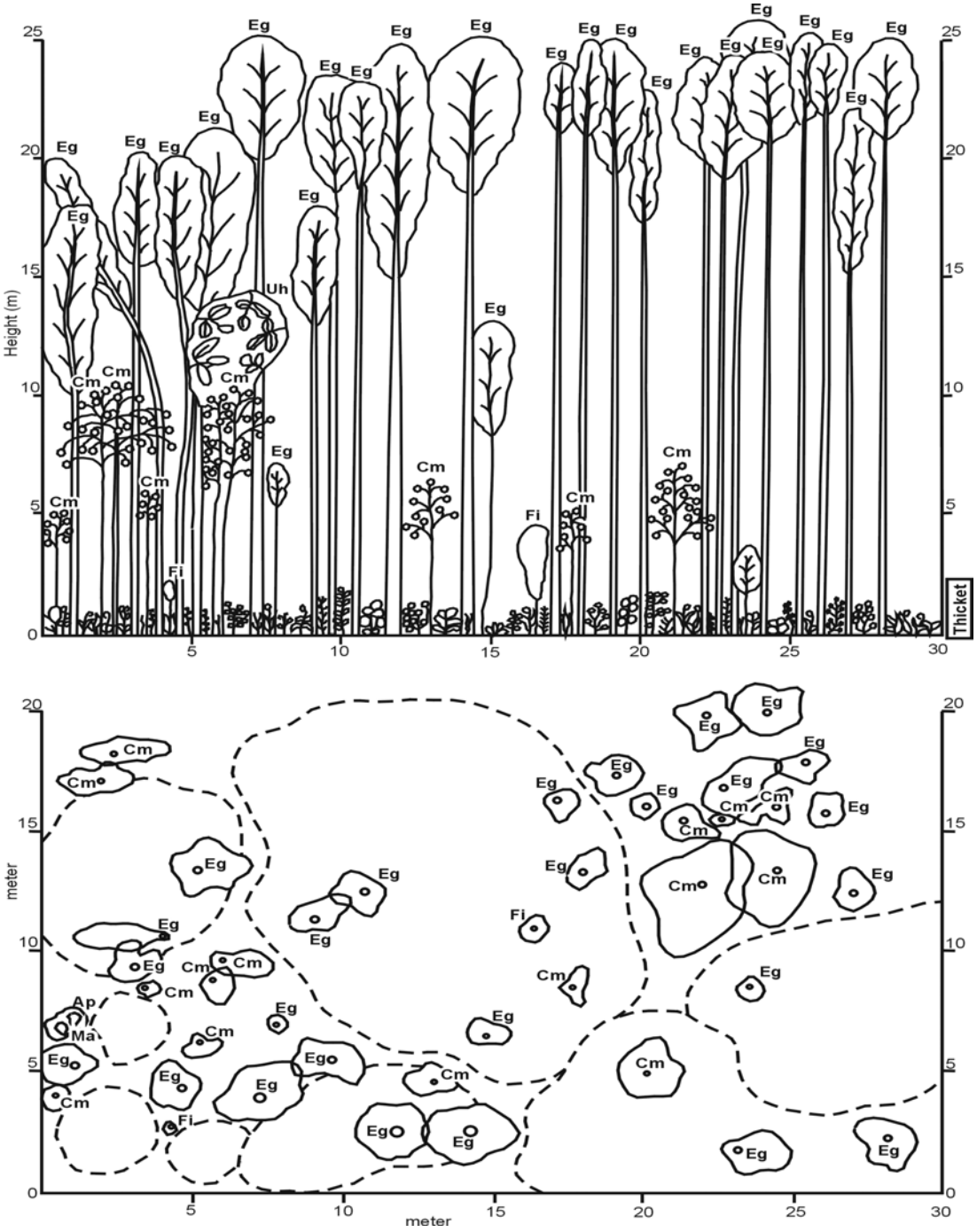


Fig. 7: Profile and canopy diagrams of the vegetation in the *E. globulus* plantation. Ap = *Acanthopale pubescens*, Cm = *Croton macrostachys*, Eg = *Eucalyptus globulus*, Dw = dead wood, Fi = *Flacourtia indica* Uh = *Urera hypselodendron*. The thickets (also indicated with broken lines in the canopy diagram) mainly include *Acanthopale pubescens* (Ap) and *Hypoestes forskaolii* (see Appendix 3 for the details).

4.2 Root system architecture

As described in section 3.2.2 above, observation of the general appearance of the root system and the diameters of tap and coarse lateral roots were used to characterize the root system of the study trees.

Figure 8 depicts the root architecture of the study trees. For all the study trees, the primary root was distinctly present and grew vertically to various depth levels. In the natural forest, *C. macrostachys* had a deeper taproot and relatively thicker tap and lateral roots compared to *P. falcatus*. The maximum lateral root horizontal length of *C. macrostachys* was also about twice the length of maximum lateral root horizontal length of *P. falcatus* (Tab. 1).

In the plantation forests, the taproot of *E. globulus* was deeper and the lateral roots were thicker and had a higher maximum lateral root length compared to *C. lusitanica* (Tab. 1).

Tab. 1: DBH and features of root system architecture of the study trees. TD = taproot diameter, LRD = lateral root diameter and LRHL = lateral root horizontal length.

Species	DBH (cm)	Taproot depth (m)	Mean* TD (cm)	Mean* LRD (cm)	Maximum LRHL (m)
P. falcatus	13	1.5	5.0	3.0	2.0
C. macrostachys	15	1.7	7.0	4.0	3.8
C. lusitanica	12	1.0	3.5	2.0	1.4
E. globulus	13	2.0	4.0	3.0	3.5

*mean diameter refers to the average diameter at the base and tip of the tap and lateral roots.

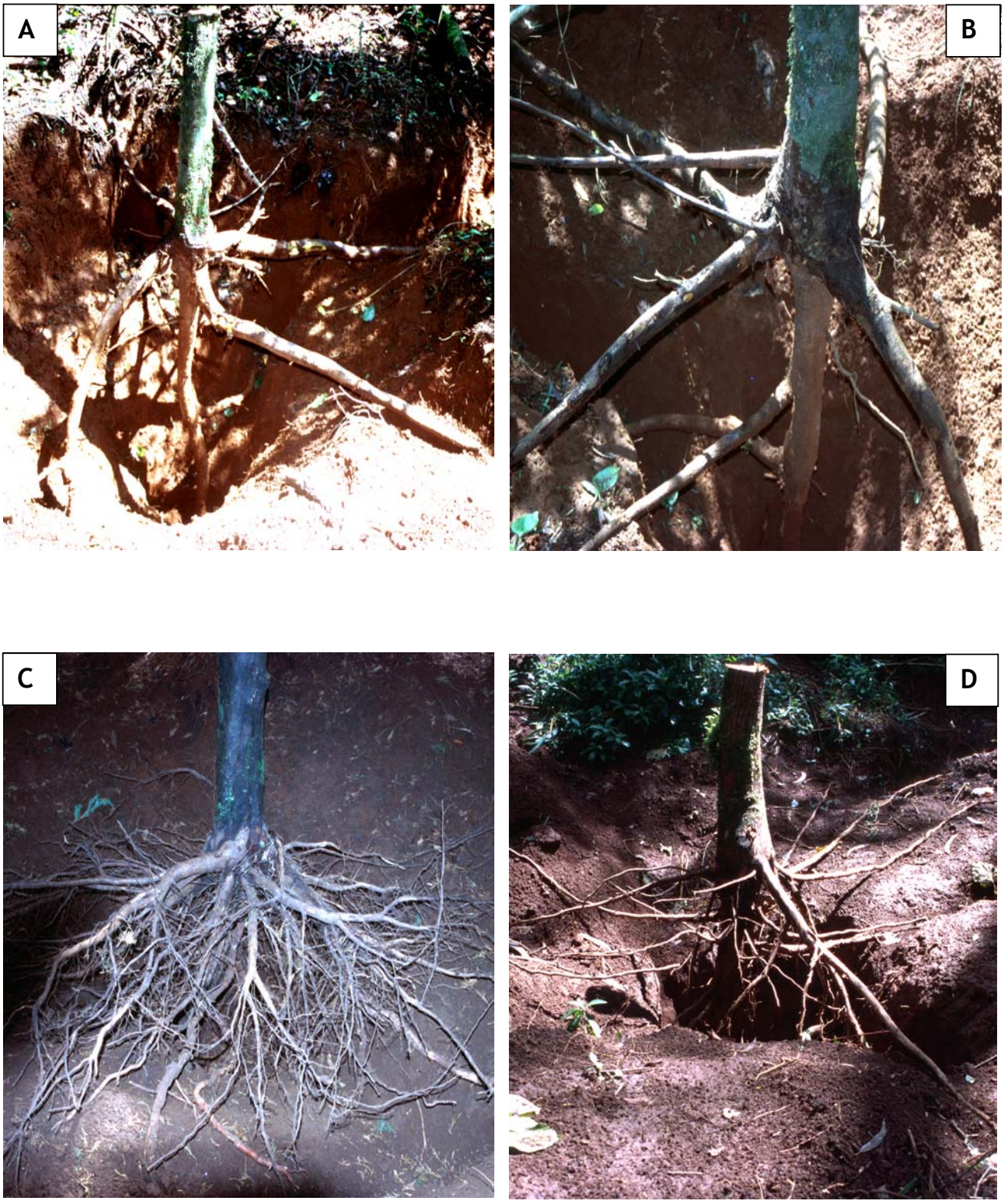


Fig. 8: Root architecture of the study trees. A = *P. falcatus*, B = *C. macrostachys*, C = *C. lusitanica*, D = *E. globulus*.

4.3 Root density

Root numbers counted along soil depths on a profile wall give information on the rooting density in a soil profile (Böhm 1979). The root density (number of roots per unit area) of the study trees was taken from a 1 m x 1m profile wall dug at 1 m and 2 m distances from the bole. It was found that for all the study trees and at both distances (except at the 2 m distance of *P. falcatus*), over 50% of the fine roots were within the upper 30 cm.

In the case of *P. falcatus*, the density of fine roots at 1 m distance was slightly lower (729 m^{-2}) than the fine root density at 2 m distance (752 m^{-2}). Of the total fine root density, 54 and 46% were found at the depth interval of 0-30 cm at 1 m and 2 m distances, respectively (Fig. 9). At both distances, the density of fine root biomass decreased sharply with depth, accounting for only 8 and 7.5% at the 80-100 cm depth interval at 1 m and 2 m distances, respectively.

The density of roots with diameter 2-5 mm was much lower compared to the fine root (< 2 mm) density at both distances with densities of 81 m^{-2} and 80 m^{-2} at 1 m and 2 m distances, respectively. As with the fine root density, the density of roots with diameter 2-5 mm decreased with depth (Fig. 9). The density of roots with diameter > 5 mm was much lower compared to the fine roots and roots with diameter 2-5 mm. The densities were 17 m^{-2} and 18 m^{-2} at 1 m and 2 m distances respectively. At both distances the density was highest at the depth interval from 0-60 cm.

In the case of *C. macrostachys*, the density of fine roots was higher at the 2 m distance (968 m^{-2}) compared to 1 m (664 m^{-2}). At both distances, over 50% of the fine root density was found at the depth interval 0-30 cm and sharply decreased with depth (Fig. 10).

The density of roots with diameter 2-5 mm was slightly higher at the 2 m distance (38 m^{-2}) compared to 1 m (34 m^{-2}). At the 1 m distance, over 50 % of the density of roots with diameter 2-5 mm was found at the depth interval 0-30 cm and decreased with depth, whereas at the 2 m distance its density was similar at the depth intervals 0-30 cm (32 m^{-2}) and 60-80 cm (34 m^{-2}) (Fig. 10).

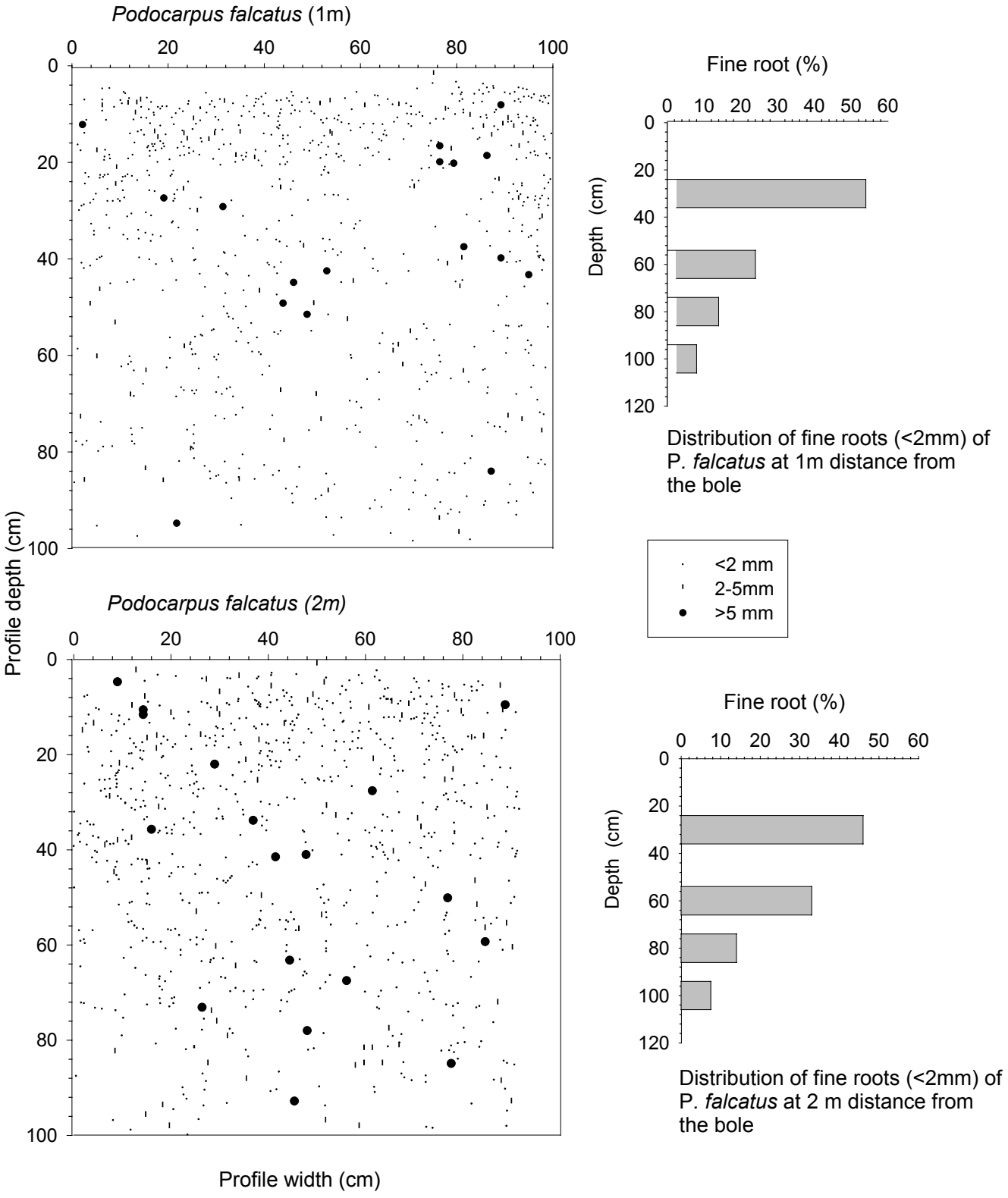


Fig. 9: Root distribution of *P. falcatus*. The profile wall diagram (left) shows the distribution of all root diameter classes. The bar graph (right) shows the distribution of only fine roots (< 2 mm).

The density of roots with diameter > 5 mm was much lower compared to both fine roots and roots with diameter 2-5 mm (Fig. 10) with values of 18 m^{-2} and 8 m^{-2} at the distances of 1 m and 2 m, respectively. At both distances there was relatively higher density at the depth interval 0-30 cm.

For *C. lusitanica*, the fine root biomass was higher at the distance of 2 m (1200 m^{-2}) compared to 1 m (920 m^{-2}). Though total density was higher at the 2 m distance, the density of roots within the first 30 cm was higher at 1 m, with 72 and 69% at 1 m and 2 m distances, respectively. At both distances density decreased sharply with depth (Fig. 11).

The density of roots with diameter 2-5 mm was much lower compared to the density of fine root density at both distances. Concurrent with the fine root biomass, there was high density at the depth intervals 0-30 cm at 1 m (75%) and 2 m (71%) and at both distances density decreased with depth (Fig. 11).

The density of roots with diameter > 5 mm was much lower compared to both fine roots and root diameter 2-5 mm (Fig. 11) with densities of to 17 m^{-2} and 6 m^{-2} at distances of 1 m and 2 m, respectively. Almost all the roots with diameter > 5 mm were found at the depth interval 0-30 cm at the 1 m distance whereas at the 2 m distance they were uniformly distributed beyond the 30 cm depth (Fig. 11).

With *E. globulus*, the density of fine root biomass was higher at the 2 m distance (1261 m^{-2}) compared to the 1 m distance (902 m^{-2}). At the depth interval of 0-30 cm, 57% and 72% of the total density were found at the 1 m and the 2 m distances, respectively. At both distances density decreased with depth (Fig. 12).

The density of roots with diameter 2-5 mm was much lower compared to the fine root density at both distances. However, similar to the fine root density, it was higher at the depth interval 0-30 cm with 57% and 48% at 1 m and 2 m distances, respectively (Fig. 12).

The density of roots with diameter > 5 mm was much lower compared to the densities of the fine root biomass and roots with diameter 2-5 mm. The densities were 14 m^{-2} and 17 m^{-2} at 1 m and 2 m distances, respectively (Fig. 12). With regard to the density distribution, 93% of the total density was found at the depth interval 0-30 cm at 1 m distance whereas at 2 m distance there was a proportional amount of roots at the depth interval 0-30 (53%) and 30-60 cm (41%).

Overall, fine root density was higher in the plantation species *C. lustitanica* and *E. globulus* compared to the species in the natural forest. In all the species the high root density at the depth interval 0-30 cm was concurrent with the high biomass values at a similar depth interval (see the section on the fine root biomass below).

4.4 Fine root biomass

4.4.1 Root coring time

The time required to take samples by auger is mainly a function of the auger diameter, soil texture and soil moisture. However, the duration required to take samples using an auger is rarely reported (Böhm 1979).

In the present study, the amount of time required to take samples was recorded to provide valuable planning information for researchers who might work under similar conditions. As described above, the soil texture of the study area consists of more than 60% clay. Particularly during the dry season (soil moisture ca. -400 hPa), auguring was a formidable task. The average time required to sample from depth intervals 0-10 cm and 10-35 cm was 20 minutes. A screw-jack was used to pull out the augur, especially from the depth intervals 35-60 cm, 60-85 cm and 85-100 cm. The average time needed to sample from these depths was 45 minutes.

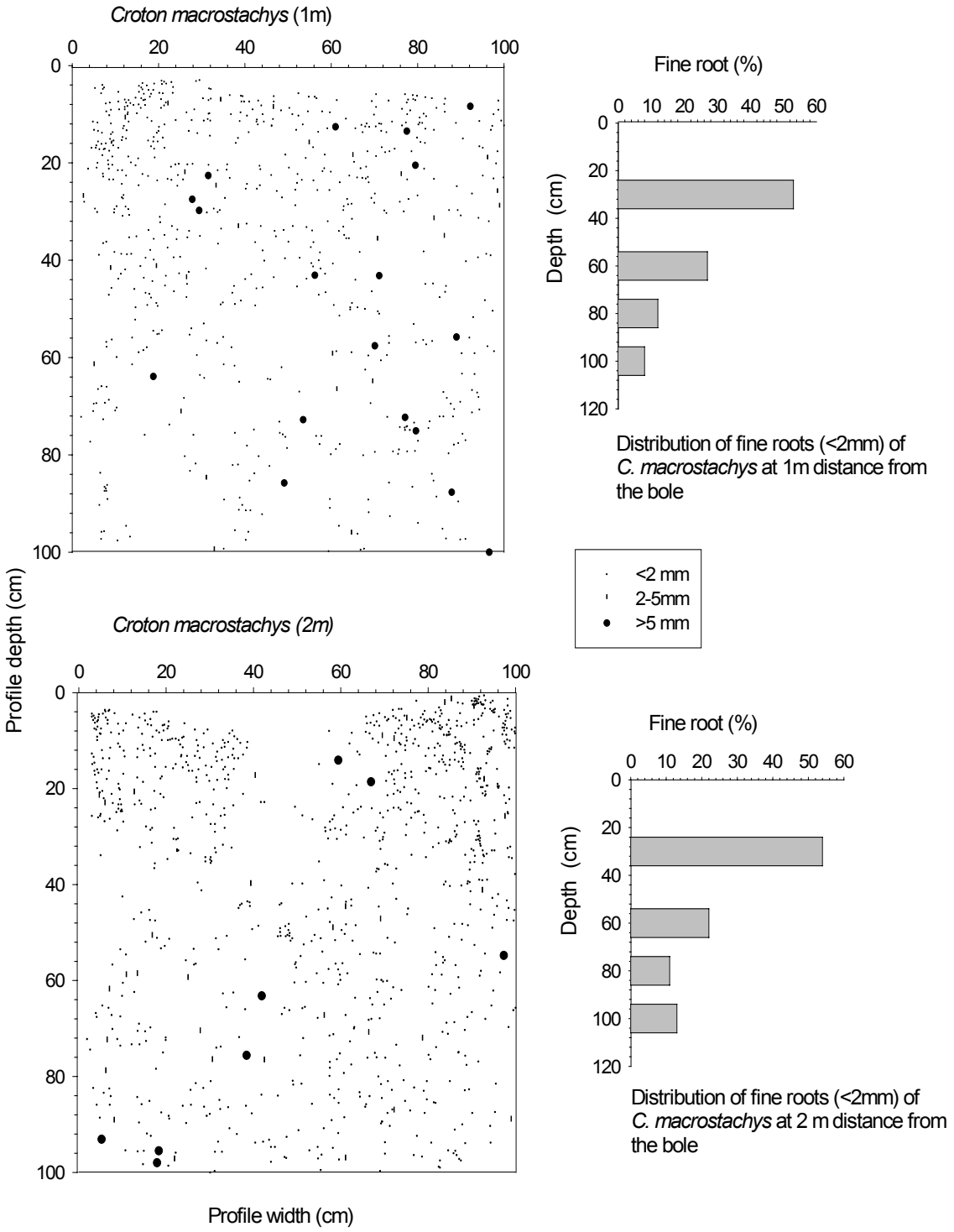


Fig. 10: Root distribution of *C. macrostachys*. The profile wall diagram (left) shows the distribution of all root diameter classes. The bar graph (right) shows the distribution of only fine roots (< 2 mm).

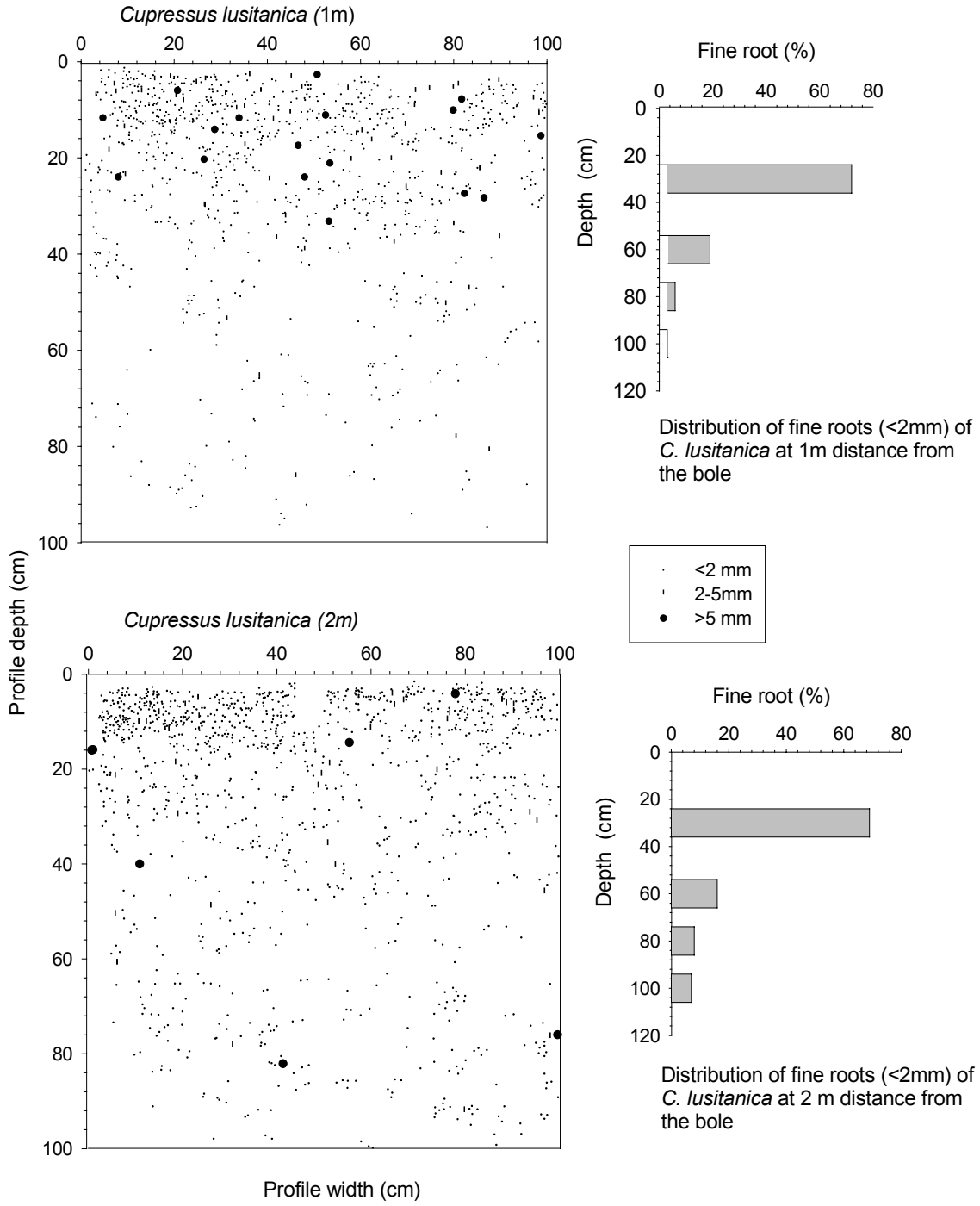


Fig. 11: Root distribution of *C. lusitanica*. The profile wall diagram (left) shows the distribution of all root diameter classes. The bar graph (right) shows the distribution of only fine roots (< 2 mm).

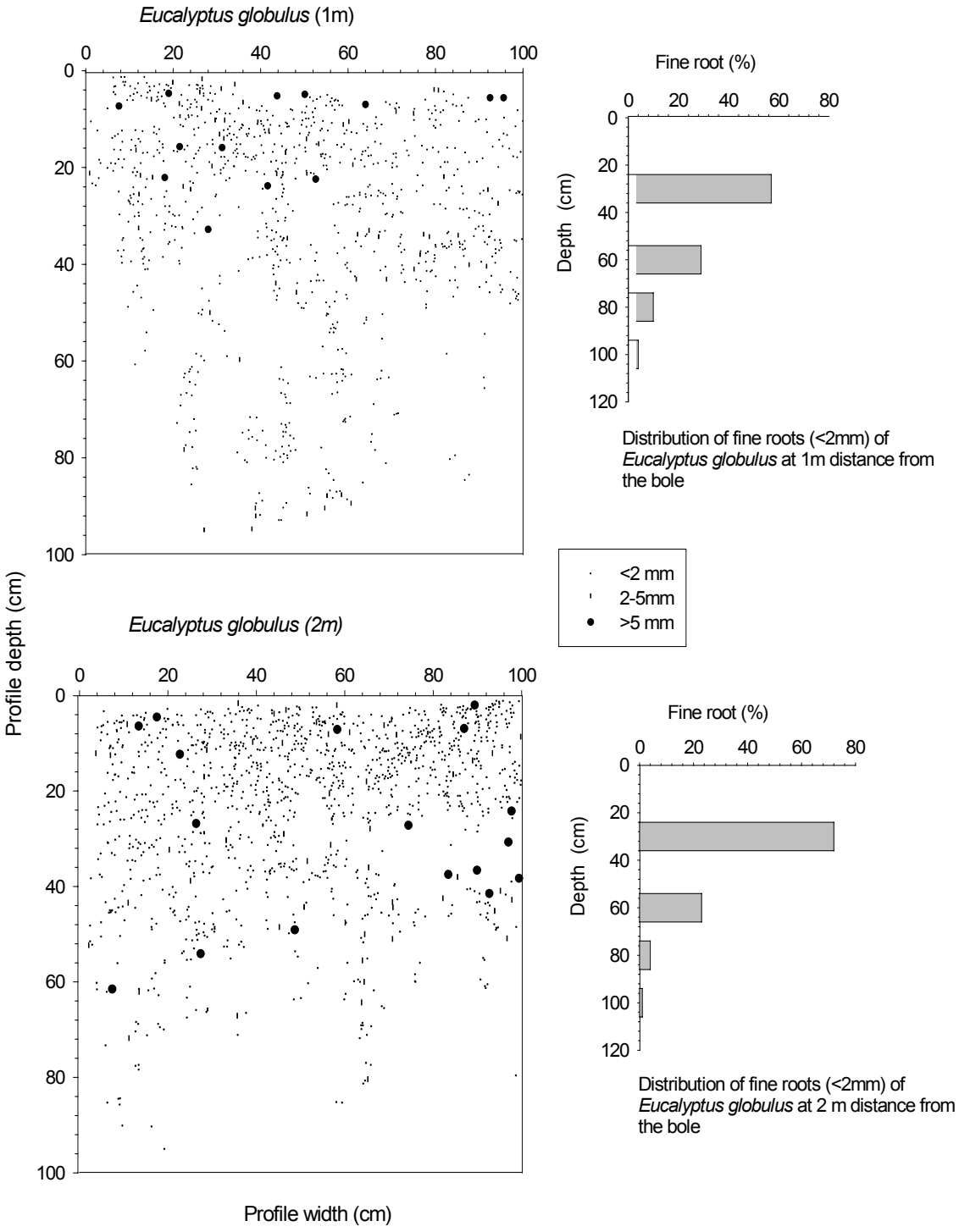


Fig. 12: Root distribution of *E. globulus*. The profile wall diagram (left) shows the distribution of all root diameter classes. The bar graph (right) shows the distribution of only fine roots (< 2 mm).

On the other hand, sampling during the rainy season (soil moisture ca. -100 hPa) was relatively easy. The average time for the depth intervals 0-10 cm and 10-35 cm was 10 minutes and the average time to take sample from the depth intervals of 35-60 cm, 60-85 cm and 85-100 cm was 30 minutes.

4.4.2 Seasonal changes in LFR biomass

For *P. falcatus*, the dry season LFR biomass was higher than the wet season LFR biomass at all distances and depth intervals (Tab. 2). However, the differences were not significant ($P < 0.05$) except at the 1 m distance and the depth intervals 10-35 cm, 35-60 cm and 85-100 cm (Tab. 2).

Tab.2: Mean dry and wet seasons LFR biomass (g/m^3) of *P. falcatus*, n = 3.

		Depth (cm)				
Distance (m)	**Season**	**0-10**	**10-35**	**35-60**	**60-85**	**85-100**
1	**Dry**	5170.55	2048.75[a]	1815.27[a]	2216.82	2726.63[a]
	Wet	3433.90	845.94[b]	548.98[b]	336.88	244.26[b]
2	**Dry**	3577.94	1659.93	2080.42	1022.52	1763.48
	Wet	3427.47	703.97	846.04	239.61	311.94
3	**Dry**	4611.32	1717.02	1359.29	900.74	1658.97
	Wet	2412.32	787.47	776.33	371.65	384.31

Means at each of the depth intervals at similar distances were compared using the t-paired test. Only means with significant difference at $p < 0.05$ are followed by different letters.

Also for *C. macrostachys*, the dry season LFR biomass was higher than the wet season LFR biomass (Tab. 3). There was no significant difference between dry and wet season LFR biomass at $p < 0.05$. Generally, LFR biomass was higher at the 1 m distance from the bole in both dry and wet seasons compared to the 2 m distance (Tab. 3).

Tab. 3: Mean dry and wet seasons LFR biomass (g/m^3) of *C. macrostachys*, n = 3.

		Depth (cm)				
Distance (m)	**Season**	**0-10**	**10-35**	**35-60**	**60-85**	**85-100**
1	**Dry**	2105.22	736.78	68.41	538.93	168.17
	Wet	439.73	326.51	23.79	17.80	72.64
2	**Dry**	1653.69	63.24	1027.37	34.11	858.02
	Wet	1132.25	66.37	75.39	33.10	35.46
3	**Dry**	1751.70	243.35	112.84	518.87	116.36
	Wet	521.56	157.32)	81.81	89.50	21.88

Similar to *P. falcatus* and *C. macrostachys*, the dry season LFR biomass of *C. lusitanica* was higher than the wet season LFR biomass (Tab. 4). There was no significant difference between dry and wet season LFR biomass at $p < 0.05$, except at the 2 m distance at the depth intervals 10-35 cm and 35-60 cm.

Tab. 4: Mean dry and wet seasons LFR biomass (g/m^3) of *C. lusitanica* , n = 3.

		Depth (cm)				
Distance (m)	**Season**	**0-10**	**10-35**	**35-60**	**60-85**	**85-100**
1	**Dry**	2625.53	920.74	1481.81	528.34	1684.79
	Wet	1661.31	586.19	69.98	50.39	108.31
2	**Dry**	3539.81	1852.40^a	1286.82^a	1520.04	945.78
	Wet	1406.79	441.79^b	85.23^b	91.04	133.12
3	**Dry**	3245.04	1015.36	763.76	584.44	1952.92
	Wet	1278.01	1017.90	280.91	74.27	83.95

Means at each of the depth intervals at similar distances were compared using the t-paired test. Only means with significant difference at $p<0.05$ are followed by different letters.

In contrast to, the results from the other study trees, the wet season LFR biomass at most of the distances and depth intervals were higher compared to the dry season biomass for *E. globulus* (Tab. 5). However, there was no significant difference between dry and wet season LFR biomass at $p < 0.05$.

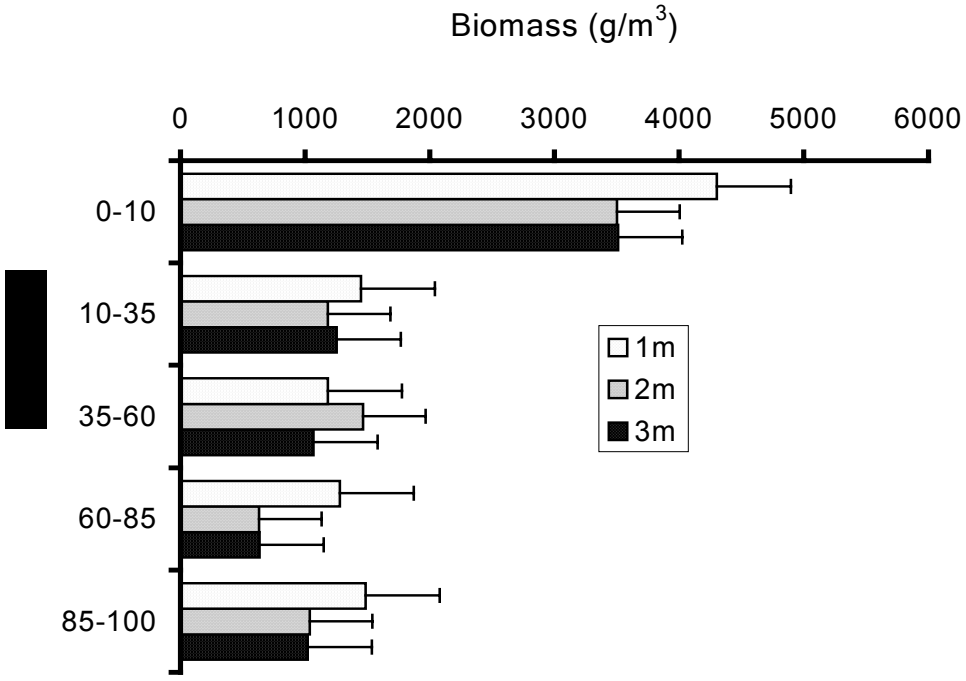
Tab.5 : Mean dry and wet seasons LFR biomass (g/m^3) of *E. globulus*, n = 3.

		Depth (cm)				
Distance (m)	**Season**	**0-10**	**10-35**	**35-60**	**60-85**	**85-100**
1	**Dry**	1464.56	692.93	152.52	84.26	72.24
	Wet	1965.76	398.29	129.82	19.92	17.51
2	**Dry**	1113.02	273.93	100.59	87.64	131.35
	Wet	1153.61	454.49	153.79	94.75	8.98
3	**Dry**	893.06	270.29	69.23	35.44	110.88
	Wet	1411.24	352.24	129.92	78.44	28.65

4.4.3 Annual fine root biomass distribution

The mean annual LFR biomass of *P. falcatus* was much higher at the depth interval 0-10 cm and at distance 1 m distance from the bole (Fig. 13). Generally, the mean annual LFR biomass was higher at the depth interval 0-10 cm at all distances and ranged from 3502.70 ± 156.65 g/m^3 to 4302.22 ± 490.343 g/m^3. Also, the mean annual LFR biomass was higher at the 1 m distance from the bole at all the depths except the depth interval 35-60 cm. Mean LFR biomass was moderately to slightly higher at the depth interval 85-100 cm compared to 60-85 cm at all distances.

Fig. 13: Fine root biomass distribution (g/m^3) of *P. falcatus* with soil depths and distances, n=6.



For *C. macrostachys*, the mean LFR annual biomass was higher at the depth interval 0-10 cm at all distances and ranged from 1136.63 ± 568.78 g/m^3 to 1392.97 ± 156.65 g/m^3 (Fig. 14).

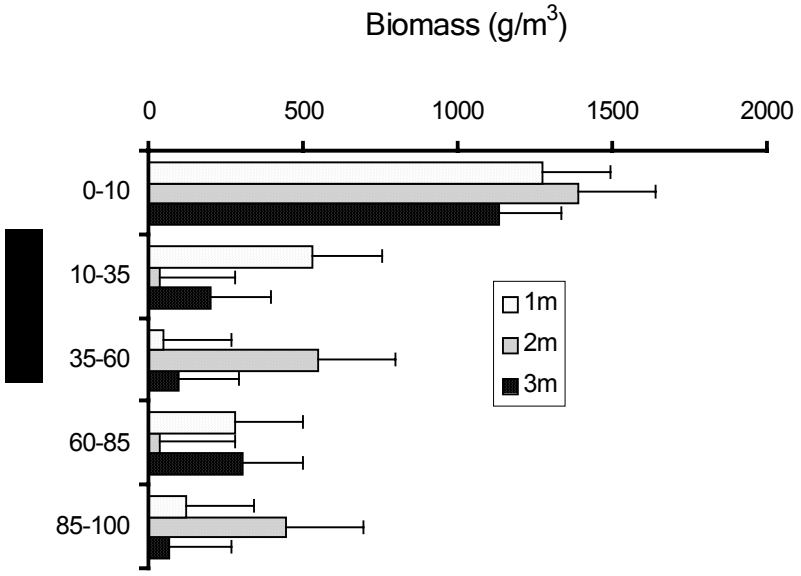


Fig. 14: Fine root biomass distribution (g/m^3) of *C. macrostachys* with soil depths and distances, n=6.

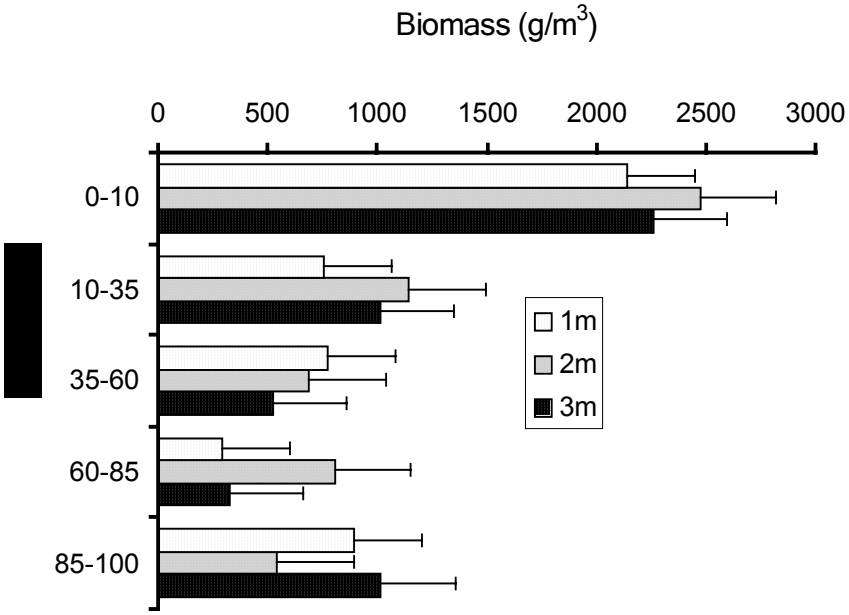


Fig. 15: Fine root biomass distribution (g/m^3) of *C. lusitanica* with soil depths and distances, n=6.

Similar to the natural forest species, the mean LFR annual biomass of *C. lusitanica* and of *E. globulus* were higher at the depth interval 0-10 cm at all distances and ranged from 2143.42 ± 642.62 g/m^3 to 2473.3 ± 746.19 g/m^3 (Fig. 15) and 1133.32 ± 246.52 g/m^3 to 1715.16 ± 328.06 g/m^3 (Fig. 16), respectively.

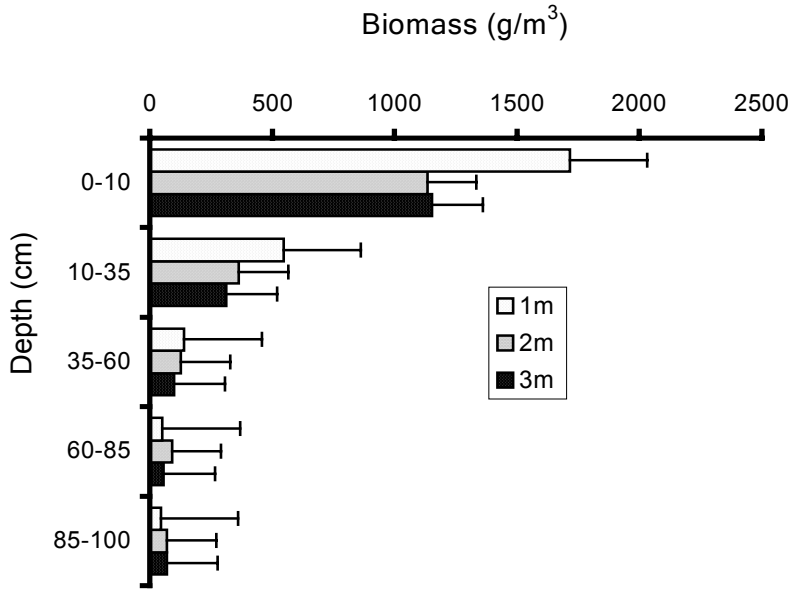


Fig. 16: Fine root biomass distribution (g/m^3) of *E. globulus* with soil depths and distances, n=6.

4.4.4 Total LFR biomass

Comparison of the total LFR biomass of the study trees up to the depth interval of 1 m revealed that *P. falcatus* had the highest LFR biomass compared to the other study trees, whereas *E. globulus* had the lowest total fine root biomass (Fig. 17).

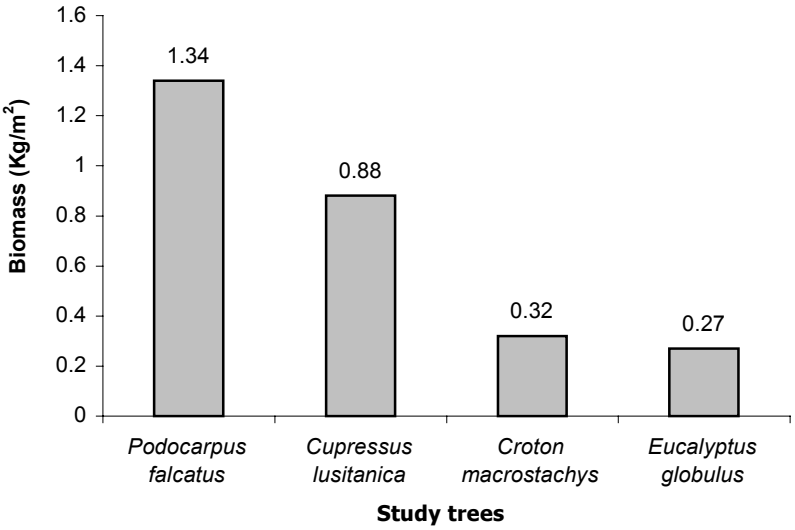


Fig. 17: Total live fine root biomass of the study trees up to 1 m depth, n=90.

4.5 Aboveground biomass

4.5.1 Stand structure

Due to differences in the densities between the natural and plantation forests, comparison of the stand structure was made only between the study trees from the natural forest, i.e. *P. falcatus* and *C. macrostachys* and the study trees from the plantation forests, i.e. *C. lusitanica* and *E. globulus*.

Thus, in the natural forest, the density of *C. macrostachys* was higher (143.2 trees ha^{-1}) than the density of *P. falcatus* (73.2 trees ha^{-1}) (Tab. 6). In the plantations, the density of *C. lusitanica* was slightly higher (610 trees ha^{-1}) than the density of *E. globulus* (595 trees ha^{-1}).

On the other hand, the mean DBH and DSH of P. falcatus were higher than the mean DBH and DSH of *C. mcarostachys*. The mean stand basal area of C. lusitanica was slightly higher than the mean stand basal area of *E. globulus* (Tab. 6). Despite the higher tree density in the Cupressus plantation, its mean DBH and mean diameter at stump height (DSH) were higher compared to the Eucalyptus plantation (Tab. 6).

Tab. 6: Structural characteristics of the study trees.

Species	Age	Height (m)	Total Density (N ha^{-1})	Stand Basal Area (m^2 ha^{-1})	Mean DBH (cm)	Mean DSH (cm)
P. falcatus	-	35	73 ± 39	56 ± 40	64 ± 16	69 ± 17
C. macrostachys	-	20	143 ± 72	5 ± 2	13 ± 1	15 ± 1
C. lusitanica	21	22	610 ± 165	37 ± 4	29 ± 24	33 ± 24
E. globulus	31	40	595 ± 192	34 ± 6	24 ± 13	27 ± 12

Values are means ± SD, n = 5

4.5.2 Biomass regression equations

For all of the study trees, except *P. falcatus*, which was not felled or sampled because of its big size and conservation interest, the best-fit equation was the linear regression equation. Figure 18 shows the relationships between the dry weights of different tree components with branch basal diameter (bbd) and DBH in *C. macrostachys*. Branch basal diameter was a good estimator of dry branch and foliage weights with R^2 values of 0.95 and 0.81 respectively. However, the total branch and foliage weights are poorly correlated with DBH with R^2 values of 0.78 and 0.48, respectively. Both the dry weights of stem wood and the total aboveground biomass showed a good correlation with DBH as indicated by a high R^2 value of 94 each (Fig. 18).

With *C. lusitanica*, all the allometric models expressing dry weight of tree components as a function of BBD and DBH had high R^2 values exceeding 90 (Fig. 19).

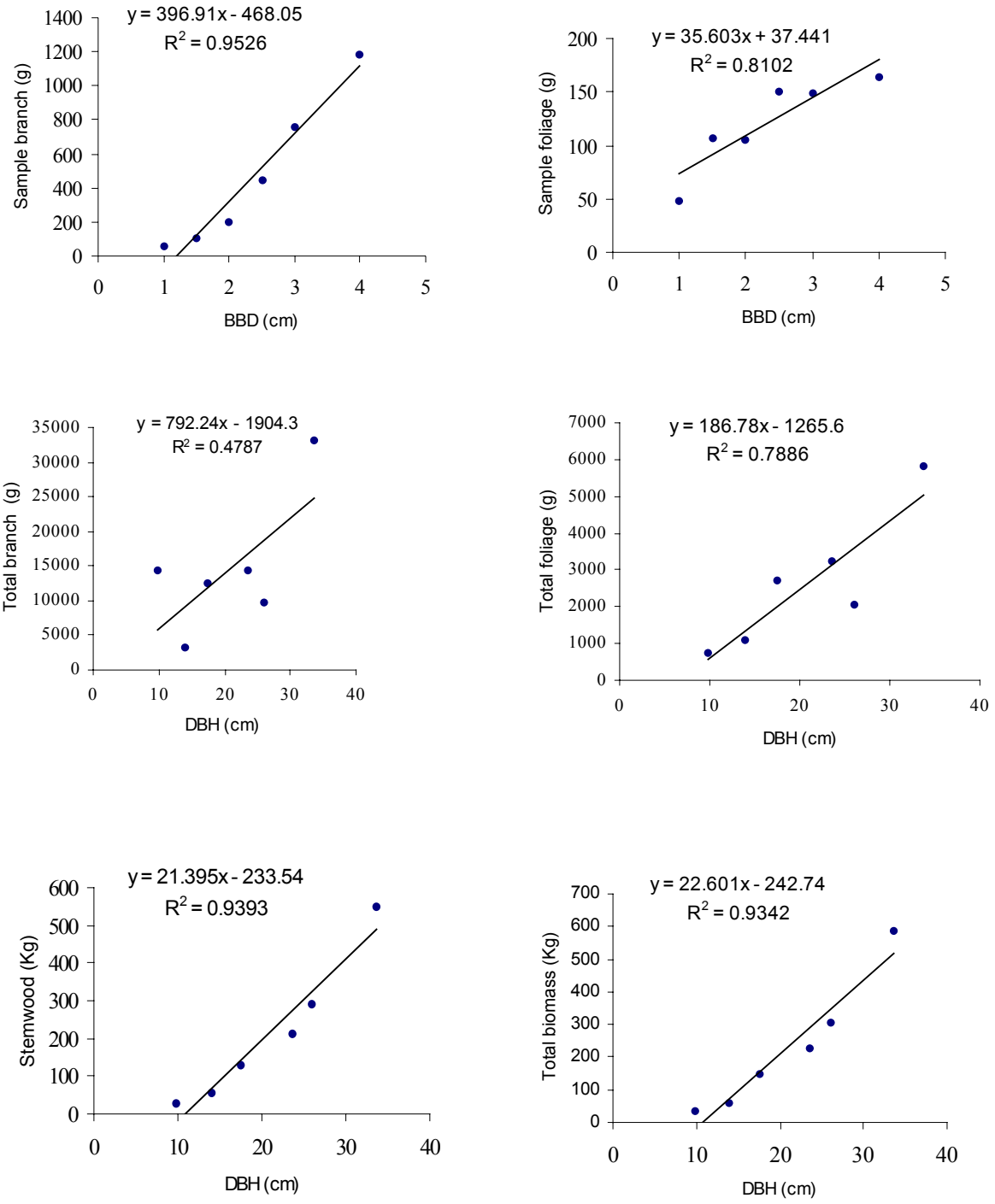


Fig. 18: Relationships between the dry weight of tree components BBD (branch basal diameter) and DBH for *C. macrostachys*. The fitted curves are linear regression equations and R^2 is the coefficient of determination.

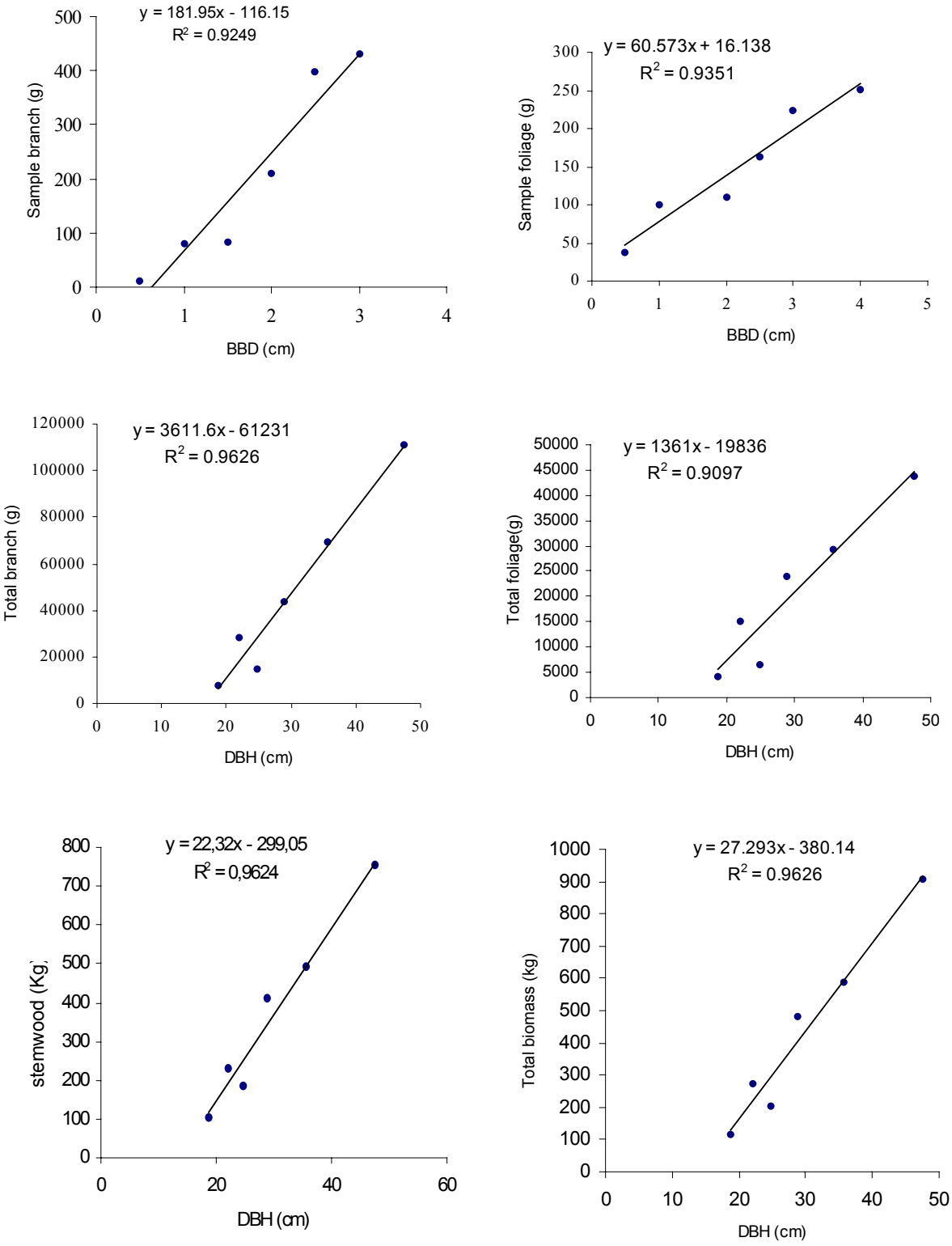


Fig. 19: Relationships between the dry weight of tree components BBD (branch basal diameter) and DBH for *C. lusitanica*. The fitted curves are linear regression equations and R^2 is the coefficient of determination.

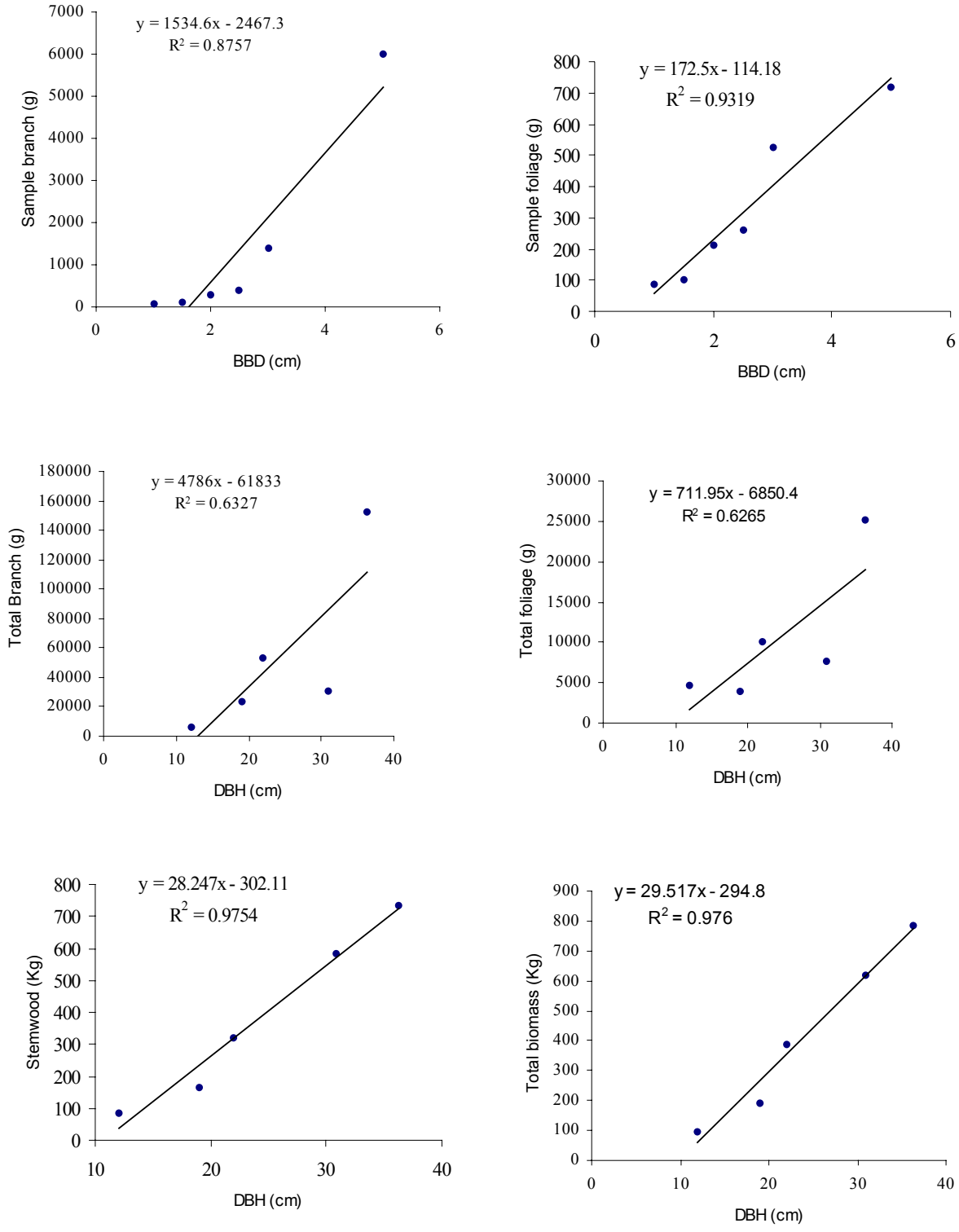


Fig. 20: Relationships between the dry weight of tree components BBD (branch basal diameter) and DBH for *E. globulus*. The fitted curves are linear regression equations and R^2 is the coefficient of determination.

4.5.3 Stand aboveground biomass

As described previously, five stands with a size of 20 m x 30 m were used in the natural forest. The DBH of all *C. macrostachys* in these stands was measured and the linear regression equation applied to estimate the total above ground biomass as a function of DBH. From this the stand biomass was estimated. Accordingly, the total aboveground biomass of *C. macrostachys* in each of the stands ranged from 1 t ha^{-1} to 46 t ha^{-1} with an average stand biomass of 13 t ha^{-1} (Tab. 7).

In *C. lusitanica* and *E. globulus* plantations, the plot size was 20 m x 20 m. The stand biomass for *C. lusitanica* ranged from 158 t ha^{-1} to 269 t ha^{-1} with an average stand biomass of 217 t ha^{-1}. The stand biomass in *E. globulus* was higher compared to *C. lusitanica*. It ranged from 203 t ha^{-1} to 426 t ha^{-1}, with an average stand biomass of 255 t ha^{-1} (Tab. 7).

Tab.7: Stand aboveground biomass (t ha^{-1}) of the study trees.

	Species		
Stand	*C. macrostachys*	*C. lusitanica*	*E. globulus*
1	2	178	177
2	1	269	426
3	46*	158	247
4	15	233	221
5	2	249	203
Average	**13**	**217**	**255**

*It was much higher as the plot sample was taken at the forest margin.

4.5.4 Aboveground biomass allocation

The aboveground biomass of *C. macrostachys* ranged from 35 kg/tree to 587 kg/tree with an average value of 227 kg/tree. Of the total biomass, 93% was allocated to the stemwood, 6% to the branches and 1% to the foliage (Fig. 21).

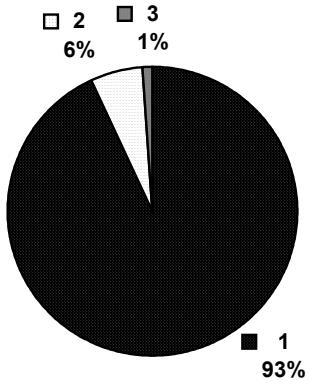


Fig. 21: Aboveground biomass (kg) allocation of *C. macrostachys* 1 = stemwood, 2 = branch; and 3 = foliage, n=5.

For *C. lusitanica*, the total aboveground biomass ranged from 116 kg/tree to 907 kg/tree with an average value of 428 kg/tree. Out of this, 85% was allocated to the stemwood, 11% to the branches and the remaining 4% was allocated to the foliage (Fig. 22). For *E. globulus* the total aboveground biomass ranged from 94 kg/tree to 783 kg/tree with an average value of 415 kg/tree. With regard to the allocation of dry weight, *Eucalyputs globulus* allocated over 90% of its aboveground biomass to the stemwood, followed by branches (8%) and foliage, (2%) (Fig. 22).

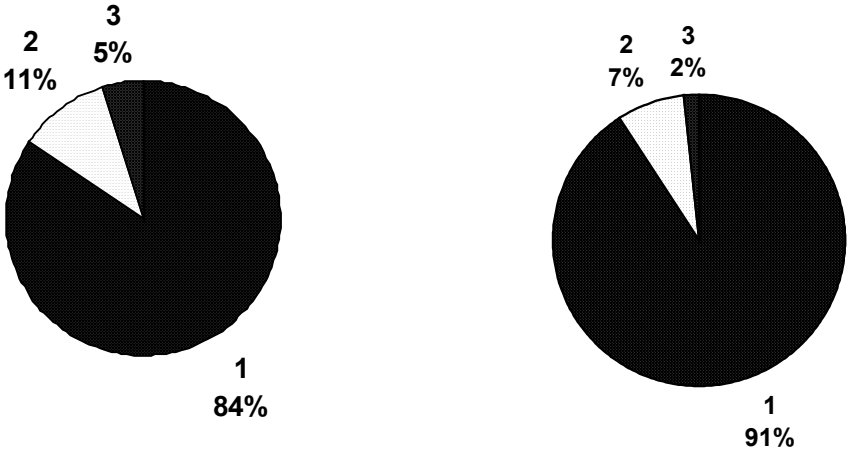


Fig. 22: Aboveground biomass (kg) allocation of *C. lusitanica* (Left) and *E. globulus* (Right), 1 = stemwood, 2 = branch; and 3 = foliage.

4.5.5 Estimation of total belowground biomass

The total aboveground biomass of a tree has been good predictors of its belowground biomass (Cairns et al. 1997; Cannell 1982). Total root biomass for each of the study trees were calculated following Cairns et al. (1997). Thus, a conversion factor of 0.25 was used to calculate the belowground biomasses of each of the study trees from their total aboveground biomass.

Accordingly, the total belowground biomass of *C. lusitanica* was slightly higher than the total belowground of *E. globulus* (Tab. 8). *C. macrostachys* had the lowest total belowground biomass.

Tab.8: Total aboveground and estimates of belowground biomass of the study trees.

Species	Average total Aboveground Biomass (kg)	Total Belowground Biomass (kg)	Total Biomass (kg)
C. macrostachys	227	57	284
C. lusitanica	428	107	535
E. globulus	415	104	519

4.6 Macronutrient concentrations in the study trees

As mentioned previously, knowledge of the macronutrient concentrations in the belowground and aboveground components of the study trees is useful for a sustainable management of forests. Therefore, the distributions of macronutrients in the belowground (fine roots) and aboveground components (foliage, twigs, bark and stemwood) of each of the study trees at the time of sampling are presented below.

4.6.1 Fine roots macronutrient concentrations

The fine root macronutrient concentrations of the study trees are indicated in Tab. 9. In the case of *P. falcatus*, the fine root concentrations of N, Ca and S were significantly higher ($p < 0.05$) at the depth interval 0-10 cm compared to lower depths (10-100 cm). The fine root concentration of P was slightly higher at the depth interval 0-10 cm. The fine root concentrations of C, Mg and Na were slightly higher at the depth interval 10-35 cm.

With *C. macrostachys*, the fine root concentrations of C, N, Ca and S were significantly higher ($p < 0.05$) at the depth interval 0-10 cm compared to the lower depths. The fine root concentrations of P, K, and Mg were slightly higher at the depth interval 0-10 cm compared to the lower depths. The concentration of Na was significantly higher ($p < 0.05$) at the depth interval 35-100 cm.

With *C. lusitanica*, the fine root concentrations of N and S were significantly higher ($p < 0.05$) at the depth interval 0-10 cm compared to the lower depths. Similarly, for *E. globulus*, the fine root concentrations of N and S were significantly higher ($p < 0.05$) at the depth interval 0-10 cm compared to the lower depths.

Comparison of the fine root macronutrient concentrations among the study trees revealed that the concentrations of N, P, K, Mg, and S were higher in the fine roots of *C. macrostachys* at all depth intervals compared to *P. falcatus* (Tab. 9). In the plantation forests, except for C, all the other macronutrients were higher in the fine roots of *E. globulus* at all depths compared to *C. lusitanica* (Tab. 9).

Generally, the concentrations of N, K, Mg and S were higher in the fine roots of *C. macrostachys* compared to the plantation species, whereas Ca and P were higher in the fine roots of *E. globulus* compared to the natural forest species. The concentration of C in the fine roots of *C. lusitanica* was higher compared to the natural forest species.

4.6.2 Fine root macronutrient stocks

Comparison of macronutrient stocks of the fine roots at the depth interval 0-10 cm at all distances revealed that in the natural forest *P. falcatus* had higher fine root macronutrient stocks than *C. macrostachys* (Fig. 23). In the plantation forest the fine root macronutrient stocks of *C. lusitanica* was higher than *E. globulus* (Fig. 23).

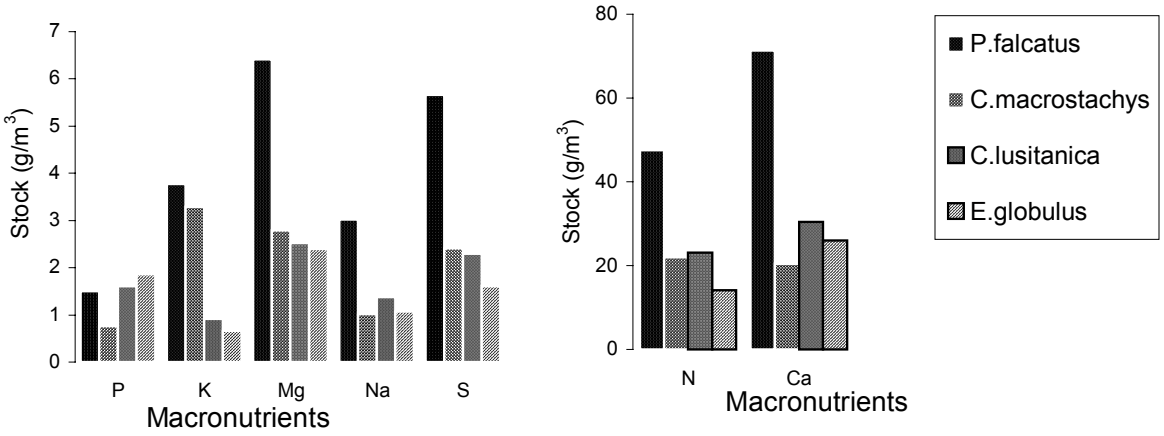


Fig. 23: Macronutrient stock in the fine roots of the study trees at the depth interval 0 - 10 at all distances, n = 18.

Tab.9: Mean macronutrient concentrations (% of dry weight) in the fine roots of the study trees (n = 12). Pf = *P. falcatus*, Cm = *C. macrostachys*, Cl = *C. lusitanica*, Eg = *E. globulus*.

Study trees	Depth	C	N	P	K	Ca	Mg	Na	S
Pf	0-10	45.50 (0.30)	1.26[a] (0.05)	0.04 (0.01)	0.10 (0.01)	1.89 [a] (0.12)	0.17 (0.01)	0.08 (0.01)	0.15[a] (0.01)
	10-35	45.74 (0.23)	0.91[b] (0.03)	0.03 (0.01)	0.10 (0.01)	1.57 [b] (0.12)	0.20 (0.03)	0.10 (0.02)	0.12[b] (0.01)
	35-100	45.20 (0.36)	0.84 [b] (0.02)	0.02 (0.01)	0.09 (0.01)	1.35 [b] (0.22)	0.18 (0.03)	0.08 (0.01)	0.11 [b] (0.01)
Cm	0-10	44.04[a] (0.30)	1.74 [a] 0.09	0.06 (0.01)	0.26 (0.02)	1.61 [a] (0.21)	0.22 (0.02)	0.08[a] (0.02)	0.19 [a] (0.03)
	10-35	42.39[b] (0.52)	1.29 [b] (0.03)	0.05 (0.01)	0.25 (0.02)	1.40 [a] (0.15)	0.17 (0.01)	0.11 [a] (0.03)	0.09 [b] (0.01)
	35-100	41.43[b] (1.12)	1.28 [b] (0.12)	0.05 (0.01)	0.25 (0.05)	0.82[b] (0.08)	0.18 (0.01)	0.16 [b] (0.05)	0.08 [b] (0.01)
Cl	0-10	47.10 (0.27)	1.01 [a] (0.04)	0.07 (0.01)	0.04 (0.01)	1.33 (0.09)	0.11 (0.01)	0.06 (0.01)	0.10 [a] (0.01)
	10-35	47.14 (0.51)	0.71 [b] (0.05)	0.11 (0.01)	0.03 (0.01)	0.85 (0.06)	0.09 (0.01)	0.06 (0.01)	0.07 [b] (0.01)
	35-100	47.09 (0.55)	0.70 [b] (0.03)	0.11 (0.01)	0.05 (0.01)	1.12 (0.33)	0.11 (0.01)	0.11 (0.04)	0.07 [b] (0.00)
Eg	0-10	43.02 (0.38)	1.06 [a] (0.05)	0.14 (0.01)	0.05 (0.01)	1.95 (0.08)	0.18 (0.02)	0.08 (0.01)	0.12 [a] (0.01)
	10-35	42.80 (0.27)	0.82 [b] (0.18)	0.17 (0.02)	0.05 (0.01)	1.72 (0.11)	0.17 (0.01)	0.09 (0.01)	0.07 [b] (0.01)
	35-100	42.57 (0.32)	1.03 (0.11)	0.15 (0.01)	0.05 (0.01)	1.65 (0.13)	0.16 (0.01)	0.15 (0.05)	0.07 [b] (0.01)

Only mean values followed with different letters are significantly different at $p < 0.05$.

4.6.3 Macronutrient concentrations in the aboveground components

a. Macronutrient concentrations in each of the study trees

The macronutrient concentrations in the aboveground components of *P. falcatus* are shown in Fig. 24. The concentrations of C and Na were highest in the stemwood with concentrations of 47.17% and 0.1%, respectively. The concentrations of N (1.39%), K (1.14%), Mg (0.22%) and S (0.14%) were highest in the foliage. The concentration of Ca (3.35%) was highest in the bark.

The macronutrient concentrations in the aboveground components of *C. macrostachys* are shown in Fig. 25. Similar to *P. falcatus*, the concentration of C (45.64%) was highest in stemwood of *C. macrostachys*. The concentrations of N (2.95%), P (0.17%), K (1.99%), Mg (0.31%) and S (0.19%) were significantly higher ($p < 0.05$) in the foliage of *C. macrostachys*. The concentration of Ca was significantly higher ($p < 0.05$) in the bark of *C. macrostachys*. There was no significant difference in Na concentration among the aboveground components.

The macronutrient concentrations in the aboveground components *C. lusitanica* are shown in Fig. 26. The concentrations C (49.00%), N (1.21%), P (0.07%), K (0.57%), Mg (0.17%), and S (0.19%) were significantly higher ($p < 0.05$) in the foliage and the concentration of Ca (2%) and Na (0.08%) were higher in the bark of *C. lusitanica*.

The macronutrient concentrations in the aboveground components of *E. globulus* are shown in Fig. 27. The concentrations of C (49.98%), N (1.59%), K (1.02%), Mg (0.31%), S (0.15%) were significantly higher ($p < 0.05$) in the foliage and P (0.19%), Ca (2.92%) and Na (0.16%) were significantly higher ($p < 0.05$) in the bark of *E. globulus*.

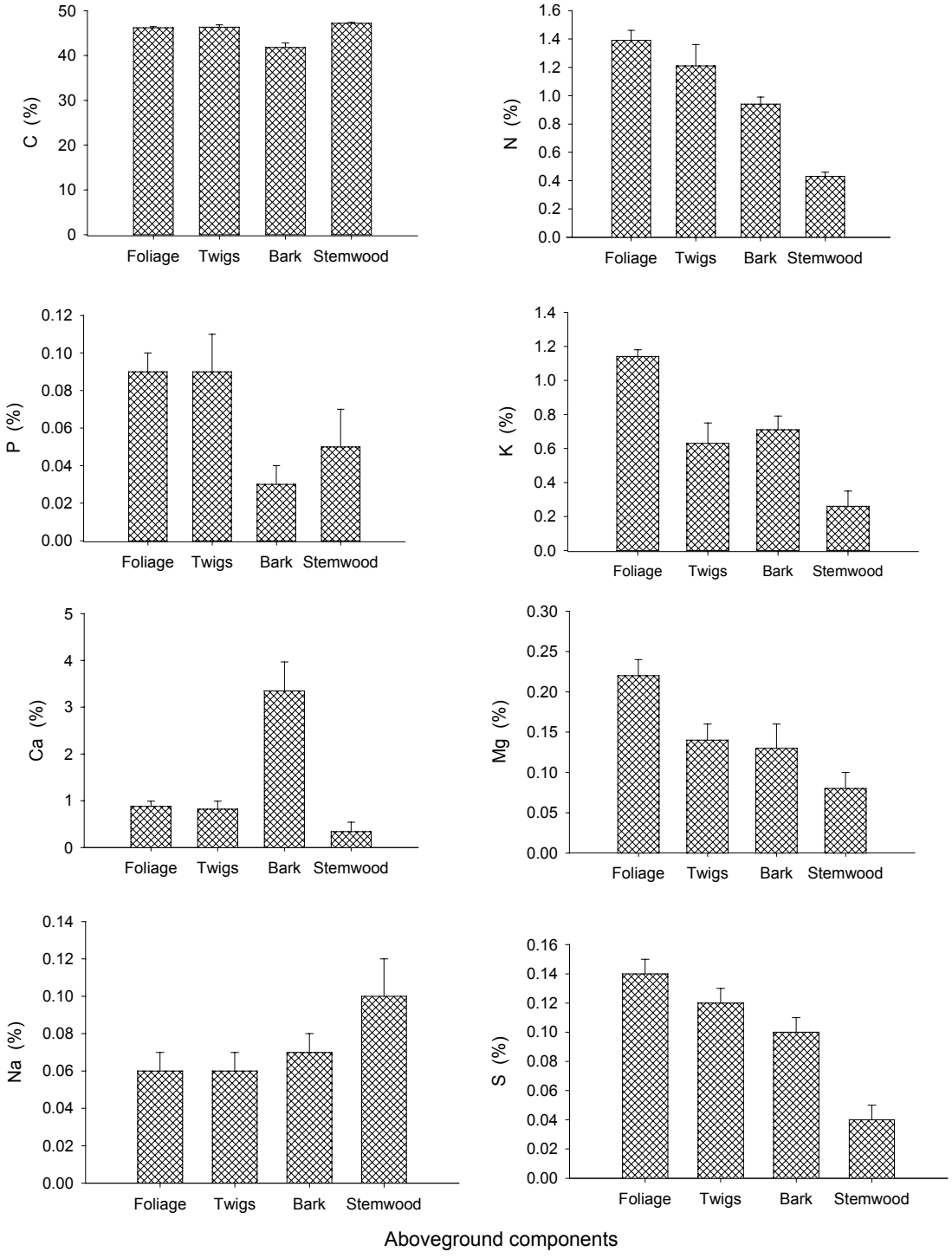


Fig. 24: Macronutrient concentrations (% dry weight) in the aboveground components of *P. falcatus*.

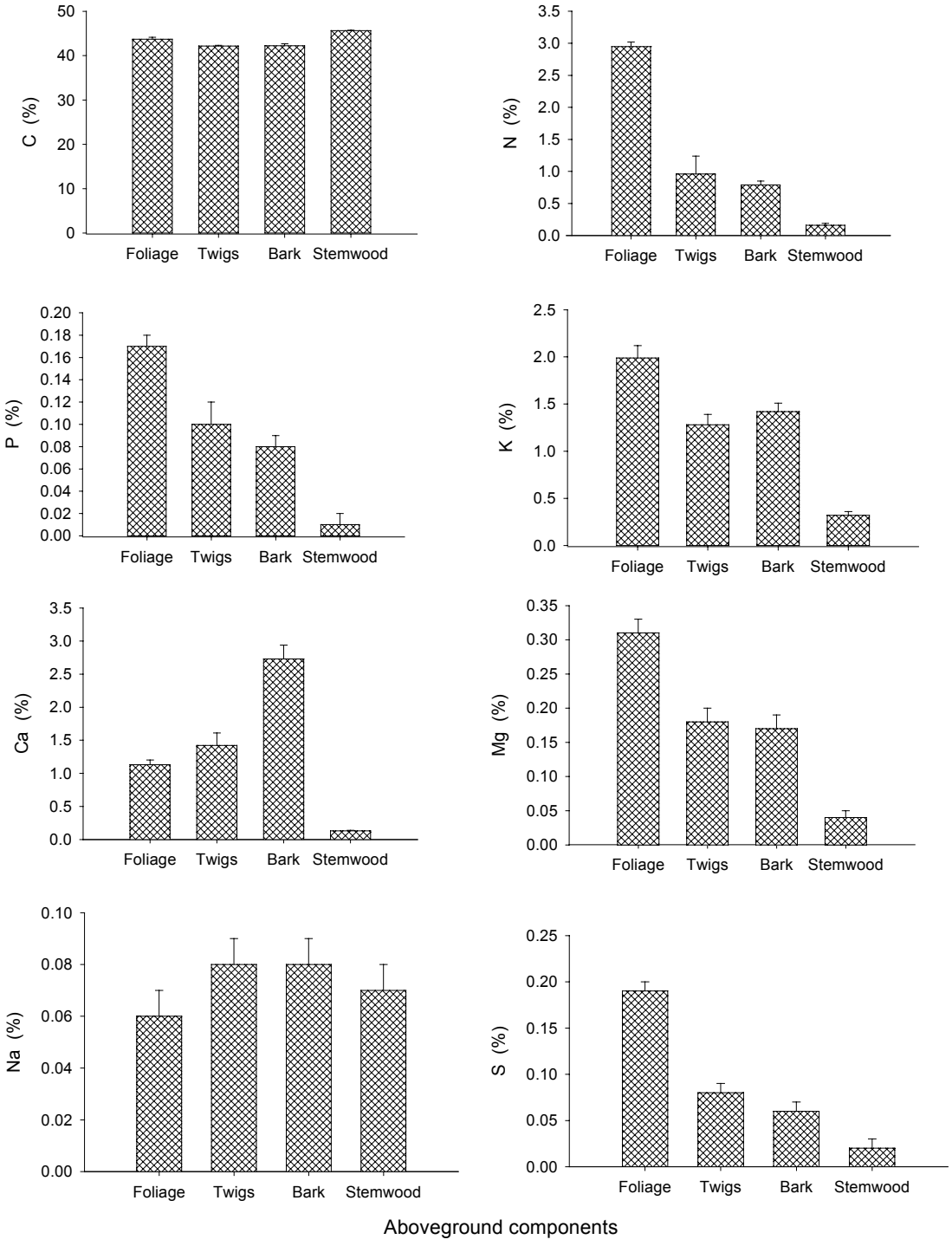


Fig. 25: Macronutrient concentrations (% dry weight) in the aboveground components of *C. macrostachys*.

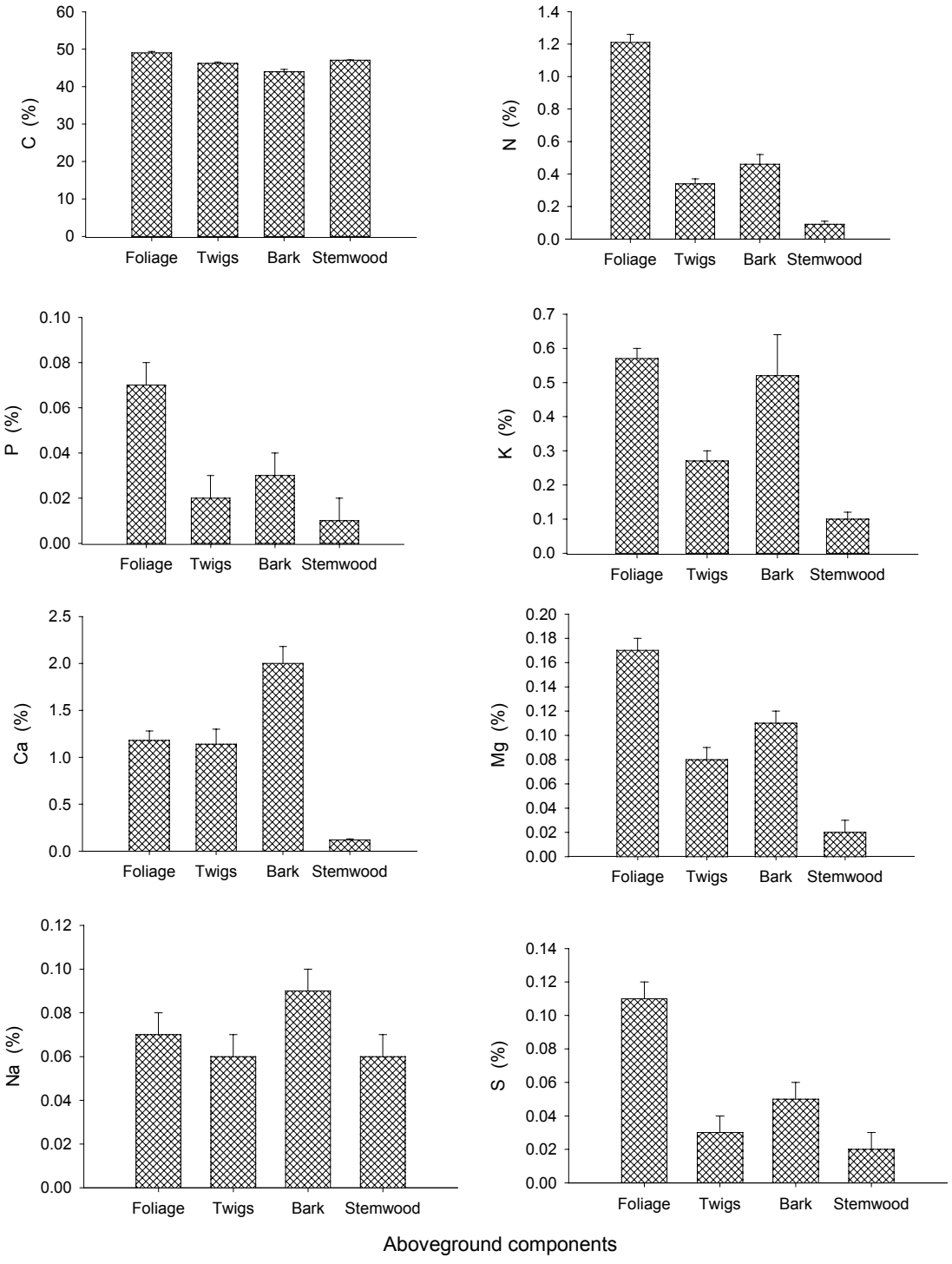


Fig. 26: Macronutrient concentrations (% dry weight) in the aboveground components of *C. lusitanica*.

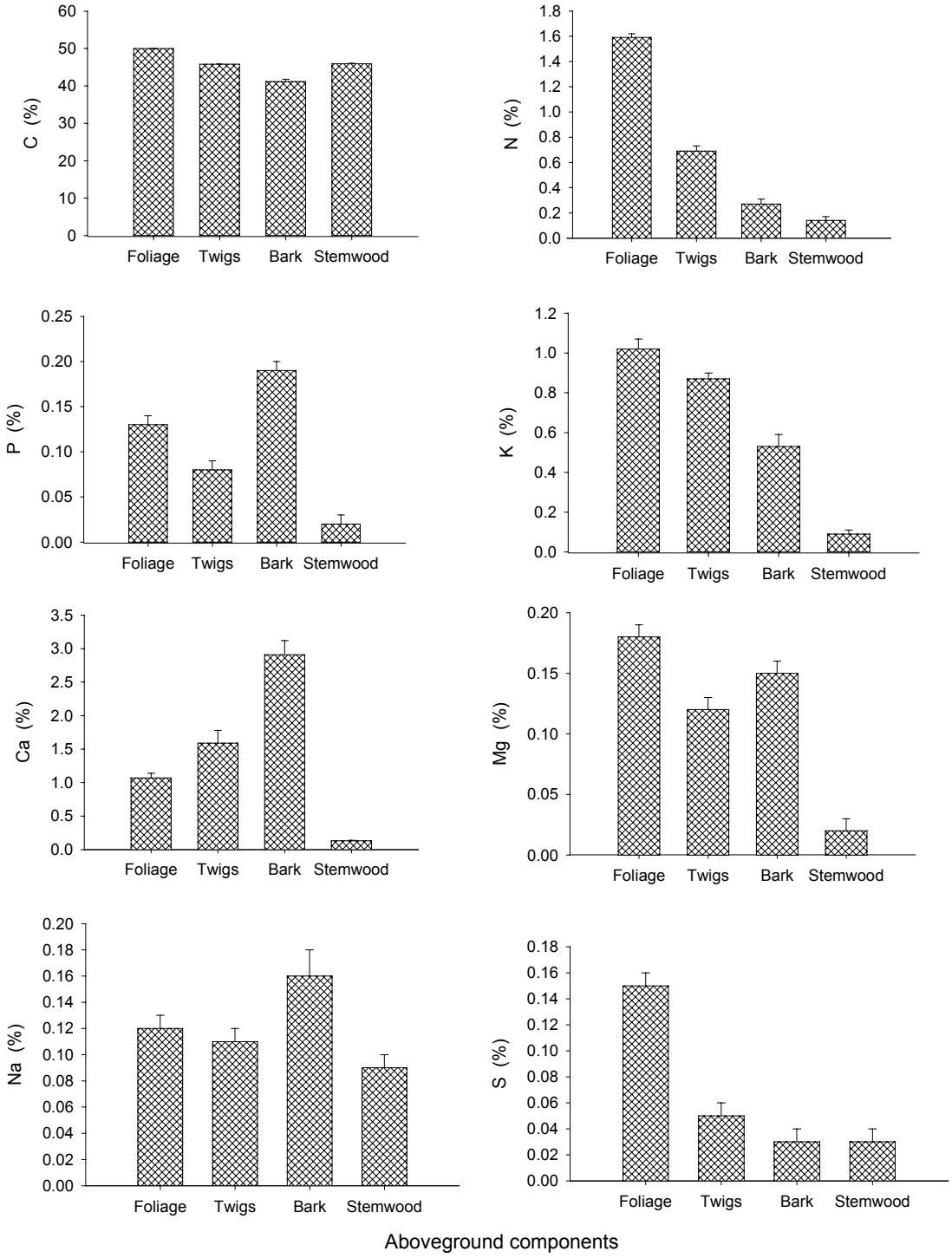


Fig. 27: Macronutrient concentrations (% dry weight) in the aboveground components of *E. globulus*.

b. Comparison of macronutrient concentrations among the study trees

Foliage macronutrients

Foliage macronutrient concentrations of *P. falcatus* decreased in the order of C > N > Ca > K > Mg > S > P > Na whereas in *C. lusitanica* it decreased in the order of C > N > Ca > K > Mg > S > P > Na (Tab. 10). With the exception of C, the concentrations of foliage macronutrients in *C. macrostachys* were significantly higher (except Na and Ca) (at $p < 0.05$) compared to foliage macronutrient concentrations of *P. falcatus* (Tab. 10).

Foliage macronutrient concentrations of *C. lusitanica* and *E. globulus* decreased in the same order as *P. falcatus* (Tab. 10). With the exception of Ca all the other macronutrient concentrations were higher in the foliage of *E. globulus* compared to the foliage macronutrient concentrations of *C. lusitanica* (Tab. 10).

With the exception of C, Ca and Na, the foliage macronutrient concentrations were higher in *C. macrostachys* compared to the foliage macronutrient concentrations of the plantation species.

Twig macronutrients

Twig macronutrient concentrations of *P. falcatus* and *C. macrotachays* had a similar pattern with foliage macronutrient concentrations and decreased in the order of C > N > Ca > K > Mg > S > P > Na (Tab. 10). Except C, N and S, the rest of macronutrients were higher in the twigs of *C. macrostachys* compared to *P. falcatus*. With the exception of C, all the other macronutrient concentrations in the twigs of *E. globulus* were significantly higher (at $p < 0.05$) compared to the twig macronutrient concentrations of *C. lusitanica*.

With the exception of Ca and Na, which were higher in the twigs of *E. globulus*, the rest of the macronutrients were higher in the twigs of the natural forest species.

Bark macronutrients

The concentration of Ca was higher in the barks of all the study trees compared to the other macronutrients. Except N, Ca and S, the bark macronutrient concentrations were higher in *C. macrostachys* (Tab. 10). Except C and N, the concentrations of all the other macronutrients were higher in the bark of *E. globulus* compared to *C. lusitanica*.

Stemwood macronutrients

With the exception of K, the concentrations of all the other macronutrients were higher in the stemwood of *P. falcatus* compared to *C. macrostachys*. In the plantation forests, all the macronutrient concentrations except C and K were higher in *E. globulus* stemwood compared to *C. lusitanica*. The macronutrient concentrations in the stemwood of *P. falcatus* were much higher compared to *C. lusitanica* and *E. globulus*.

4.6.3 Aboveground macronutrient stock

Despite the higher concentrations of the macronutrients in the stemwood and foliage of *C. macrostachys* compared to the plantation forests (Tab. 10), its macronutrient stocks were lower because of its lower aboveground biomass (Fig. 28)

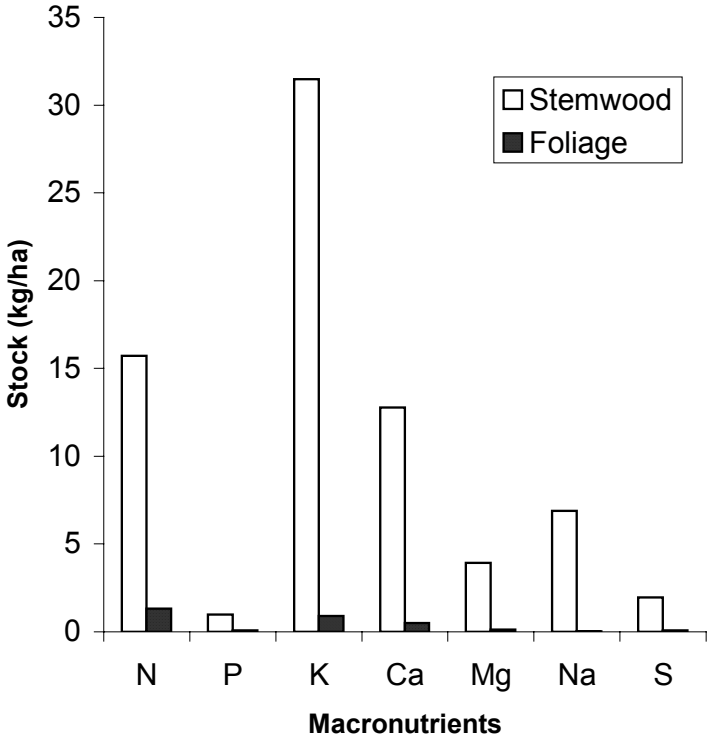


Fig. 28: Macronutrient stock in the stemwood and foliage of *C. macrostachys*.

Tab. 10: Mean macronutrient concentrations (% dry weight) in the aboveground components of the study trees. Pf = *Podocarpus falcatus*, Cm = *Croton macrostachys*, Cl = *Cupressus lusitanica*, Eg = *Eucalyptus globulus*. Mean values followed by different letters in each of plant components and macronutrients are significantly different at $p < 0.05$. In parentheses are standard errors (n = 6).

Component	Spp.	C	N	P	K	Ca	Mg	Na	S
Foliage	Pf	46.21^{a} (0.23)	1.39^{a} (0.07)	0.09^{a} (0.01)	1.14^{a} (0.04)	0.88^{a} (0.11)	0.22^{a} (0.02)	0.06^{a} (0.01)	0.14^{ad} (0.01)
	Cm	43.70^{b} (0.45)	2.95^{b} (0.07)	0.17^{b} (0.01)	1.99^{b} (0.13)	1.13^{a} (0.07)	0.31^{b} (0.02)	0.06^{a} (0.01)	0.19^{b} (0.01)
	Cl	49.00^{c} (0.40)	1.21^{a} (0.05)	0.07^{ca} (0.01)	0.57^{c} (0.03)	1.18^{a} (0.10)	0.17^{a} (0.01)	0.07^{a} (0.01)	0.11^{a} (0.01)
	Eg	49.98^{c} (0.06)	1.59^{a} (0.03)	0.13^{d} (0.01)	1.02^{a} (0.05)	1.07^{a} (0.10)	0.18^{a} (0.01)	0.12^{b} (0.01)	0.15^{d} (0.01)
Twigs	Pf	46.35^{a} (0.50)	1.21^{a} (0.15)	0.09^{a} (0.02)	0.63^{a} (0.12)	0.82^{a} (0.17)	0.14^{a} (0.02)	0.06^{a} (0.01)	0.12^{a} (0.01)
	Cm	42.15^{b} (0.18)	0.96^{a} (0.28)	0.10^{a} (0.02)	1.28^{b} (0.11)	1.42^{a} (0.19)	0.18^{a} (0.02)	0.08^{a} (0.01)	0.08^{b} (0.01)
	Cl	46.18^{a} (0.34)	0.34^{b} (0.03)	0.02^{b} (0.01)	0.27^{c} (0.03)	1.14^{a} (0.16)	0.08^{b} (0.01)	0.06^{a} (0.01)	0.03^{c} (0.01)
	Eg	45.80^{b} (0.09)	0.69^{a} (0.04)	0.08^{a} (0.01)	0.87^{a} (0.03)	1.59^{b} (0.16)	0.12^{a} (0.01)	0.11^{a} (0.01)	0.05^{c} (0.01)
Bark	Pf	41.81^{a} (0.99)	0.94^{a} (0.05)	0.03^{a} (0.01)	0.71^{a} (0.08)	3.35^{a} (0.62)	0.13^{b} (0.03)	0.07^{a} (0.01)	0.10^{a} (0.01)
	Cm	42.22^{a} (0.47)	0.79^{a} (0.06)	0.08^{a} (0.01)	1.42^{b} (0.09)	2.73^{a} (0.21)	0.17^{b} (0.02)	0.08^{a} (0.01)	0.06^{b} (0.01)
	Cl	43.99^{a} (0.63)	0.46^{b} (0.06)	0.03^{a} (0.01)	0.52^{a} (0.12)	2.00^{a} (0.18)	0.11^{d} (0.01)	0.09^{a} (0.01)	0.05^{b} (0.01)
	Eg	41.18^{a} (0.62)	0.27^{b} (0.04)	0.19^{a} (0.01)	0.53^{a} (0.06)	2.92^{a} (0.18)	0.15^{a} (0.01)	0.10^{b} (0.02)	0.03^{b} (0.01)
Stemwood	Pf	47.17^{a} (0.24)	0.43^{a} (0.03)	0.05^{a} (0.02)	0.26^{a} (0.09)	0.34^{a} (0.20)	0.08^{a} (0.02)	0.10^{a} (0.02)	0.04^{a} (0.01)
	Cm	45.64^{b} (0.09)	0.16^{b} (0.03)	0.01^{a} (0.01)	0.32^{a} (0.04)	0.13^{a} (0.01)	0.04^{a} (0.01)	0.07^{a} (0.01)	0.02^{b} (0.01)
	Cl	47.05^{a} (0.10)	0.09^{b} (0.02)	0.01^{a} (0.01)	0.10^{b} (0.02)	0.12^{a} (0.01)	0.02^{b} (0.01)	0.06^{a} (0.01)	0.02^{b} (0.01)
	Eg	45.96^{b} (0.10)	0.14^{b} (0.03)	0.02^{a} (0.01)	0.09^{b} (0.02)	0.13^{b} (0.01)	0.02^{b} (0.01)	0.09^{a} (0.01)	0.03^{b} (0.01)

In the case of the plantation forests, the foliage macronutrient stock was higher in *C. lusitanica* than *E. globulus* (Fig. 29A). Whereas, stemwood macronutrient stock was higher in *E. globulus* than *C. lusitanica* (Fig. 29B).The stemwood and foliage macronutrient stocks were higher in *E. globulus* compared to *C. lusitanica*.

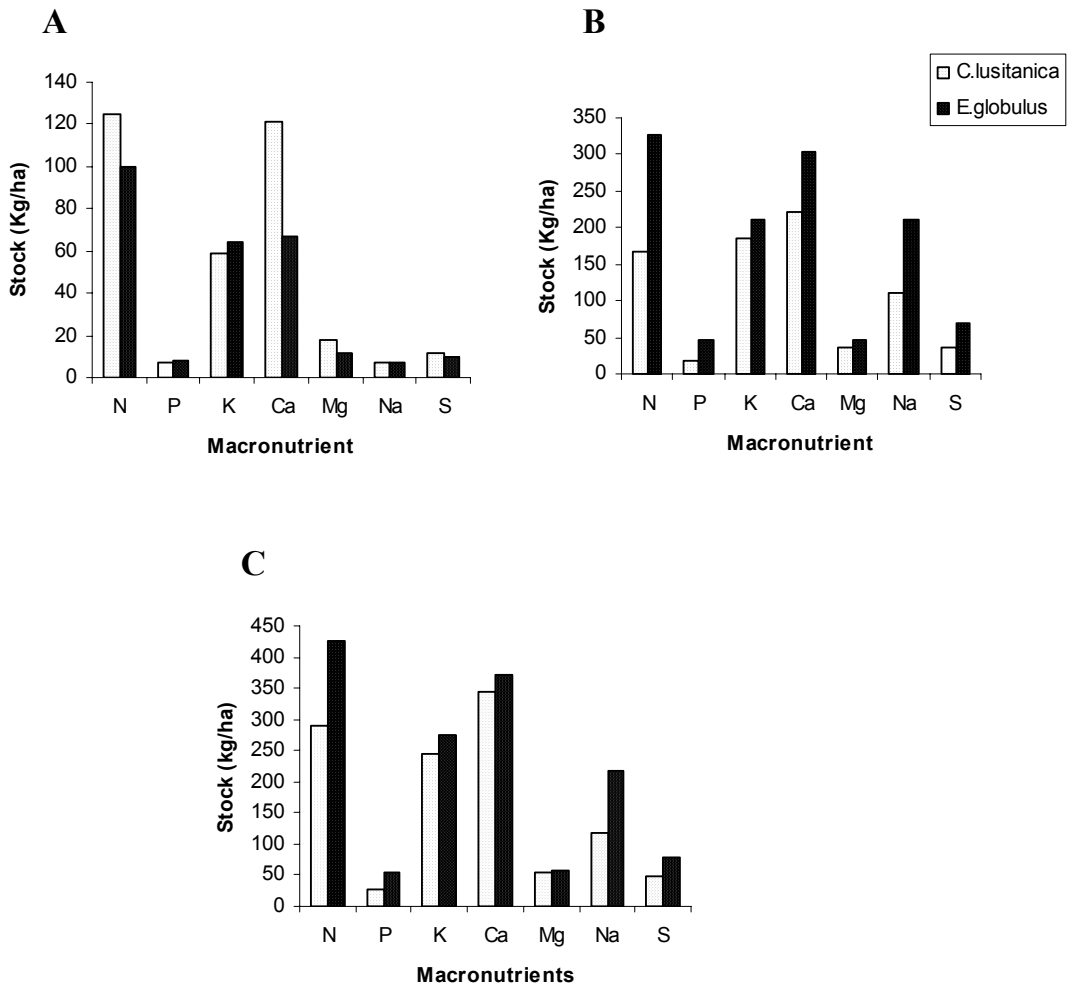


Fig. 29: Macronutrient stock in the stemwood and foliage of *C. lusitanica* and *E. globulus*. A = foliage, B = stemwood, and C = stemwood and foliage macronutrient stocks.

5 Discussion

5.1 Root architecture of the study trees

The term root architecture refers to the spatial configuration of the root system (Lynch 1995). A number of studies have dealt with root system architecture. For example, classifications of plant root system architecture are given in Cannon (1949), Weaver (1958) and Krasilnikov (1968). A major organizational model of root systems in dicotyledonous tropical trees was developed by Jeník (1976). Descriptions of root system architecture based on branching patterns are given in Berntson (1992) and Fitter (1991).

The importance of root system architecture in plant productivity stems from the fact that many soil resources are unevenly distributed and the spatial deployment of the root system will, to a large extent determine, the ability of a plant to exploit these resources (Lynch 1995). Therefore, the root systems of plants play an important role in ecosystem water fluxes, carbon and nutrient cycling (Canadell et al. 1996; Fitter 1987). In the present study, a general comparison of the root system architecture of the study trees was made on the basis of the vertical and horizontal extents of their tap and lateral roots (Tab. 1).

Both *C. lusitanica* and *E. globulus* had taproots. The deep taproot and long lateral roots in *E. globulus* might be attributed to its ecological adaptation for acquiring water and nutrients from greater depths and laterally far distances to cover its high demands as a fast growing species. Additionally, the deep and laterally spread roots give *Eucalyptus* a strong anchorage and good wind resistance. In contrast, the shallow tap and lateral roots of *C. lusitanica* might have contributed to its susceptibility to wind throw. According to our personal observation, some *C. lusitanica* trees in the study area had fallen as a result of wind throw.

An additional disadvantage of the shallow root system of *C. lusitanica* might be its negative impact on the growth of understory vegetation. As explained in section

4.1, the growth of herbs and shrubs under *C. lusitanica* was poor. A similar poor understory vegetation growth was also reported by Michelsen and Lisanework, (1993) and Yirdaw and Luukkanen (2003). Elsewhere, it was also reported that allelopathic substances from the roots of *E. globulus* hinder the growth of understory vegetation (Poore and Fries 1985).

The study by Yirdaw and Luukkanen (2003) attributed light as a limiting factor for the poor understory growth in *C. lusitanica* plantations. Besides the light factor, the shallow root system of *C. lusitanica* might have also contributed to limit the growth of understory vegetation by competing with newly established seedlings. The poor understory growth in *C. lusitanica* plantation could also affect the soil nutrient status through erosion (Michelsen et al. 1996). Therefore, the loss of soil nutrients through erosion might have a negative impact on the sustainability of *C. lusitanica* plantations in the long run.

Given the relatively large areas planted with *C. lusitanica*, 62% out of the total plantation area of 6000 ha, the negative impacts of poor understory vegetation and wind throw require serious consideration. One of the most important benefits of the local people living around the forest is the free access for their cattle to graze in the forested area (Müller-Hohenstein and Abate 2002). With the poor understory vegetation and an increasing number of cattle, the demands for more grazing areas would increase. This in turn might cause more encroachment and deforestations of *Cupressus* plantations in the future.

In the natural forest, *P. falcatus* and *C. macrostachys* had similar root branching patterns characterized by thicker tap and lateral roots (Fig. 8). The thick tap and lateral roots of *P. falcatus* might be one of the factors for its success as a dominant tree in the natural forest, at least in its early growth stage. Thicker and deeper lateral roots are important both to provide strong anchorage and to acquire nutrients from deeper layers, hence out competing herbs, shrubs and shallow rooted trees growing more abundantly in the natural forest. The same reasoning might also hold true for *C. macrostachys*.

It should be emphasized that the vertical and horizontal distributions of roots vary with increasing age and changes with environmental factors. For instance, comparison of the root system architecture of a young and mature *P. falcatus* revealed the occurrence of significance changes in the root system architecture with increasing age. In general, when *P. falcatus* matures, the taproot is absent and the roots develop much more branched lateral roots (personal observation).

Furthermore, several studies have shown that besides the prime role of genetic makeup in determining the root architecture of an individual plant, environmental factors such as interspecific competition, depth of water table and bedrock, amount of rain, soil texture and degree of weathering including the presence of cracks and channels are important (Canadell and Zedler 1995; Fitter and Stickland 1991; Fogel 1983).

Additionally, root diameter of individual trees varies widely both within and between species depending on their association with mycorrhizas and the availability of nutrients in the soil (Fogel 1983).

5.2 Distributions of fine roots

Unlike root architecture, which deals with the orientations of the entire root system, root distribution refers to the presence or absence of individual roots in a positional gradient or grid (Lynch 1995). Typically, studies on root distributions are concerned with root density and root biomass as a function of soil depth and distance from the stem. In the present study, the LFR biomass of the study trees was studied as a function of soil depth and distance from the bole. Before discussing the results of the fine root biomass, a general consideration on the importance of fine roots to forest ecosystem and some methodological aspects in studying them are presented below.

The focus on the fine roots was made because of their significant role in forest ecosystem carbon and nutrient cycling. Little is known about the dynamics of tropical forest fine roots but the few data available indicate that fine root turnover rate is higher in the tropics than it is in temperate and boreal forests (Lauenroth and Gill 2003). According to Vogt et al. (1986), belowground inputs from fine root turnover may contribute more to the organic matter cycling than aboveground litter fall in temperate forests. The fine roots' maintenance and respiration costs also account for a significant portion of the net primary production in temperate forest ecosystems (Harris et al. 1977; Santantonio et al. 1977). Nadelhoffer et al. (1985) reported that 27% of the net primary production in nine temperate forests was allocated to the fine roots, which was similar to that allocated to leaf litter (26%). Given the generally high root turnover of fine roots in the tropics, their role in carbon and nutrient cycling might be higher compared to their role in the temperate forests.

Generally, studies on roots are limited and still at their formative stage. This can be attributed to two main reasons. First, the importance of fine roots in the ecosystem functioning was underestimated for a long time (Böhm 1979; Persson 1990). Second, the study of roots is tedious and discourages many from researching them. Since the last few decades, however, a number of studies have been conducted towards understanding the root system architecture, root biomass, root production and root turnover in ecosystem functioning. A detailed description of methods for root studies can be found in Böhm (1979), Smit et al. (2000), Mackie-Dawson and Atkinson (1991), Persson (1990) and Vogt and Persson (1991).

Root studies in the last few years have not only contributed to the understanding of the importance of fine roots in ecosystem functioning, but they have also led to the improvement of some of the methods of their sampling and analysis. For instance, soil coring and the extraction of roots by washing and hand-sorting the roots under suitable magnification are the most frequently used methods in fine root studies (Mackie-Dawson and Atkinson 1991; Vogt and Persson 1991). However, since these

methods normally take from 2 to 8 hours for processing a single sample (Persson 1990), they are prohibitive in quantitative fine root studies, particularly when replicated field trials with several treatments are required.

A method which significantly reduces the time for processing fine roots was suggested by Schroth and Kolbe (1994). This method involves combining and homogenizing several soil cores from a plot and then a reasonable number of subsamples are taken from the homogenized samples for root extraction.

There has also been a lot of improvement in the minirhizotron method. This method is a non-destructive method for the *in situ* observation and quantification of root length distribution, root dynamics and other root parameters. The minirhizotrons consist of a transparent access tube, such as a glass or acrylic tube, or a hole in the soil, through which a fiber optic probe, miniaturized video camera, or simply a mirror and a camera with a macro-lens is inserted (Mackie-Dawson and Atkinson 1991; Schroth 2003). The latest developments in the minirhizotron method can be found in Johnson et al. (2001).

Despite these and other improvements, methods on fine root studies still need to be developed and standardized further in order to make studies on roots at different forest ecosystems comparable. Some of the methodological constraints that require due consideration include:

i) *Different methods to measure the same root parameter often yield different results*: a typical case was given by Hertel and Leuschner (2002) in which the use of four different methods to quantify fine root production yielded four significantly different results. Similar situations were also reported by Böhm (1979) and Fogel (1983).

ii) *Different soil core sampling and processing methods yield significantly different results*: the differences in sampling include differences between soil coring using auger and monolith techniques and a wide variation in coring depths. The variations in soil sample processing include variations in washing techniques,

variations in root isolation techniques and variation in sieving methods. All the various approaches in soil cores sampling and processing could lead to wide differences in the estimate of fine root biomass and other parameters. For example, Fogel (1983) reported that washing soil cores on 0.53 mm sieve size retained one third more roots than washing it on 0.91 mm sieve. In general, the smaller the sieve size, the more fine roots retained and the more the biomass estimate.

iii) *Differences in fine root diameter classes*: there is no conventional definition on the diameter class of fine roots. In most studies roots < 2 mm in diameter are considered as fine roots (Vogt et al. 1986). But still, in several studies different-sized roots have been defined as fine roots. For example, results from a broad-leaved evergreen forests in Cost Rica were based on fine roots with diameters < 5 mm (Gower 1987). In the rain forests of Amazonia, roots with diameters < 6 mm were defined as fine roots (Klinge 1973). Others also reported fine root biomass based on a diameter <1 mm, e.g. Burton et al. (2000) and Castellanos et al. (2001), < 3 mm e.g. Melillo (1982) <10 mm e.g. Deans et al. (1996).

The fact that different diameter classes are considered as fine roots affects the estimation of fine roots biomass significantly. For example, Millikin and Bledsoe (1999) indicated that the exclusion of the fine root diameter between 2-5 mm reduced their estimation of fine root biomass by 81% compared to the fine root biomass estimate that was based on a fine root diameter of < 2mm.

Thus, comparison of our results with similar studies was difficult because of the above-mentioned methodological problems inherent with root biomass studies and the scarcity of information on the fine root biomass of the study trees in particular and tropical ecosystem in general.

5.2.1 Seasonal changes in LFR biomass

The dry season LFR biomass was higher than the wet season LFR biomass for *P. falcatus*, *C. macrostachys* and *C. lusitanica* at all depth intervals and distances from the bole (Tab. 2-4). The change in LFR biomass with season can be attributed to changes in the soil moisture content of the study area.

The dry season LFR biomass samples were taken in April 2002 during which the soil water potential in the study area was between -300 and -420 hPa at all depth intervals (Fig. 30). The wet season samples were taken in September 2002 during which the soil water potential was between -80 and -120 hPa at all the depth intervals (Fig. 30). The change in the LFR biomass with soil moisture can be attributed to two factors. First, the higher soil moisture content during the wet season sampling period might have resulted in low fine root growth due to a higher availability of soil moisture, whereas the low moisture content of the soil during the dry season might have resulted in a higher LFR biomass as root growth is stimulated to maximize moisture absorption (Canadell and Zedler 1995). Second, the moisture level in April might have favored the high growth of fine roots, whereas the high moisture content in September might have the opposite effect.

The high root biomass during the dry season contradicts some findings that reported high root biomass during the rainy season in the tropics (Kummerow et al. 1990; Sundarapandian and Swamy 1996). However, these studies did not report on the moisture content of the soil. Comparison of seasonal variation in fine root biomass makes sense when information on the soil moisture is included since the effect of precipitation on soil moisture is dependent on many factors.

In the case of *E. globulus*, the wet season biomass was higher in most of the depth intervals and distances from the bole (Tab. 5). The existence of high and low LFR biomass during the wet season in *E. globulus* could not be explained. This warrants taking more samples at regular interval both during the dry and wet season in order to establish a clear pattern in the seasonal variations of fine roots biomass.

5.2.2 Annual LFR biomass

The annual LFR biomass was highest at the first 10 cm soil depth and sharply decreased at the lower depth intervals for all the study trees (Figs. 13-16). Concurrent with the high LFR biomass at the upper 10 cm, the root number (density) was also higher at this depth interval (Figs. 9-12). The high fine root biomass at the depth interval of 0-10 cm for *C. lusitanica* and *E. globulus* agreed with the high fine root biomass reported for the similar tree species in Menagesha State Forest (Michelsen et al. 1993). Additionally, high fine root biomass and density at a similar depth was also reported for tropical forests by Jackson et al. (1996) and Priess (1999).

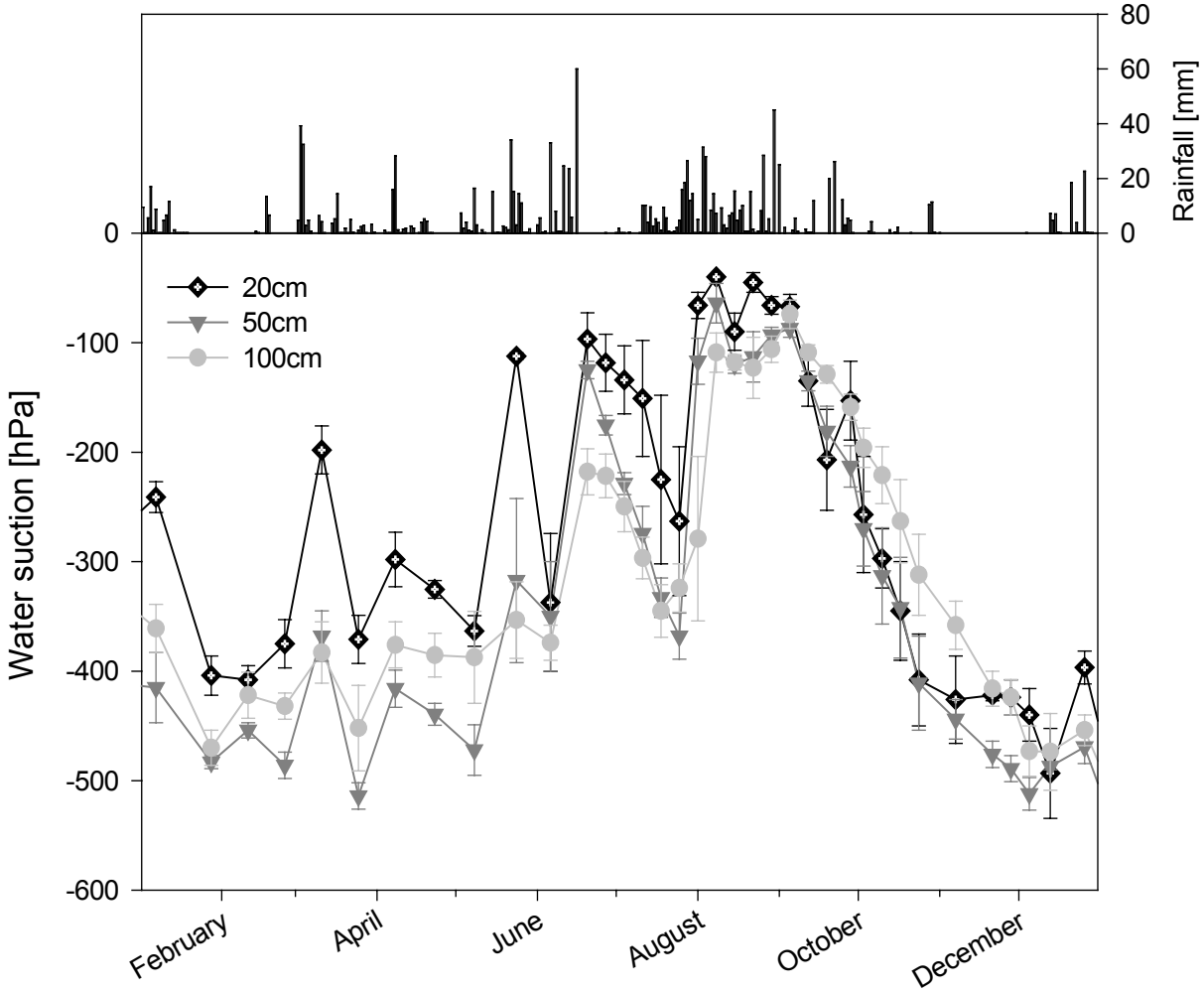


Fig. 30: Rainfall distribution and soil water potential of the study area for the year 2002. (Source: meteorological station at the study site, compiled by Fritzsche).

The highest LFR biomass and density at the upper 10 cm depth interval can be attributed to three factors. First, higher clay content, more than 60% of clay, at the depths lower than 30 cm might have contributed to hindering the fine root growth at lower depths (Tab. 11). The high clay content could result in poor aeration hence in poor growth of fine roots (Bennett et al. 2002). Second, the higher acidity at lower depths (Tab. 11) might have also contributed to the decrease in fine root biomass with depth (Jentschke and Drexhage 2001).

Third, the relatively high concentration of organic matter (C) and N in the upper 30 cm of the soils of the study area compared to the lower soil depths might have contributed to a higher fine root growth at this soil depth (Tab. 12). For example, Roy and Singh (1995) reported a higher fine root biomass as a result of a higher amount of soil nitrogen in a dry tropical forest. Millikin and Bledsoe (1999) reported higher soil N concentration at this depth to be one of the main factors for a higher fine root biomass of blue oak (*Quercus douglasii*).

However, it should be noted that the correlations between fine root biomass and nutrient concentration are not always positive. For example, Priess et al. (1999) found a high fine root biomass in extremely nutrient poor tropical premontane rain forests. Also some studies conducted in Costa Rica lowland tropical forest by Gower (1987) indicated the inverse relationship between the availability of phosphorus and calcium with root biomass. Similarly, studies conducted in the temperate forests indicated that soil nutritional status is inversely related to the amount and production of fine roots (Vanninen and Annikki 1999).

Tab. 11: Soil pH and texture of the study area.

				Soil Texture (g kg^{-1} soil)		
Sites	**Soil Horizon**	**Soil Depth (cm)**	**PH KCl**	**Sand**	**Silt**	**Clay**
Natural forest	A	0-15	5.4	200	300	500
	AB	15-29	5.3	230	230	540
	Bt1	29-68	4.7	80	180	740
	Bt2	68-108 +	4.5	80	180	740
C. lusitanica *plantation*	A	0-25	5.6	90	270	640
	AB	25-41	5.1	140	360	500
	Bt1	41-81	4.8	60	170	770
	Bt2	81-105 +	4.6	60	310	630
E. globulus *plantation*	A	0-10	5.3	140	370	490
	AB	10-27	5.1	140	300	560
	B1	27-69	4.8	100	240	660
	B2	69-106 +	4.7	100	170	730

Source: Ashagri et al. 2003 (unpublished).

Tab. 12: Soil organic carbon (C) and nitrogen (N) (g Kg^{-1}) under the natural forest (NF), *C. lusitanica* (CL) and *E. globulus* (EG) plantations.

	C			**N**		
Soil Depth (cm)	**NF**	**CL**	**EG**	**NF**	**CL**	**EG**
0-20	61.3	65.2	59.3	5.2	6.5	6.3
20-40	32.3	20.9	27.7	3.0	2.1	3.1
40-70	28.8	17.4	17.0	2.4	1.8	1.9
70-100	17.4	16.1	12.9	1.7	1.7	1.5

Source: Ashagri et al. 2003 (unpublished).

5.3 Fine roots contribution to the soil macronutrient

5.3.1 Fine root turnover

Fine roots are constantly in flux, with death and replacement occurring simultaneously (Persson 1983). Changes in biomass during the growing season have been reported by many researchers (López et al. 2001; Makkonen and Helmisaari 1998). Root turnover is a specific aspect of root dynamics referring to the fraction of a root system that is renovated during a certain time period through death of some roots and their replacement by new root growth (Schroth 2003). Root turnover plays a significant role in carbon budget and nutrient cycling of forest ecosystems (Eissenstat et al. 2000).

As a result of the large fluxes in fine roots, a limited number of biomass estimates do not satisfactorily answer the question how much the fine roots contribute to carbon budget and nutrient cycling (Fogel 1983). Since in the present study only the LFR biomass was estimated, it was not possible to quantify the fine root turnover of the study trees. This precluded a direct quantitative comparison of the fine root turnover of the study trees.

Nonetheless, the seasonal changes in LFR biomass described above strongly suggest the occurrence of fine root turnover in the study trees on a seasonal basis. Furthermore, several studies have indicated that fine root turnover is generally higher in tropical forests than in temperate or boreal forests, with the majority of the estimates of turnover exceeding 100% annually (Lauenroth and Gill 2003). Also, Persson (1980) reported that 30-86% of the fine roots turnover annually.

Considering the changes in dry and wet season biomass of the study trees and the fact that there is generally a high fine root turnover rate in the tropical forest ecosystems (Lauenroth and Gill 2003), it might be possible to expect that the fine roots of the study trees contribute to the soil nutrients within a period ranging from a few months to one year. It was also reported by Vogt (1986) that a high fine root biomass is positively correlated to a high rate of fine root turnover.

5.3.2 Macronutrient inputs of the study tress

As shown in Figs. (13-16), the fine root biomass for all the study trees was higher at the depth interval 0-10 cm at all the distances. Similarly, the concentration of most of the macronutrients was higher at the depth interval 0-10 cm (Tab. 9). In particular, the concentration of N and S were significantly higher ($P < 0.05$) at the depth interval 0-10 cm for all the study trees. This was concurrent with the higher concentrations of soil N and S in the study area (Ashagri, unpublished and Rückamp, unpublished).

Since biomass and macronutrient values were higher at the depth interval 0-10 cm, comparison of the stock of macronutrients in the fine roots of the study trees at this depth interval was made in order to get a general idea as to the contribution of the fine root of the study trees to the macronutrient content of the soil. Accordingly, in the natural forest the fine roots P, N, Mg, and S stocks in *P. falcatus* were more than twice the amount of the fine root stocks of *C. macrostachys* (Fig. 23).

Also the stocks of Na in the fine roots of *P. falcatus* were more than three times higher compared to *C. macrostachys* stocks (Fig. 23). This suggests that the fine roots of *P. falcatus* play an important role in the sustainability of the natural forest by transferring more macronutrients to the soil. Particularly the transfer of a high amount of organic matter by *P. falcatus* has a positive implication for the sustainability of the natural forest ecosystem since organic matter improves the ability of the soil to retain plant available nutrients against leaching (Schroth 2003). Furthermore, soil organic matter may act either as a source or a temporary sink of nutrients such as nitrogen, phosphorus and sulphur (Schroth 2003).

A comparison of the fine root macronutrient stock in the plantation forest at the depth interval 0-10 cm revealed that, with the exception of P, *C. lusitanica* had greater fine root macronutrient stocks. This might imply that the *C. lusitanica*

plantation is more efficient in returning macronutrients back to the system through the fine roots compared to the *E. globulus* plantation.

5.3.3 Impact of forest conversion on fine root macronutrient inputs

The total LFR biomass of *P. falcatus* (1.34 kg m^{-2}) is more than four times greater than the LFR biomass of *C. macrostachys* (0.32 kg m^{-2}) (Fig. 17). This implies the large reduction of the LFR biomass as a result of the replacement of the climax species *P. falcatus* with a pioneer species, *C. macrostachys*. This, in turn, will have a negative impact on the sustainability of the natural forest by reducing nutrient inputs to the soil. Similarly, the total LFR biomass of *C. lusitanica* (0.88 kg m^{-2}) was about three times more than the LFR biomass of *E. globulus* (0.27 kg m^{-2}) (Fig. 17). This might indicate a relatively lower depletion of soil resources by *C. lusitanica* compared to *E. globulus*.

The high LFR biomass in *P. falcatus* compared to in the plantation species might indicate loss of fine root biomass due to the conversion of the natural forest into plantation forests with only exotic tree species. However, the consequences of such changes with regard to the sustainability of the forest ecosystem should be studied along with inputs from aboveground components (e.g. litter) in a time series.

In general, maintaining, and if possible increasing, soil fertility is a major goal for sustainable forest management because it determines to a large extent the site's capacity for wood production. The higher inputs of macronutrients in the soil by the fine roots of *P. falcatus* and *C. lusitanica* in the natural and plantation forests, respectively, is valuable for sustaining the productivity of these forests.

However, as mentioned above, the macronutrient stock values give only general information regarding the contribution of the study trees, assuming that all of the study trees have more or less similar root turnover and decomposition rates. But in reality, the fine root turnover and decomposition rates are affected by genetic and environmental factors. A general account of the effect of environmental factors on

root turnover is given in Lauenroth and Gill (2003). Furthermore, the fact that only LFR biomass was estimated in this study might have underestimated the fine root biomass of the study trees and hence their contribution to the soil nutrient input.

Therefore, the interpretation given above with regard to the contribution of the study trees to the nutrient inputs should be taken with caution. More work on the rate of fine root turnover and decomposition as well as on the seasonal variations of the fine root nutrient concentrations is required to reach to a more conclusive answer with regard to the sustainability of the study trees.

5.4 Aboveground biomass

Biomass is defined as total plant mass per unit area at the time of sampling (Kimmins 1988) and it is usually expressed as oven-dry tons per hectare (Brown 1997; Satoo and Madgwick 1982). Historical background on forest biomass research and detailed methods for its estimation can be found in Satoo and Madgwick (1982) and Brown (1997). Cannell (1982) compiled data on the biomass and productivity of over 1200 forest stands in 46 countries.

Forest biomass is important to quantitatively describe forest ecosystems and indicate the biomass resources available. For instance, the biomass of plant components such as foliage and branches can be determined to assess the amount of resources available for traditional uses in rural areas such as firewood and fodder.

Forest biomass is also used to quantify and compare natural and manmade changes in structural and functional attributes of forest ecosystems. For instance, assessment of plant biomass along with nutrient concentration can be used to analyse the effects of forest degradation or harvesting on the soil nutrient capital (Deans et al. 1999; Rytter 2002). Such studies also assist in evaluating forest site conditions and thereby form the basis for considering compensatory measures for

nutrient replacement through fertilization or other means. In this way, they ultimately contribute to a sustainable management of forests (Lim 1993).

Last but not least, forests play an important role in the global carbon cycle. Estimates on biomass of forests is also used to assess the potential of forests in the global carbon cycle (Brown and Lugo 1982; Houghton et al. 1990).

The most important factors that affect biomass accumulation in forest trees are site quality, stand age, stand density and genetic variations (Satoo and Madgwick 1982). For this reason, biomass estimations should take these variables into consideration in order to make a useful assessment. Studies on biomass, therefore, mainly focus on assessing the biomass of:

- a single species under different site conditions (Helmisaari et al. 2002);
- a single species with different age group (Gresham 2002; Laclau et al. 2000); and
- different species of similar age under similar site conditions (Wang et al. 2000).

As already described in the introduction section, this study is part of an integrated approach to quantify the basic ecosystem processes in natural and plantation forests with the objective of developing a guideline for their sustainable management. Thus, the sampling strategy for the present study was designed as part of this integrated approach. Biomass sampling was, therefore, taken from four different species that were different in age and stand density (Tab. 6). Nevertheless, their site conditions were similar.

5.4.1 Biomass regression equations

Despite their practical value for a sustainable management of plantation forests, for instance, for deciding thinning and clear harvesting time, site specific biomass estimating equations have been lacking in the Munessa Forest (Silvanova 1996). The regression equations developed in the present study, expressing tree dry weight as a function of DBH, had a high coefficient of determination (R^2) (Figs. 18-20). Therefore, these equations can be used by the Munessa-Shashemene Forest Enterprise, particularly for the plantation forests, for making a rapid estimation of the total tree biomass, total foliage biomass and total branch biomass of *C. lusitanica* and *E. globulus* by measuring their DBH alone.

5.4.2 Stand structure

Density of a forest stand, or the number of individuals per unit area, is a common descriptor of stand structure (Davis and Roberts 2000). The stand structure of the natural and plantation forests differed largely. The density of *C. macrostachys* was much higher (143 ± 71.98 trees ha^{-1}) than the density of *P. falcatus* (73 ± 38.61 trees ha^{-1}). In contrast, *C. macrostachys* had much lower stand DBH and stand basal area compared with *P. falcatus* (Tab. 6).

The present high density of the pioneer species *C. macrostachys* implies the change in the structure of the natural forest. This could be attributed to the selective cutting of *P. falcatus* and other climax tree species that are common in the natural forest. The few big *P. falcatus*, with a DBH greater than 1 m, were left in the forest mainly because of two factors. First, their bole structure was crooked and unsuitable for timber making. Second, due to their big size, it was too difficult for the local people to fell and process them using traditional tools. The change in the forest structure seemed to have accelerated in the last few decades. For example, Russ (1944) described the vegetation of the Arssi region, the area that covers the present study sites, as characterized by many big P*odocarpus* trees in the 1940's.

Generally, structural change of the natural forest due to the selective cutting of *P. falcatus* would have a negative implication on the sustainability of the natural forest. According to Negash (1995), the positive ecosystem function of *P. falcatus* include:

- protection of soil erosion: its massive evergreen plant body and dense crown is suitable for protecting the soil from stormy and erosive rainfall that characterizes many of the watersheds where the tree occurs,
- water catchment: as a result of its high canopy water reception, *Podocarpus* forests contribute greatly to the formation of springs,
- source of food for wildlife: its fleshy fruit serves as source of food for many birds, mammals such as bats and the rare Colobus monkey,

In addition to these functions, *P. falcatus* may also provide habitat to plants and animals, which might play a significant role in the ecosystem process. For example, some lichens living in the forest canopy convert atmospheric nitrogen into biologically useful forms (Christensen et al. 1996).

These might be only some of the functions *P. falcatus* has in the natural forest ecosystem. Therefore, it is necessary to undertake a detailed study in order to gather more information on its role in sustainable management of the natural forest.

Obviously, the density of the exotic tree species was much higher since they were planted in pure stand. The density of *C. lusitanica* was 610 trees ha^{-1} with a mean stand basal area and a mean DBH of 37 ± 3.59 m^2 ha^{-1} and 29 ± 23.64 cm, respectively. The mean DBH and mean basal area is comparable with the mean DBH and mean stand basal area of a similar *Cupressus* plantation in Menagesha-Suba forest (Feyera and Demel 2001).

The stand aboveground biomass of *C. lusitanica* ranged from 158 t ha^{-1} to 269 t ha^{-1} with an average stand biomass of 217 t ha^{-1} (Tab. 7). It was not possible to compare this result with other studies as studies on the biomass of *C. lusitanica* are scarce. According to the general study made on the biomass of tropical plantation species by Lugo et al. (1988), the stemwood biomass of *C. lusitanica* from 5 to 35 years ranges from 2.6 t ha^{-1} to 506 t ha^{-1}. The stand biomass of the 21 year old *C. lusitanica* (217 t ha^{-1}) fits well to this range.

The density of *E. globulus* was 595 trees ha^{-1} with a mean stand basal area and a mean DBH of 34 ± 5.87 m^2 ha^{-1} and 24 ± 13.13 cm, respectively. The mean stand aboveground biomass of *E. globulus* was higher than the mean stand aboveground biomass of *C. lusitanica* (Tab. 7). Given that *E. globulus* was 10 years older than *C. lusitanica* and its ability to grow fast, it is not surprising that it had a higher aboveground biomass. An important structural difference noticed between the two plantation species were their differences in mean stand basal area and height. *E. globulus* had lower stand basal area compared to *C. lusitanica*, whereas *E. globulus* had higher tree height (Tab. 6). According to measurement taken by the Munessa-Shashemene Forest Enterprise the mean tree height of *E. globulus* was more than the mean tree height of *C. lusitanica* by 68%.

The differences in the structure of *C. lusitanica* and *E. globulus*, despite their similar densities, resulted in a significantly lower understory ground cover by herbaceous and shrub species in the former (see section 4.1). This is mainly attributed to the dense crown and low light penetration in *C. lusitanica* plantations (Yirdaw and Luukkanen 2003). The effect of a poor understory growth on the floor litter thickness and thereby nutrient capital of the soil may negatively affect the sustainability of *C. lusitanica* plantations. Site nutrient retention depends to a large extent on organic matter (Lundgren 1980). Furthermore, the surface organic layer is important for the nutrient cycling of tropical forests. Thus, the integrity of this layer and how it is affected by human activities including siliviculture is critical for sustainability.

With regard to the allocation of aboveground biomass in the plantation forests, the *E. globulus* stemwood accounted for 91% of the total aboveground biomass, whereas in *C. lusitanica* it was 84% (Fig. 22). According to Guo et al. (2002), *E. globulus* accumulates more biomass to the stemwood with increasing age. Thus, the shorter the rotation, the more the leaves and branches contribute to the total aboveground biomass.

The branches of *C. lusitanica* had a higher share in the total aboveground biomass Compared to *E. globulus* (Fig. 22). Future silvicultural management of *C. lusitanica* plantations should consider pruning its branches at regular interval. Pruning might enable more light penetrate to the forest floor and thereby allow more understory vegetation growth.

5.5 Aboveground macronutrient concentrations of the study trees

According to Munson (1998), a plant nutrient is considered essential:

- if the life cycle of a plant cannot be completed without it;
- if it can not be replaced by any other element; and
- if it performs a direct essential function in the plant, such as an ingredient for photosynthesis process.

Essential plant nutrients are categorized into macronutrients and micronutrients. Macronutrients are those nutrients required by the plant in large amount and include carbon (C), oxygen (O), hydrogen (H), nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) and sulfur (Smit et al.). Whereas micronutrients are those nutrients required in little amount and include boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn). Micronutrients are important, among others, for the synthesis and function of enzymes, phloem transport and cell elongation (Munson 1998). In the present study

all the macronutrients with the exception of oxygen and hydrogen were considered.

While there are a large number of physiological and biochemical studies on plant nutrient requirements, knowledge on the nutrient requirements of trees under field conditions is much less advanced (Linder and Rook 1984). In general, macronutrients play a key role in the productivity of forest ecosystems and information about the amount and distribution of macronutrients in different tree species is crucial for their sustainable management.

Given the fact that plantation forests in the tropics involve more species and soil types, knowledge of nutrient cycling in these forests is of paramount importance for a sustainable silivicultural practices (Drechsel and Zech 1993; Lugo et al. 1990; Mead 1984; Miller 1984). Such practices include site preparations, application of fertilizers and the decision on appropriate rotation periods. The concentrations of macronutrients in the foliage, twigs, bark and stemwood of the study trees is discussed below in the context of their role in contributing to the nutrient cycling.

5.5.1 Macronutrient concentrations in aboveground components

Foliage

As depicted in Figs. 24-27, with the exception of Ca and Na, the concentrations of all macronutrients were highest in the foliage followed by twigs, bark and stemwood for all the study trees. The higher foliar nutrient concentrations in the plantation species concur with the findings of Fölster and Khanna (1997) which reported high nutrient concentrations in the foliage of tropical plantations. Also, the highest concentration of N, P, K and Mg in the foliage of all the study trees agree with the similar trend reported for tropical conifers and broadleaved species (Drechsel and Zech 1993).

The foliage N concentration of *C. macrostachys* and *E. globulus* was higher compared to the other study trees. Foliar nitrogen concentration is correlated with

photosynthetic rates (Field and Mooney 1986; Reich et al. 1995), implying that species with high foliar nitrogen concentrations may possess a competitive advantage. The high concentration of foliage nitrogen in *C. macrostachys* and *E. globulus* might be one of the factors for the high performance of these species as pioneer and fast growing species, respectively.

According to Miller (1984), foliage accounts for between 75 and 95% of the total litter fall in managed forests. Thus, foliage plays an important role in the nutrient dynamics of the forest ecosystem. The higher macronutrient stock in the foliage of *C. lusitanica* compared to *Eucalyputs* (Fig. 29A) suggests the higher contribution of the former to the soil nutrients.

In tree species, foliage analyses have been shown to be reasonably sensitive for detecting deficiencies in forest sites (Mead 1984). The approximate concentration ranges of macronutrients categorized as deficient, normal and toxic for a mature leaf tissue of various plant species is given by Munson (1998). According to these ranges, N, P and S were deficient both in the natural and plantation forests. The general shortage of N, P and S in the tropical plantation sites has been also reported by Drechsel and Zech (1993). The lower concentration of P in the foliage of the study trees might be attributed to the generally limited availability of P in the soils derived from volcanic rocks of the study area (Lundgren 1971; Solomon et al. 2002).

It is, however, important to emphasize that foliage macronutrient concentrations vary with age (Mead 1984) and season (Drechsel and Zech 1993), hence nutrient content of foliage at a certain point in time does not necessarily imply that the site is poor in macronutrients. Furthermore, additional information on nutrient stock of the soil and litter as well as the decomposition rate of the litter should be known to determine the actual site macronutrient status. As an integral part of this study, determination of the nutrient status of soil solution of the study area is being carried out (Ashagrie in preparation). Hence, a better insight on the site nutrient status and its sustainability will be obtained when data on the soil nutrient pool is

known. Bearing this in mind, the general deficiency of N, P and S warrants replenishing N, P and S to sustain forest production. Thus, on site conservation of foliage to replenish these nutrients should be considered for sustainable forest production.

Bark

The concentration of Ca was higher in the bark of all the study trees compared to the other macronutrient concentrations. The higher concentration of Ca in the bark also agrees with the general trend for tropical conifers and broadleaved species (Drechsel and Zech 1993). The high concentration of Ca in the bark of the study tree will have an implication for future site management, particularly in the plantation forests. A relatively high concentration of Ca is required in soil since it is phloem immobile and must be taken up by apical roots (Marschner 1986). Furthermore, addition of Ca to the soil might help neutralize the acidic soil of the plantation sites (Tab. 11). Root growth and penetration can be inhibited in acidic soil (Jentschke and Drexhage 2001). Thus, in order to increase the availability of Ca to plants and maintain soil pH at an optimum level, a future management strategy may include debarking the plantation species on site.

Stemwood

The stemwood was generally characterized by the lowest concentration of macronutrients in all of the study trees (Tab. 10). However, its high biomass implies large macronutrient concentrations per unit area and subsequently a large removal of macronutrients from sites during forest thinning and clear cutting. For example, the macronutrient stock in the stemwood of *E. globulus* was higher than that of *C. lusitanica* (Fig 29 C) suggesting a higher nutrient removal when the former is harvested.

The impact of nutrient removal due to harvesting should be considered together with the site management practices employed. For example, the use of a mechanized system for tree harvesting could cause heavy erosion and soil

compaction. Furthermore, soil burning causes a significant amount of nutrient loss. It has been reported that nutrient loss caused by poor site management such as burning could be as high as, and often considerably higher than the nutrient loss by stemwood harvesting alone (Evans 2001). Since the current site management practices in the Mnuessa plantation forests do not use a mechanized system and rarely involve site burning, the effect on forest productivity due to soil compaction and nutrient loss are minimal.

Since the biomass of *P. falcatus* was not estimated due to the reasons described in section 3.3.1, the macronutrient stock in its aboveground component was not calculated. However, the big *P. falcatus*, with DBH, greater than 1 m, suggests that its contribution to the aboveground biomass of the natural forest is significant. Due to its high biomass, the macronutrient stock in the aboveground components, particularly in the stemwood will be much higher compared to the much lower stemwood macronutrient stock of *C. macrostachys* (Fig. 28). Thus, the deforestation of *P. falcatus* not only affects the structure of the natural forest, but also causes a large removal of essential nutrients. Furthermore, the lower water use efficiency of *C. macrostachys* compared to *P. falcatus* (Fetene and Beck 2004) contributes more to the unsustainably of the natural forest as a result of human induced replacement of the latter with the former.

5.5.2 Some alternative approaches to nutrient management

As described above, for the sustainability of plantation forests, particularly in the tropics where the soils are often poor in nutrients, site nutrient management should be given a high priority (Evans 2001; Miller 1984). As indicated in Fig. 29, harvesting of *C. lusitanica* and *E. globulus* stemwood at the age of 21 and 31, respectively, remove a substantial amount of nutrient from the plantation sites. On top of this, the current practice of collecting foliage, twigs and branches for firewood by the local people result even in a much higher depletion of nutrients. In order to make the plantation forests sustainable, the silvicultrual practice in the future should consider on site conservation of foliage and bark. A strategy to

balance the demand of the local people for firewood and site conservation of foliage and bark should be sought.

It should also be noted that the most important factor in managing nutrient is to find the best compromise between natural and silivicultral rotation. More data are required on the nutrient use efficiency of the plantation species at their different ages in order to suggest a more viable strategy for the management of site nutrients in the Munessa Forest. However, given the most common phenomenon of increased nutrient use efficiency in the stand with time (Drechsel and Zech 1993), the *C. lusitanica* and *E. globulus* considered in the present study might have reached a high nutrient efficiency stage compared to their younger counterparts. Thus, lengthening the rotation age of especially fast-growing species will reduce net nutrient loss. It is, therefore, necessary to increase the rotation period of *E. globulus* to minimize its negative impact on nutrients. According to the current silivicultural practice, the final rotation period of *E. globulus* could be as short as five years (personal communication). Such practice should be avoided as it might cause the removal of high amounts of nutrients from sites.

Furthermore, given the importance of N for forest production and its deficiency in the plantation forests, mixing *E. globulus* plantation with a suitable *Acacia* or other nitrogen fixing species can reduce site N depletion. For example, Khanna (1997) reported a higher growth rate of *E. globulus* when it grew mixed with *Acacia mearnsii* in Australia. Similarly, plantations mixed with indigenous tree species showed an improved growth compared to a pure stand in Costa Rica (Montagnini et al. 1995). Nonetheless, since these findings were only from an early stage of plantation establishment, the advantage of mixing plantations over single stand is difficult to generalize. It is, therefore, necessary to conduct site-specific studies to select an appropriate species for mixed plantation. For example, the positive role of *E. globulus* species in fostering the regeneration of indigenous trees has been well documented (Feyera 1998; Yirdaw 2002). Such studies, however, should also

include the impact of indigenous species on the productivity of the exotic plantation species.

6 References

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Appendix 1[1]: Species name, abundance and families of plants in the permanent plots of the natural forest.

No.	Species List	Abundance	Family
1	*Acanthopale pubescens* (Engl.) C.B.Cl.	1	Acanthaceae
2	*Achyranthus aspera* L.	+	Amaranthaceae
3	*Achyrospermum schimperi* (Hochst.) Perkins	1	Lamiaceae
4	Allophyllus abyssinicus (Hochst.) Radlkofer	1	Sapindaceae
5	*Apodytes dimidiata* (A.Rich.) Boutique	+	Icacinaceae
6	*Ardisiandra sibthorpioides* Hook. f.	+	Primulaceae
7	*Bersama abyssinica* Fresen	+	Melianthaceae
8	*Bothriocline schimperi* Oliv. & Hiern ex Benth.	1	Asteraceae
9	*Brucea antidysenterica* J. F. Miller	+	Simaroubaceae
10	*Calpurnia aurea* (Ait.) Benth	+	Fabaceae
11	*Carex spicato-paniculata* Bock. Ex C. B. Clarke	r	Cyperaceae
12	*Carissa edulis* Vahl	+	Apocynaceae
13	*Cassipourea malosana* Alston	+	Rhizophoraceae
14	*Celtis africana* Burm.f.	1	Ulmaceae
15	*Croton macrostachys* Hochst. ex Del	1	Euphorbiaceae
16	*Cynoglossum amplifolium* Hochst. ex A. Rich.	r	Boraginaceae
17	*Ekebergia capensis* Sparmm	+	Meliaceae
18	*Fagaropsis angolensis* (Engl.) H.M.Gardner	+	Rutaceae
19	*Galiniera coffeoides* Del.	+	Rubiaceae
20	*Hypoestes forskaolii* (Vahl) R. Sch.	1	Acanthaceae
21	*Ilex mitis* (Arroyo et al.) Radlk.	+	Aquifoliaceae
22	*Jasminum abyssinicum* Hochst. ex DC.	+	Oleaceae

[1] The scientic names of the plant species were based on the already published volumes of the Flora of Ethiopia and the Kew Botanical Garden Herbarium collections.

Appendix 1 (continued): Species name, abundance and families of plants in the permanent plots of the natural forest.

No.	Species List	Abundance	Family
23	*Maesa lanceolata* Forssk.	+	Myrsinaceae
24	*Maytenus arbutifolia* (Hochst ex A. Rich.) Wilczek	1	Celastraceae
25	*Nuxia congesta* R. Br. ex Fresen.	+	Loganiaceae
26	*Ochna holstii* Engl.	r	Ochnaceae
27	*Olea europaea* subsp. *cuspidata* (Wall. Ex. DE) Cifferri	+	Oleaceae
28	*Oplismenus compositus* (Arroyo et al.) P. Beauv.	3	Poaceae
29	*Periploca linearifolia* Dillon & A.Rich.	r	Asclepiadaceae
30	*Podocarpus falcatus* (Thunb.) Mirb.	2	Phytolaccaceae
31	*Prunus africana* (Hook.f.) Kalkm.	1	Rosaceae
32	*Rubia cordifolia* L	r	Anacardiaceae
33	*Rubus steudneri* Schweinf.	1	Rubiaceae
34	*Rytigynia neglecta* (Hiren.) Robyns	1	Rubiaceae
35	*Solanum indicum* L.	+	Solanaceae
36	*Stephania abyssinica* (Dill. & A. Rich.) Walp.	+	Menispermaceae
37	*Syzygium guineense* F. White	1	Myrtaceae
38	*Tacazzea conferta* N.E.Br.	r	Asclepiadaceae
39	*Teclea nobilis* Del.	+	Rutaceae
40	*Thalictrum rhynchocarpum* Dillon & A. Rich.	+	Ranunculaceae
41	*Toddalia asiatica* (Arroyo et al.) Lam.	+	Rutaceae
42	*Trichocladus ellipticus* Eckyl & Zeyh.	+	Hamamelidaceae
43	*Urera hypselodendron* (A. Rich.) Wedd.	+	Urticaceae
44	*Vernonia auriculifera* Hiren	+	Asteraceae

Appendix 2: Species name, abundance and families of plants in the permanent plots of *C. lusitanica* plantation.

No	Species	Abundance	Family
1	*Acanthopale pubescens* (Engl.) C.B.Cl.	+	Acanthaceae
2	*Achyrospermum schimperi* (Hochst.) Perkins	+	Lamiaceae
3	*Acmella caulirhiza* Del	+	Asteraceae
4	*Allophyllus abyssinicus* (Hochst.) Radlkofer	+	Sapindaceae
5	*Ardisiandra sibthorpioides* Hook. f.	+	Primulaceae
6	*Bersama abyssinica* Fresen	+	Melianthaceae
7	*Bothriocline schimperi* Oliv. & Hiern ex Benth.	+	Asteraceae
8	*Brucea antidysenterica* J. F. Miller	+	Simaroubaceae
9	*Canarina eminii* Schweinf	r	Campanulaceae
10	*Carex spicato-paniculata* Bock. Ex C. B. Clarke	1	Cyperaceae
11	*Cassipourea malosana* Alston	+	Rhizophoraceae
12	*Celtis africana* Burm.f.	+	Ulmaceae
13	*Croton macrostachys* Hochst. ex Del	+	Euphorbiaceae
14	*Cupressus lusitanica* Mill.	4	Cupressaceae
15	*Cyathula uncinulata* (Schrad.) Schinz	+	Amaranthaceae
16	*Droguetia inersa* (Forssk.) Schweinf.	+	Urticaceae
17	*Euphorbia depauperata* Hochst.	r	Euphorbiaceae
18	*Fagaropsis angolensis* (Engl.) H.M.Gardner	+	Rutaceae
19	*Flacourtia indica* Merrill	+	Flacourtiaceae
20	*Hypoestes forskaolii* (Vahl) Soland. ex Roem & Schult.	1	Acanthaceae
21	*Maytenus arbutifolia* (Hochst ex A. Rich.) Wilczek	+	Celastraceae

Appendix 2 (continued): Species name, abundance and families of plants in the permanent plots of *C. lusitanica* plantation.

No	Species	Abundance	Family
22	*Oplismenus compositus* (Arroyo et al.) P. Beauv.	+	Poaceae
23	*Oxalis radicosa* A. Rich.	r	Oxalidaceae
24	*Protea gaguedi* J. F. Gmel.	+	Protaceae
25	*Rytigynia neglecta* (Hiren.) Robyns	+	Rubiaceae
26	*Schrebera alata* (Hochst.) Welw.	r	Oleaceae
27	*Solanum indicum* L.	+	Solanaceae
28	*Stellaria sennii* Chiov.	+	Caryophyllaceae
29	*Stephania abyssinica* (Dill. & A. Rich.) Walp.	r	Menispermaceae
30	*Thalictrum rhynchocarpum* Dillon & A. Rich.	r	Ranunculaceae
31	*Toddalia asiatica* (Arroyo et al.) Lam.	+	Rutaceae
32	*Vernonia auriculifera* Hiren	+	Asteraceae

Appendix 3: Species name, abundance and families of plants in the permanent plots of E. *globulus* plantation.

No	Species	Abundance	Family
1	*Acanthopale pubescens* (Engl.) C.B.Cl.	2	Acanthaceae
2	*Achyrospermum schimperi* (Hochst.) Perkins	1	Lamiaceae
3	*Acmella caulirhiza* Del	+	Asteraceae
4	*Ardisiandra sibthorpioides* Hook. f.	+	Primulaceae
5	*Bersama abyssinica* Fresen	+	Melianthaceae
6	*Bothriocline schimperi* Oliv. & Hiern ex Benth.	1	Asteraceae
7	*Brucea antidysenterica* J. F. Miller	+	Simaroubaceae
8	*Canarina eminii* Schweinf	+	Campanulaceae
9	*Carex spicato-paniculata* Bock. Ex C. B. Clarke	1	Cyperaceae
10	*Cassipourea malosana* Alston	+	Rhizophoraceae
11	*Commelina* sp.	+	Commelinaceae
12	*Croton macrostachys* Hochst. ex Del	2	Euphorbiaceae
13	*Cynoglossum amplifolium* Hochst. ex A. Rich.	+	Boraginaceae
14	*Cyphostemma cyphopetalum* (Fresen.) Descoings ex Wild & R.B.Drumm.	+	Vitaceae
15	*Droguetia inersa* (Forssk.) Schweinf.	+	Urticaceae
16	*Eucalyptus globulus* Labill.	4	Myrtaceae
17	*Flacourtia indica* Merrill	+	Flacourtiaceae
18	*Girardinia bullosa* (Hochst. ex Steud.) Weddell	+	Urticaceae
19	*Hydrocotyle mannii* Hook. f. (ALCHEMELLA 2)	+	Apiaceae
20	*Hypoestes forskaolii* (Vahl) Soland. ex Roem & Schult.	2	Acanthaceae
21	*Kalanchoe laciniata* (Arroyo et al.) DC.	+	Crassulaceae
22	*Maytenus arbutifolia* (Hochst ex A. Rich.) Wilczek	+	Celastraceae

Appendix 3 (continued): Species name, abundance and families of plants in the permanent plots of E. *globulus* plantation.

No	Species	Abundance	Family
23	*Oplismenus compositus* (Arroyo et al.) P. Beauv.	+	Poaceae
24	*Oxalis radicosa* A. Rich.	r	Oxalidaceae
25	*Plectranthus ornatus* Codd	+	Lamiaceae
26	*Protea gaguedi* J. F. Gmel.	+	Proteaceae
27	*Rubus steudneri* Schweinf.	+	Rubiaceae
28	*Rytigynia neglecta* (Hiren.) Robyns	+	Rubiaceae
29	*Schrebera alata* (Hochst.) Welw.	+	Oleaceae
30	*Solanum indicum* L.	+	Solanaceae
31	*Stellaria sennii* Chiov.	+	Caryophyllaceae
32	*Stephania abyssinica* (Dill. & A. Rich.) Walp.	+	Menispermaceae
33	*Thalictrum rhynchocarpum* Dillon & A. Rich.	+	Ranunculaceae
34	*Urera hypselodendron* (A. Rich.) Wedd.	+	Urticaceae

Appendix 4: LFR dry weight (g) of *P. falcatus* at different depths (cm) and distances (m). Ln represents sampling lines around the bole.

Distance/Depth (cm)	10	35	60	85	100
Ln1, 1m	2.760	2.967	1.999	1.999	2.343
Ln1, 2m	1.895	1.084	0.970	0.340	0.111
Ln1, 3m	2.612	1.099	0.609	0.161	0.330
Ln2, 1m	2.200	2.397	2.296	4.474	1.965
Ln2, 2m	2.000	2.809	2.146	1.879	1.999
Ln2, 3m	1.800	2.812	2.010	1.325	1.978
Ln3, 1m	2.837	2.360	2.548	1.884	1.860
Ln3, 2m	1.500	2.365	4.728	1.635	1.879
Ln3, 3m	2.541	2.562	2.506	1.910	1.445
Ln4, 1m	2.223	0.937	0.765	0.409	0.064
Ln4, 2m	1.712	1.246	1.491	0.225	0.101
Ln4, 3m	1.430	1.776	0.684	0.261	0.138
Ln5, 1m	1.296	1.352	0.502	0.569	0.464
Ln5, 2m	1.866	0.972	0.805	0.544	0.253
Ln5, 3m	0.836	0.538	1.587	0.950	0.605
Ln6, 1m	1.659	0.900	0.803	0.293	0.024
Ln6, 2m	1.590	0.436	0.894	0.135	0.353
Ln6, 3m	1.372	0.655	0.655	0.191	0.127

Appendix 5: LFR dry weights (g) of *C. macrostachys* at different depths (cm) and distances (m). Ln represents sampling lines around the bole.

Distance/Depth (cm)	10	35	60	85	100
Ln1, 1m	0.296	0.018	0.043	0.025	0.369
Ln1, 2m	0.222	0.055	0.027	0.018	0.029
Ln1, 3m	0.185	0.083	0.284	0.003	0.006
Ln2, 1m	0.402	0.232	0.171	1.975	0.006
Ln2, 2m	0.256	0.089	1.861	0.017	0.035
Ln2, 3m	0.335	0.134	0.032	0.029	0.226
Ln3, 1m	2.476	2.528	0.044	0.032	0.005
Ln3, 2m	2.016	0.094	1.985	0.093	1.877
Ln3, 3m	2.121	0.700	0.109	1.924	0.031
Ln4, 1m	0.220	0.113	0.002	0.008	0.026
Ln4, 2m	0.492	0.085	0.088	0.041	0.062
Ln4, 3m	0.384	0.094	0.121	0.167	0.008
Ln5, 1m	0.245	0.703	0.016	0.047	0.071
Ln5, 2m	0.383	0.151	0.105	0.061	0.011
Ln5, 3m	0.313	0.101	0.024	0.013	0.003
Ln6, 1m	0.198	0.415	0.071	0.013	0.067
Ln6, 2m	0.833	0.014	0.091	0.023	0.008
Ln6, 3m	0.090	0.398	0.164	0.158	0.038

Appendix 6: LFR dry weight (g) of *C. lusitanica* at different depths (cm) and distances (m). Ln represents sampling lines around the bole.

Distance/Depth (cm)	10	35	60	85	100
Ln1, 1m	0.778	2.936	0.628	0.012	0.005
Ln1, 2m	0.552	2.272	0.419	1.957	0.253
Ln1, 3m	1.888	1.298	0.334	0.127	2.065
Ln2, 1m	0.567	0.535	0.640	0.026	1.911
Ln2, 2m	2.066	2.337	2.497	1.917	0.084
Ln2, 3m	0.346	0.240	0.587	0.231	0.214
Ln3, 1m	2.614	0.000	4.318	1.955	1.895
Ln3, 2m	2.719	2.374	1.935	1.857	1.802
Ln3, 3m	2.660	2.290	1.959	1.845	2.138
Ln4, 1m	0.542	1.062	0.087	0.025	0.023
Ln4, 2m	0.670	0.124	0.000	0.005	0.006
Ln4, 3m	0.971	0.411	0.155	0.077	0.066
Ln5, 1m	0.745	0.500	0.000	0.018	0.052
Ln5, 2m	0.832	0.818	0.153	0.196	0.169
Ln5, 3m	0.309	1.963	0.399	0.077	0.016
Ln6, 1m	1.219	0.648	0.177	0.147	0.170
Ln6, 2m	0.619	0.723	0.168	0.142	0.127
Ln6, 3m	0.647	1.463	0.506	0.127	0.107

Appendix 7: LFR dry weight (g) of *E. globulus* at different depths (cm) and distances (m). Ln represents sampling lines around the bole.

Distance/Depth (cm)	10	35	60	85	100
Ln1, 1m	0.818	0.134	0.181	0.069	0.050
Ln1, 2m	0.504	0.123	0.153	0.091	0.032
Ln1, 3m	0.338	0.149	0.065	0.047	0.038
Ln2, 1m	0.967	0.559	0.153	0.228	0.032
Ln2, 2m	1.051	0.652	0.077	0.085	0.192
Ln2, 3m	0.567	0.553	0.064	0.054	0.209
Ln3, 1m	0.423	1.920	0.241	0.021	0.082
Ln3, 2m	0.123	0.259	0.149	0.154	0.073
Ln3, 3m	0.442	0.318	0.132	0.032	0.004
Ln4, 1m	0.912	0.449	0.310	0.021	0.018
Ln4, 2m	0.584	0.386	0.339	0.305	0.010
Ln4, 3m	0.755	0.136	0.069	0.204	0.016
Ln5, 1m	1.553	0.860	0.104	0.001	0.003
Ln5, 2m	0.467	0.645	0.044	0.034	0.007
Ln5, 3m	0.868	0.723	0.298	0.063	0.005
Ln6, 1m	0.500	0.193	0.075	0.053	0.019
Ln6, 2m	0.689	0.682	0.197	0.019	0.003
Ln6, 3m	0.506	0.469	0.123	0.029	0.044

Appendix 8: Raw data used for developing aboveground biomass estimator for *C. macrostachys*. The numbers from 1 to 6 represent an individual *Croton* tree.

A. DBH, DSH and tree height.

	1	2	3	4	5	6
DBH	14.0	23.6	9.8	26	17.5	33.7
DSH	17.2	30.5	12.0	31.2	21.1	36.5
Height	16.5	20.6	10.0	20.17	16.3	19.4

B. Log fesh weight (LFW) (kg).

	1	2	3	4	5	6
Log No.	LFW	LFW	LFW	LFW	LFW	LFW
1	28.50	74.20	14.35	95.95	42.95	149.00
2	18.40	57.60	10.15	74.00	36.85	121.10
3	16.30	50.15	9.15	69.95	32.60	109.40
4	12.20	43.10	6.10	72.40	26.55	120.95
5	10.15	46.00	2.10	55.50	24.45	107.05
6	8.10	42.95		49.10	22.40	95.30
7	5.10	33.80		37.15	18.40	49.50
8	2.10	25.40		23.25		38.70
9		14.20		12.15		20.50
10		4.15		5.10		6.30
11						32.75

C. Fresh disk weight (FDW) and dry disk weight (DDW) (kg)

FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW
0.50	0.30	1.20	0.68	0.35	0.20	1.95	1.22	0.95	0.60	3.00	1.70
0.40	0.22	1.60	0.90	0.15	0.10	2.00	1.20	0.85	0.50	3.10	1.90
0.30	0.20	1.15	0.60	0.15	0.10	1.95	1.30	0.60	0.40	2.40	1.40
0.20	0.12	1.10	0.60	0.10	0.09	2.40	0.88	0.55	0.35	1.45	1.70
0.15	0.10	1.00	0.52	0.10	0.05	1.50	0.60	0.45	0.29	3.05	1.55
0.10	0.02	0.95	0.38			1.10	0.60	0.40	0.63	1.30	1.00
0.10	0.02	0.80	0.43			1.15	0.16	0.40	0.26	1.50	0.33
0.10	0.01	0.40	0.22			0.25	0.10	0.20	0.10	0.70	0.50
		0.20	0.14			0.15				0.50	0.31

D. Branch diameter (BD) and foliage dry weight (FoDW) (g).

1		2		3		4		5		6	
BD	FoDW	BD	FoDW	BD	FoDW	BD	FoDW	BD	FoDW	BD	FoDW
1.00	37.70	1.00	58.10	1.00	22.80	2.00	50.60	1.00	65.30	1.50	54.50
1.00	44.30	1.00	61.90	1.50	160.00	2.50	116.40	2.00	180.00	2.00	177.00
2.00	18.00	2.00	101.15	4.00	91.40	3.00	300.00	3.00	181.80	2.50	200.00
3.00	59.90	2.50	134.10	4.50	159.90	4.00	135.00	4.00	29.00	3.00	200.00
4.00	260.00	4.00	370.00					5.00	147.50	4.00	96.40

E. Branch diameter (BD) and branch dry weight (BDW) (g)

1		2		3		4		5		6	
BD	**BDW**	**BD**	**BDW**	**BD**	**BDW**	**BD**	**BDW**	**BD**	**BDW**	**BD**	**BDW**
1.00	53	1.00	32	1.00	48	2.00	220	1.00	115	1.50	160
1.00	51	1.00	61	1.50	55	2.50	410	2.00	200	2.00	350
2.00	89	2.00	130	4.00	900	3.00	640	3.00	710	2.50	380
3.00	163	2.50	540	4.50	1290	4.00	1200	4.00	620	3.00	920
4.00	1920	4.00	1280					5.00	1220	4.00	1180

Appendix 9: Raw data used for developing aboveground biomass estimator for *Cupressus lusitanica*. The number from 1 to 6 refers to an individual *Cupressus* tree.

A. DBH, DSH and tree height.

	1	2	3	4	5	6
DBH	24.80	35.70	18.70	22.10	28.90	47.50
DSH	29.40	41.50	21.50	26.50	34.00	59.00
Height	22.10	26.60	16.40	23.00	26.10	26.30

B. Log fresh weight (LFW) (kg).

	1	2	3	4	5	6
Log No.	LFW	LFW	LFW	LFW	LFW	LFW
1.00	68.00	188.00	36.65	71.25	119.90	279.00
2.00	49.00	128.50	26.50	56.45	93.10	201.25
3.00	41.00	114.00	22.40	52.45	88.20	181.00
4.00	35.00	103.10	17.35	49.30	87.05	167.70
5.00	29.00	90.80	14.35	48.40	80.85	76.65
6.00	23.00	84.25	11.30	43.25	72.80	140.95
7.00	18.00	75.65	7.25	38.05	64.20	129.65
8.00	14.00	63.80	3.15	31.80	56.05	122.90
9.00	10.00	49.90		23.45	42.85	70.05
10.00	6.00	32.70		12.45	31.50	41.60
11.00	2.00	14.20		5.75	16.25	20.75
12.00		4.20			7.30	7.65
13.00		0.80			0.85	0.95

C. Fresh disk weight (FDW) and dry disk weight (DDW) (kg)

	1		2		3		4		5		6
	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW	FDW
1.00	2.00	1.20	11.00	5.89	0.65	0.52	1.25	0.80	2.90	1.48	13.00
2.00	1.50	0.90	2.50	1.40	0.50	0.38	1.45	0.80	2.10	1.11	6.25
3.00	1.50	0.82	9.00	3.71	0.40	0.31	1.45	0.80	2.20	1.20	4.00
4.00	1.20	0.80	3.10	1.88	0.35	0.25	1.30	0.58	2.05	1.22	4.70
5.00	0.80	0.54	2.80	1.40	0.35	0.22	1.40	0.70	1.85	0.94	4.65
6.00	0.50	0.33	2.25	1.02	0.30	0.22	1.25	0.61	1.80	0.98	3.95
7.00	0.40	0.30	1.65	0.80	0.25	0.20	1.05	0.51	1.20	0.65	3.65
8.00	0.30	0.21	1.80	0.78	0.15	0.08	0.80	0.40	1.05	0.55	2.90
9.00	0.20	0.12	1.10	0.65			0.45	0.23	0.85	0.50	2.05
10.00	0.20	0.10	0.70	0.42			0.45	0.21	0.50	0.30	1.60
11.00	0.20	0.10	0.20	0.12			0.35	0.19	0.25	0.13	0.75
12.00			0.20	0.12					0.30	0.16	0.65
13.00			0.15	0.10					0.05	0.03	0.50

D. Branch diameter (BD) and foliage dry weight (FoDW) (g).

1		2		3		4		5		6	
BD	FoDW	BD	FoDW	BD	FoDW	BD	FoDW	BD	FoDW	BD	FoDW
1.00	79.10	1.00	76.70	0.50	18.10	2.00	118.05	2.50	205.00	1.00	82.60
1.00	68.20	4.00	398.00	1.50	98.70	2.00	72.10	1.00	41.00	2.00	485.00
		5.00	918.20	2.00	54.30	3.00	118.00	2.00	76.00	2.00	250.00
		4.00	115.05	1.00	46.60			3.00	632.30	3.00	340.00
		1.00	320.00	0.50	56.00						
				1.00	57.70						

E. Branch diameter (BD) and branch dry weight (BDW) (g)

1		2		3		4		5		6	
BD	**BDW**	**BD**	**BDW**	**BD**	**BDW**	**BD**	**BDW**	**BD**	**BDW**	**BD**	**BDW**
1.00	29.00	2.00	47.90	0.50	9.70	2.00	300.00	2.50	398.10	1.00	115.40
1.00	34.10	4.00	1225.00	1.50	59.00	2.00	112.30	1.00	51.40	2.00	345.00
		5.00	150.20	2.00	200.00	3.00	398.00	2.00	269.10	2.00	104.00
		2.00	380.00	1.00	80.50	1.40	101.20	3.00	650.00	3.00	75.40
		0.50	3.70	3.00	500.00	2.00	132.60	4.00	1480.00	4.00	2468.20

Appendix 10: Raw data used for developing aboveground biomass estimator for *Eucalyptus globulus*. The number from 1 to 6 refers to an individual *Eucalyptus* tree.

A. DBH, DSH and tree height.

	1	2	3	4	5	6
DBH	22.0	12.0	30.9	19.0	50.0	36.3
DSH	24.7	14.2	35.5	22.8	53.5	38.5
Height	29.0	21.0	38.2	24.8	43.5	38.7

B. Log fresh weight (LFW) (kg).

Log No.	**LFW**	**LFW**	**LFW**	**LFW**	**LFW**	**LFW**
1	84.40	26.50	164.35	64.10	400.00	207.05
2	69.00	20.45	115.25	47.30	348.00	100.75
3	59.80	18.45	104.80	40.20	312.00	100.15
4	55.35	16.35	94.45	33.85	312.00	81.70
5	49.30	13.31	84.05	29.70	268.00	81.10
6	43.95	11.25	78.15	25.55	268.00	73.50
7	36.80	9.20	70.00	22.50	210.00	73.25
8	31.70	8.12	61.75	17.40	210.00	59.20
9	28.70	5.10	52.45	14.30	180.00	59.15
10	23.65	1.40	47.30	10.20	152.00	89.20
11	19.30		40.00	8.15	152.00	78.05
12	13.25		35.80		152.00	77.40
13	8.10		29.55		155.45	66.45
14	3.10		25.45		108.20	55.20
15			21.45		91.00	50.95
16			15.45		89.00	32.70
17			12.20		63.00	16.65
18			5.20		43.00	26.50
19			3.10		26.00	13.35
20					17.00	
21					8.00	

C. Fresh disk weight (FDW) and dry disk weight (DDW) (kg)

	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW	FDW	DDW
1	2.40	1.35	0.50	0.30	4.35	1.24	1.10	0.52	8.80	5.05	5.05	2.53
2	2.00	1.10	0.45	0.30	3.25	1.78	1.30	0.62	10.40	5.42	4.75	2.38
3	1.80	1.00	0.45	0.30	2.80	1.60	1.20	0.60	8.20	4.30	4.15	2.20
4	1.35	0.82	0.35	0.22	2.45	1.38	0.85	0.48	8.45	4.64	4.70	2.41
5	1.30	0.80	0.31	0.20	2.05	1.20	0.70	0.40	7.20	3.92	4.10	2.18
6	0.95	0.60	0.25	0.18	2.15	1.22	0.55	0.30	6.00	3.20	3.50	1.80
7	0.80	0.51	0.20	0.13	2.00	1.20	0.50	0.28	6.15	3.40	3.25	1.78
8	0.70	0.49	0.12	0.10	1.75	1.10	0.40	0.20	4.45	2.60	3.20	1.81
9	0.70	0.48	0.10	0.03	1.45	0.90	0.30	0.19	4.30	2.45	3.15	1.80
10	0.65	0.40	0.10	0.02	1.30	0.80	0.20	0.10	4.45	2.61	2.20	1.32
11	0.30	0.20			1.00	0.60	0.15	0.09	4.85	2.83	2.05	1.22
12	0.25	0.19			0.80	0.55			2.95	2.00	1.40	0.82
13	0.10	0.08			0.55	0.50			3.45	1.76	1.45	0.88
14	0.10	0.08			0.45	0.32			2.20	1.25	1.20	0.70
15					0.45	0.23			1.75	1.08	0.95	0.60
16					0.45	0.22			1.45	0.82	0.70	0.40
17					0.20	0.13			0.60	0.34	0.65	0.42
18					0.20	0.10			0.55	0.29	0.50	0.17
19					0.10	0.02			0.25	0.15	0.35	0.20
20									0.20	0.12		
21									0.18	0.10		

D. Branch diameter (BD) and foliage dry weight (FoDW) (g).

BD	FDW	BD	FDW	BD	FDW	BD	FDW	BD	FDW	BD	FDW
2.0	138.3	1.5	38.5	1.0	210.0	2.0	400.0	1.5	148.5	1.0	84.2
4.0	420.0	2.0	109.5	1.5	39.9	1.5	73.4	2.0	500.0	1.5	162.4
3.0	179.5	1.5	77.6	1.0	62.6	1.0	146.5	3.0	545.0	2.0	280.0
2.0	113.8	2.0	85.5	2.0	70.3	2.0	205.0	5.0	720.0	2.5	260.0
1.0	48.1	0.5	5.9			1.0	95.4	3.0	970.0	3.0	400.0

E. Branch diameter (BD) and branch dry weight (BDW) (g).

BD	BDW	BD	BDW	BD	BDW	BD	BDW	BD	BDW	BD	BDW
2	300	1.5	60	1	127.2	2	720	1.5	1827	1	1080
4	400	2	106.1	1.5	103	1.5	104	2	800	1.5	280
3	626	1.5	84.7	1	148.4	1	74.2	3	2200	2	129
2	194	2	84.4	2	290	2	230	5	1600	2.5	37.3
1	48.8	0.5	11.5		230	1	80.6	3	6000	3	400

Appendix 11: Stand density, diameter at stump height (DSH) and diameter at breast height (DBH) of the study trees.

A. Podocarpus falcatus

	Stand one		Stand two		Stand three		Stand four		Stand five	
Density	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**
1	23,50	21,00	21,60	20,50	51,00	46,00	170,00	152,00	206,00	190,00
2	8,00	7,30	8,80	7,90	37,20	32,90	175,00	152,00	223,00	212,00
3	10,00	9,00	8,10	7,40					201,00	187,00
4	8,30	6,50	4,50	2,50					197,00	200,00
5	46,00	41,50	25,70	25,30					71,00	65,00
6	1,70	1,57	7,50	5,50						
7			15,50	14,30						

B. Croton macrostachys

	Stand one		Stand two		Stand three		Stand four		Stand five	
Density	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**
1	15,80	14,50	12,70	11,10	12,50	11,50	32,50	28,10	10,50	9,50
2	7,30	6,00	11,90	9,60	24,90	21,00	19,00	15,70	15,00	12,90
3	11,00	9,00	6,50	6,30	12,00	9,70	15,50	13,00	7,10	6,50
4	11,90	11,00	5,40	4,10	13,30	10,10	20,90	18,50	5,10	4,10
5	11,00	9,00	11,60	8,30	9,50	7,60	6,50	5,50	4,70	3,50
6	11,50	9,50	14,10	13,20	27,00	24,00	11,50	9,00	9,00	8,10
7					23,40	19,10			6,70	4,30
8					14,00	10,90			7,00	6,00
9					23,30	18,40			14,10	12,30
10					26,90	22,30				
11					13,30	11,50				
12					33,90	26,20				
13					33,70	27,00				
14					20,50	17,90				
15					10,90	10,10				
16					20,90	18,00				
17					14,60	12,90				

C. Cupressus lusitanica

	Stand one		Stand two		Stand three		Stand four		Stand five	
Density	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**
1	24,50	21,00	38,90	30,00	33,30	31,10	30,50	27,50	24,30	22,50
2	39,00	32,00	34,80	35,50	36,40	33,30	25,30	21,00	58,00	50,70
3	39,50	32,00	24,70	22,00	35,00	29,70	25,00	21,00	38,00	34,50
4	37,50	31,00	25,00	19,80	39,10	37,10	28,00	23,00	23,00	20,20
5	29,70	26,20	3,00	26,60	37,00	31,00	38,80	31,00	21,20	17,50
6	29,20	27,80	35,10	31,50	20,10	18,30	30,50	25,00	30,00	25,70
7	23,80	21,00	36,40	29,60	21,80	18,50	22,90	20,20	39,00	33,60
8	36,00	30,30	36,80	30,40	22,20	19,10	36,50	30,20	22,00	18,20
9	279,00	24,60	22,00	20,50	39,10	34,10	26,20	22,00	35,50	28,50
10	27,90	24,60	28,30	24,40	43,20	37,70	35,20	27,90	33,30	24,20
11	25,50	22,00	30,00	23,40	43,00	39,50	23,00	20,00	29,00	25,50
12	33,60	30,00	34,40	29,00	26,40	23,80	24,60	22,10	32,00	27,50
13	39,80	32,70	39,60	32,60	33,20	28,50	46,00	37,00	36,00	30,20
14	22,50	18,90	36,00	31,70	43,00	37,20	32,50	27,50	30,00	26,00
15	39,20	33,50	38,80	34,10	23,70	21,20	27,50	23,90	26,00	20,00
16	24,00	19,90	24,00	20,50			37,20	30,50	35,20	33,00
17	29,30	25,50	45,70	38,90			40,10	34,80	33,60	27,70
18	28,70	23,50	25,60	22,50			26,00	21,60	26,00	21,20
19	34,00	279,00	28,70	24,00			23,90	28,50	42,00	35,00
20	42,90	35,70	25,00	19,00			17,50	16,00	25,00	21,00
21			42,00	34,10			35,60	29,00	31,60	26,00
22			33,60	26,70			30,50	25,40	26,00	23,50
23			28,60	24,00			32,00	28,00	22,20	17,10
24			24,50	20,70			34,00	28,00	30,60	25,90
25			33,10	27,70			32,00	28,60	27,00	22,00
26			31,20	25,00			27,00	23,50	27,50	23,00
27			22,40	19,40			26,00	22,50	31,00	26,50
28			47,50	39,30			43,00	35,70	27,70	24,00
29			42,60	35,50					28,60	24,00
30									32,50	27,50

D. Eucalyptus globulus

	Stand one		Stand two		Stand three		Stand four		Stand five	
Density	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**	**DSH**	**DBH**
1	43,00	37,90	17,00	14,90	45,50	38,40	21,50	17,20	13,00	11,30
2	17,50	16,60	29,00	25,10	43,00	39,00	38,70	34,50	19,10	16,50
3	11,45	7,30	17,50	18,00	28,50	24,00	43,50	38,50	2,50	19,00
4	16,00	13,20	21,80	19,10	53,00	46,80	17,00	11,70	23,80	19,80
5	24,10	19,50	28,00	21,70	60,00	56,50	24,20	22,70	35,00	31,30
6	24,60	21,00	26,10	22,70	29,40	26,00	32,10	37,80	47,00	39,50
7	12,50	10,10	35,60	32,60	18,00	16,50	31,00	28,10	14,50	12,50
8	18,50	15,50	28,50	25,10	56,00	51,50	40,00	33,20	30,50	28,40
9	17,20	15,40	52,00	46,20	26,10	23,10	28,50	27,20	36,60	32,50
10	7,30	6,00	27,50	24,50	25,00	18,50	29,70	26,20	17,50	14,50
11	14,10	13,50	33,20	24,30	57,00	48,50	34,40	31,50	19,80	16,80
12	25,50	23,50	16,00	14,50	37,00	30,50	33,90	31,80	17,50	13,15
13	7,00	6,50	35,40	32,40	20,50	18,50	28,00	27,30	6,00	3,20
14	23,00	19,20	28,50	21,00	42,00	37,50	28,60	30,50	5,70	6,70
15	34,50	39,50	16,00	15,50			9,30	8,20	36,90	32,60
16	41,40	37,80	34,50	23,80			35,90	32,30	13,50	12,10
17	15,50	15,20	32,20	29,20			29,25	26,80	10,00	8,70
18	22,10	20,20	37,00	32,50			17,00	13,30	21,20	18,80
19	10,40	9,70	34,60	31,20					46,50	42,30
20	19,00	16,50	37,00	32,40					6,00	5,00
21	41,70	37,40	47,20	39,90					30,50	27,00
22	21,50	17,90	15,40	13,60					10,50	10,00
23	31,00	28,00	63,00	56,50					7,10	6,50
24	23,50	20,90	18,10	16,80					23,30	21,60
25	9,60	7,40	44,00	40,40					10,00	8,00
26	12,50	10,90	47,50	45,00					30,00	23,60
27			43,50	38,50					48,00	41,00
28			28,10	25,50					6,80	5,50
29			21,10	18,00						
30			23,50	20,00						
31			26,00	23,50						
32			32,00	27,40						
33			41,00	35,10						

Appendix 12: Macronutrient concentration (% dry weight) in the aboveground plant components of the study trees.

		Macronutrients							
Species	**Components**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**S**
P. falcatus	Foliage	46,77	1,29	0,09	1,08	0,72	0,23	0,05	0,11
		45,77	1,46	0,09	1,27	1,03	0,20	0,08	0,13
		46,84	1,43	0,11	1,17	0,54	0,15	0,06	0,13
		46,52	1,12	0,08	0,98	1,04	0,23	0,11	0,11
		45,54	1,39	0,07	1,16	1,23	0,24	0,05	0,19
		45,79	1,64	0,12	1,19	0,71	0,26	0,03	0,14
	Twigs	45,48	1,17	0,14	0,77	1,01	0,24	0,04	0,11
		45,94	1,27	0,07	0,69	0,77	0,13	0,06	0,14
		45,47	1,26	0,12	0,96	1,38	0,14	0,07	0,12
		48,41	1,84	0,12	0,77	0,87	0,10	0,08	0,15
		45,54	0,94	0,08	0,49	0,72	0,12	0,06	0,09
		47,27	0,80	0,02	0,13	0,15	0,13	0,07	0,10
	Stemwood	46,33	0,47	0,17	0,64	1,35	0,15	0,09	0,04
		47,39	0,39	0,01	0,11	0,14	0,04	0,08	0,04
		47,24	0,43	0,01	0,10	0,17	0,10	0,11	0,03
		47,07	0,52	0,03	0,29	0,10	0,05	0,04	0,05
		48,09	0,34	0,04	0,11	0,17	0,06	0,20	0,04
		46,89	0,40	0,02	0,30	0,13	0,05	0,08	0,04
	Bark	40,05	1,09	0,03	0,89	5,76	0,10	0,12	0,11
		45,78	0,79	0,02	0,43	2,32	0,13	0,07	0,09
		39,17	0,83	0,03	0,99	4,63	0,13	0,09	0,10
		43,06	0,96	0,04	0,75	2,10	0,07	0,05	0,11
		40,45	1,02	0,04	0,63	3,03	0,25	0,04	0,12
		42,37	0,96	0,03	0,59	2,24	0,12	0,04	0,09

Appendix 12 (continued): Macronutrient concentration (% dry weight) in the aboveground plant components of the study trees.

		Macronutrients							
Species	**Components**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**S**
C. macrostachys	Foliage	42,38	2,96	0,17	2,22	1,26	0,35	0,04	0,19
		42,63	2,90	0,18	2,29	1,26	0,32	0,07	0,19
		43,31	2,96	0,19	2,07	1,26	0,36	0,04	0,17
		44,09	3,21	0,19	2,10	0,87	0,24	0,07	0,20
		45,00	2,67	0,15	1,40	1,12	0,29	0,05	0,18
		44,79	3,00	0,13	1,85	0,99	0,28	0,07	0,20
	Twigs	41,46	0,00	0,07	1,23	1,39	0,15	0,07	0,08
		42,38	0,83	0,09	0,98	1,20	0,17	0,07	0,09
		41,98	0,76	0,08	1,11	1,20	0,14	0,06	0,08
		42,78	1,47	0,12	1,40	1,38	0,26	0,08	0,09
		42,30	1,97	0,20	1,74	1,06	0,21	0,06	0,10
		41,99	0,71	0,07	1,22	2,31	0,15	0,10	0,05
	Stemwood	45,28	0,10	0,01	0,41	0,17	0,03	0,06	0,02
		45,75	0,11	0,01	0,34	0,12	0,04	0,06	0,02
		45,60	0,16	0,01	0,26	0,08	0,03	0,04	0,02
		45,52	0,30	0,03	0,42	0,12	0,05	0,06	0,03
		45,96	0,17	0,02	0,33	0,15	0,05	0,11	0,02
		45,70	0,11	0,01	0,19	0,14	0,04	0,08	0,02
	Bark	40,61	0,57	0,05	1,55	3,16	0,14	0,09	0,06
		41,99	0,98	0,10	1,50	3,49	0,24	0,09	0,07
		43,31	0,76	0,09	1,40	2,15	0,16	0,08	0,06
		43,63	0,75	0,06	1,16	2,33	0,17	0,08	0,06
		41,36	0,88	0,06	1,71	2,71	0,18	0,06	0,05
		42,41	0,78	0,11	1,19	2,53	0,14	0,06	0,05

Appendix 12 (continued): Macronutrient concentration (% dry weight) in the aboveground plant components of the study trees.

		Macronutrients							
Species	**Components**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**S**
C. lusitanica	Foliage	49,24	1,27	0,07	0,54	0,87	0,14	0,05	0,11
		50,10	1,27	0,07	0,54	1,05	0,17	0,07	0,11
		50,05	1,24	0,08	0,65	1,20	0,19	0,12	0,11
		48,72	1,33	0,08	0,59	1,09	0,15	0,09	0,11
		47,66	1,01	0,06	0,47	1,55	0,17	0,05	0,11
		48,21	1,12	0,07	0,62	1,31	0,20	0,06	0,10
	Twigs	46,41	0,25	0,02	0,36	0,96	0,06	0,05	0,03
		45,11	0,47	0,02	0,28	1,39	0,11	0,06	0,04
		45,98	0,31	0,02	0,20	1,02	0,06	0,05	0,03
		47,63	0,33	0,03	0,18	0,53	0,05	0,04	0,03
		45,73	0,37	0,02	0,35	1,62	0,09	0,10	0,03
		46,22	0,33	0,03	0,24	1,29	0,08	0,08	0,03
	Stemwood	47,11	0,11	0,01	0,10	0,09	0,01	0,05	0,02
		47,14	0,10	0,02	0,08	0,12	0,02	0,05	0,02
		47,35	0,12	0,01	0,08	0,15	0,02	0,06	0,02
		46,69	0,04	0,00	0,08	0,12	0,02	0,06	0,01
		46,84	0,12	0,02	0,19	0,12	0,03	0,08	0,02
		47,14	0,04	0,01	0,04	0,12	0,02	0,06	0,02
	Bark	43,40	0,67	0,05	1,04	2,32	0,14	0,07	0,05
		44,83	0,38	0,03	0,35	1,83	0,12	0,08	0,03
		41,67	0,59	0,03	0,22	2,58	0,14	0,07	0,05
		43,07	0,36	0,03	0,69	2,10	0,09	0,08	0,05
		45,79	0,26	0,03	0,33	1,27	0,06	0,13	0,04
		45,18	0,48	0,04	0,50	1,89	0,09	0,09	0,05

Appendix 12 (continued): Macronutrient concentration (% dry weight) in the aboveground plant components of the study trees.

		Macronutrients							
Species	**Components**	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**S**
Eucalyptus globulus	Foliage	50,01	1,69	0,15	1,09	1,11	0,19	0,12	0,16
		49,91	1,60	0,14	1,12	1,09	0,18	0,15	0,16
		49,96	1,57	0,12	1,01	1,25	0,19	0,12	0,15
		49,75	1,60	0,12	0,87	1,25	0,19	0,09	0,15
		50,15	1,52	0,13	1,16	1,04	0,19	0,12	0,13
		50,09	1,53	0,12	0,89	0,67	0,14	0,10	0,13
	Twigs	46,00	0,52	0,08	0,82	1,95	0,08	0,10	0,04
		45,95	0,73	0,08	1,01	1,24	0,13	0,12	0,06
		45,77	0,71	0,08	0,89	1,56	0,12	0,12	0,06
		45,55	0,68	0,08	0,86	1,66	0,14	0,11	0,05
		45,51	0,78	0,09	0,84	1,80	0,14	0,13	0,06
		46,04	0,74	0,07	0,82	1,31	0,11	0,10	0,05
	Stemwood	46,23	0,22	0,03	0,09	0,10	0,02	0,08	0,04
		45,73	0,09	0,02	0,04	0,14	0,02	0,08	0,02
		45,92	0,08	0,01	0,12	0,12	0,03	0,10	0,02
		45,95	0,16	0,02	0,13	0,15	0,03	0,12	0,03
	Bark	40,47	0,37	0,26	0,67	3,60	0,15	0,13	0,03
		40,98	0,25	0,17	0,61	2,75	0,14	0,16	0,03
		40,29	0,18	0,07	0,40	3,21	0,19	0,12	0,02
		42,98	0,28	0,25	0,44	21,11	0,13	0,22	0,03

Appendix 13: Fine roots C, N and S (% dry weight) of the study trees at different depths (cm) and distances (m), Cu = *C.lusitanica*, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus,* ln = sampling lines

		Nutrient		
No	Species and sampling positions	C	N	S
1	Cu ln_1, 1m 10	48,37	0,96	0,09
2	Cu ln_1, 1m 35	48,59	0,53	0,05
3	Cu ln_1, 1m A	49,23	0,48	0,04
4	Cu ln_1, 2m 10	45,53	1,06	0,11
5	Cu ln_1, 2m 35	40,43	0,95	0,09
6	Cu ln_1, 2m A	47,17	0,65	0,05
7	Cu ln_1, 3m 35	44,92	0,94	0,10
8	Cu ln_1, 3m A	46,00	0,86	0,09
9	Cu ln_2, 1m 10	47,18	0,99	0,11
10	Cu ln_2, 1m 35	49,05	0,84	0,08
11	Cu ln_2, 1m A	49,11	0,64	0,07
12	Cu ln_2, 2m 35	48,72	0,53	0,05
13	Cu ln_2, 2m A	50,15	0,61	0,06
14	Cu ln_2, 3m 10	48,25	0,97	0,10
15	Cu ln_2, 3m 35	49,31	1,07	0,10
16	Cu ln_2, 3m A	44,93	0,54	0,06
17	Cu ln_3, 1m 10	46,73	1,08	0,11
18	Cu ln_3, 1m A	46,76	0,75	0,08
19	Cu ln_3, 2m 10	47,68	0,68	0,07
20	Cu ln_3, 2m 35	47,94	0,57	0,06
21	Cu ln_3, 2m A	45,72	0,90	0,07
22	Cu ln_3, 3m 10	44,89	0,87	0,09
23	Cu ln_3, 3m 35	47,88	0,44	0,06
24	Cu ln_3, 3m A	46,74	0,55	0,06
25	Cu ln_4, 1m 10	45,72	1,26	0,13
26	Cu ln_4, 1m 35	47,89	0,56	0,05
27	Cu ln_4, 1m A	40,79	0,82	0,06
28	Cu ln_4, 2m 10	47,26	1,10	0,12
29	Cu ln_4, 2m 35	45,87	0,84	0,09
30	Cu ln_4, 2m A	44,99	0,83	0,07
31	Cu ln_4, 3m 10	46,37	1,02	0,10
32	Cu ln_4, 3m 35	48,61	0,79	0,08
33	Cu ln_4, 3m A	47,67	0,97	0,11
34	Cu ln_5, 1m 10	48,09	0,87	0,06

Appendix 13 (continued): Fine roots C, N and S (% dry weight) of the study trees at different depths (cm) and distances (m), Cu = *C.lusitanica*, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus*, ln = sampling lines

		Nutrient		
No	**Species and sampling positions**	**C**	**N**	**S**
35	Cu ln_5, 1m 35	47,43	0,85	0,08
36	Cu ln_5, 1m A	47,92	0,66	0,05
37	Cu ln_5, 2m 10	49,07	0,69	0,06
38	Cu ln_5, 2m 35	47,19	0,53	0,05
39	Cu ln_5, 2m A	47,23	0,84	0,05
40	Cu ln_5, 3m 10	47,55	1,20	0,09
41	Cu ln_5, 3m 35	47,37	0,41	0,05
42	Cu ln_5, 3m A	49,54	0,56	0,08
43	Cu ln_6, 1m 10	47,19	0,88	0,11
44	Cu ln_6, 1m 35	47,94	0,74	0,08
45	Cu ln_6, 1m A	46,82	0,70	0,07
46	Cu ln_6, 2m 10	46,51	1,08	0,13
47	Cu ln_6, 2m 35	45,65	0,79	0,11
48	Cu ln_6, 2m A	47,49	0,75	0,05
49	Cu ln_6, 3m 10	48,79	0,88	0,11
50	Cu ln_6, 3m 35	46,37	0,77	0,09
51	Po ln_1, 1m 10	43,67	1,15	0,13
52	Po ln_1, 1m 35	45,12	1,01	0,13
53	Po ln_1, 1m A	44,57	0,81	0,11
54	Po ln_1, 2m 10	45,64	1,49	0,16
55	Po ln_1, 2m 35	47,02	0,83	0,11
56	Po ln_1, 2m A	43,01	0,84	0,12
57	Po ln_1, 3m 10	43,56	1,55	0,19
58	Po ln_1, 3m 35	44,86	0,75	0,09
59	Po ln_1, 3m A	45,14	1,07	0,14
60	Po ln_2, 1m 10	44,84	1,10	0,13
61	Po ln_2, 1m 35	46,91	0,85	0,10
62	Po ln_2, 1m A	47,30	0,87	0,12
63	Po ln_2, 2m 10	47,32	1,19	0,16
64	Po ln_2, 2m 35	47,13	0,90	0,11
65	Po ln_2, 2m A	47,83	0,90	0,12
66	Po ln_2, 3m 10	46,38	1,37	0,19
67	Po ln_2, 3m 35	45,77	0,96	0,12
68	Po ln_2, 3m A	44,14	0,87	0,10
69	Po ln_3, 1m 10	43,56	1,63	0,18

Appendix 13 (continued): Fine roots C, N and S (% dry weight) of the study trees at different depths (cm) and distances (m), Cu = *C.lusitanica*, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus*, ln = sampling lines

		Nutrient		
No	Species and sampling positions	C	N	S
70	Po ln_3, 1m 35	44,81	0,96	0,11
71	Po ln_3, 1m A	46,97	0,86	0,10
72	Po ln_3, 2m 10	44,05	1,15	0,12
73	Po ln_3, 2m 35	45,01	1,02	0,13
74	Po ln_3, 2m A	45,72	0,65	0,09
75	Po ln_3, 3m 10	47,78	0,95	0,12
76	Po ln_3, 3m 35	45,47	1,16	0,24
77	Po ln_3, 3m A	45,21	0,80	0,18
78	Po ln_4, 1m 10	45,94	1,12	0,13
79	Po ln_4, 1m 35	44,09	0,81	0,09
80	Po ln_4, 1m A	45,79	0,74	0,09
81	Po ln_4, 2m 10	46,64	1,13	0,15
82	Po ln_4, 2m 35	46,62	0,96	0,13
83	Po ln_4, 2m A	44,92	0,82	0,10
84	Po ln_4, 3m 10	45,84	0,98	0,11
85	Po ln_4, 3m 35	46,41	0,79	0,10
86	Po ln_4, 3m A	46,10	0,85	0,12
87	Po ln_5, 1m 10	46,54	1,42	0,17
88	Po ln_5, 1m 35	46,98	0,85	0,13
89	Po ln_5, 1m A	41,91	0,89	0,10
90	Po ln_5, 2m 10	44,75	1,32	0,14
91	Po ln_5, 2m 35	45,41	0,93	0,11
92	Po ln_5, 2m A	44,16	0,92	0,10
93	Po ln_5, 3m 10	44,72	1,60	0,17
94	Po ln_5, 3m 35	44,73	0,98	0,13
95	Po ln_5, 3m A	45,49	0,73	0,08
96	Po ln_6, 1m 10	46,38	1,17	0,16
97	Po ln_6, 1m 35	46,01	0,83	0,12
98	Po ln_6, 1m A	43,49	0,80	0,09
99	Po ln_6, 2m 10	45,52	1,12	0,12
100	Po ln_6, 2m A	45,28	0,86	0,06
101	Eu ln_1, 3m 35	40,12	1,43	0,08
102	Eu ln_2, 3m A	43,59	0,96	0,06
103	Eu ln_4, 1m 10	44,09	0,70	0,08
104	Eu ln_5, 1m 35	43,04	0,68	0,08

Appendix 13 (continued): Fine roots C, N and S (% dry weight) of the study trees at different depths (cm) and distances (m), Cu = *C.lusitanica*, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus*, ln = sampling lines

No	Species and sampling positions	C	N	S
105	Eu ln_6, 1m A	42,96	1,03	0,06
106	Cr ln_2, 3m 35	42,92	1,38	0,09
107	Cr ln_4, 2m 35	42,46	1,10	0,07
108	Cr ln_5, 2°	41,74	1,19	0,07
109	Cr ln_6, 3°	38,65	1,57	0,10
110	Eu ln_1, 3m 10	43,79	0,77	0,05
111	Eu ln_2, 3m 35	42,31	0,79	0,10
112	Eu ln_3, 3m A	43,12	0,73	0,05
113	Eu ln_5, 1m 10	41,20	1,03	0,09
114	Eu ln_6, 1m 35	43,49	0,77	0,06
115	Cr ln_2, 1m A	41,30	1,15	0,10
116	Cr ln_4, 2m 10	44,72	1,21	0,10
117	Cr ln_5, 2m 35	43,94	1,28	0,12
118	Cr ln_6, 3m 35	41,37	1,35	0,08
119	Eu ln_1, 2m A	40,64	1,32	0,08
120	Eu ln_2, 3m 10	43,77	0,84	0,09
121	Eu ln_3, 3m 35	42,84	0,76	0,06
122	Eu ln_4, 3m A	42,38	0,68	0,05
123	Eu ln_6, 1m 10	43,42	1,20	0,14
124	Cr ln_2, 2m 35	40,24	1,44	0,09
125	Cr ln_5, 2m 10	43,64	1,85	0,21
126	Cr ln_6, 3m 10	43,46	2,04	0,16
127	Eu ln_1, 2m 10	43,39	0,89	0,09
128	Eu ln_2, 2m 85	42,05	1,30	0,08
129	Eu ln_3, 3m 10	42,66	1,33	0,13
130	Eu ln_4, 3m 35	43,45	0,84	0,06
131	Eu ln_5, 3m A	41,73	0,87	0,07
132	Cr ln_2, 1m 10	45,00	1,94	0,21
133	Cr ln_4, 1m 35	42,41	1,19	0,08
134	Cr ln_5, 1m A	40,06	1,57	0,07
135	Eu ln_1, 1m A	43,11	1,22	0,09
136	Eu ln_2, 2m 35	41,17	0,79	0,05
137	Eu ln_3, 2m A	44,04	0,64	0,06
138	Eu ln_4, 3m 10	43,64	0,73	0,08
139	Eu ln_5, 3m 35	43,24	0,69	0,06

Appendix 13 (continued): Fine roots C, N and S (% dry weight) of the study trees at different depths (cm) and distances (m), Cu = *C.lusitanica*, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus,* ln = sampling lines

		Nutrient		
No	**Species and sampling positions**	**C**	**N**	**S**
140	Cr ln_1, 1m 10	41,91	2,27	0,15
141	Cr ln_4, 1m 10	43,79	1,51	0,14
142	Cr ln_5, 1m 35	43,97	1,19	0,09
143	Cr ln_6, 2m 10	44,70	1,38	0,13
144	Eu ln_1, 3m 35	44,82	0,78	0,06
145	Eu ln_2, 2m 10	41,61	1,08	0,10
146	Eu ln_3, 2m 35	42,29	0,68	0,05
147	Eu ln_4, 2m A	43,68	0,69	0,07
148	Eu ln_5, 3m 10	42,68	1,24	0,12
149	Eu ln_6, 3m A	43,33	0,75	0,05
150	Cr ln_3, 3m 10	44,31	2,02	0,18
151	Cr ln_5, 1m 10	43,62	2,14	0,16
152	Cr ln_6, 1m A	39,76	1,46	0,07
153	Eu ln_1, 1m 10	42,01	1,17	0,13
154	Eu ln_2, 1m A	42,11	0,82	0,06
155	Eu ln_3, 2m 10	44,35	1,04	0,08
156	Eu ln_4, 2m 35	42,35	1,04	0,06
157	Eu ln_5, 2m A	43,46	1,37	0,08
158	Eu ln_6, 3m 35	43,11	0,62	0,05
159	Cr ln_3, 2m A	40,25	1,31	0,09
160	Cr ln_4, 3m A	45,78	0,89	0,06
161	Cr ln_6, 1m 35	44,12	1,19	0,09
162	Po ln_6, 3m A	46,65	0,84	0,11
163	Eu ln_2, 1m 35	40,69	0,88	0,09
164	Eu ln_3, 1m A	42,12	0,88	0,05
165	Eu ln_4, 2m 10	39,44	1,47	0,15
166	Eu ln_5, 2m 35	43,20	1,06	0,09
167	Eu ln_6, 3m 10	43,40	0,80	0,06
168	Cr ln_3, 2m 10	42,52	1,75	0,18
169	Cr ln_4, 3m 35	41,52	1,35	0,08
170	Cr ln_6, 1m 10	45,22	1,32	0,12
171	Po ln_6, 3m 35	45,30	0,83	0,09
172	Eu ln_2, 1m 10	41,79	1,22	0,14
173	Eu ln_3, 1m 35	43,22	0,51	0,06
174	Eu ln_4, 1m A	41,28	0,64	0,06

Appendix 13 (continued): Fine roots C, N and S (% dry weight) of the study trees at different depths (cm) and distances (m), Cu = *C.lusitanica*, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus,* ln = sampling lines

		Nutrient		
No	**Species and sampling positions**	**C**	**N**	**S**
175	Eu ln_5, 2m 10	46,98	1,25	0,12
176	Eu ln_6, 2m A	44,82	0,68	0,05
177	Cr ln_3, 1m 35	44,65	1,54	0,18
178	Cr ln_4, 3m 10	45,78	1,46	0,12
179	Cr ln_5, 3m 35	41,53	1,35	0,08
180	Po ln_6, 3m 10	45,89	1,32	0,20
181	Eu ln_1, 3m A	39,94	1,77	0,13
182	Eu ln_3, 1m 10	43,53	0,89	0,07
183	Eu ln_4, 1m 35	43,09	1,20	0,14
184	Eu ln_5, 1m A	43,37	2,05	0,07
185	Eu ln_6, 2m 10	43,60	1,00	0,35
186	Cr ln_3, 1m 10	43,81	1,72	0,57
187	Cu ln_4, 3m, 10	48,59	2,66	0,54

Appendix 14: Fine roots K, P, Ca, Na and Mg (mg/g) of the study trees at different depths (cm) and distances (m), Cu = C. lusitanica, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus, ln = sampling lines*

		Macronutrient				
No.	**Species and sampling position**	**K**	**P**	**Ca**	**Na**	**Mg**
1	Cu ln_1, 1m 10	1,92	0,89	22,70	2,10	2,78
2	Cu ln_1, 1m 35	3,50	0,57	17,95	0,95	1,62
3	Cu ln_1, 1m A	2,98	0,65	16,44	1,07	2,01
4	Cu ln_1, 2m 10	3,88	1,72	48,16	1,52	4,23
5	Cu ln_1, 2m 35	1,56	0,29	5,97	1,22	1,55
6	Cu ln_1, 3m 35	2,04	0,91	47,99	1,05	4,04
7	Cu ln_1, 3m A	4,80	1,36	46,36	1,80	5,29
8	Cu ln_2, 1m 10	3,72	1,68	56,65	1,64	4,06
9	Cu ln_2, 1m A	1,76	0,23	8,18	0,87	0,95
10	Cu ln_2, 2m 35	4,56	0,95	28,43	1,35	2,61
11	Cu ln_2, 2m A	3,64	0,87	30,99	1,33	2,83
12	Cu ln_2, 3m 10	0,63	0,45	19,93	1,78	1,41
13	Cu ln_2, 3m A	1,46	0,67	181,83	1,13	3,04
14	Cu ln_3, 1m 10	1,96	1,65	68,54	1,53	5,19
15	Cu ln_3, 1m A	4,30	1,29	25,45	1,29	3,49
16	Cu ln_3, 2m 10	2,29	1,02	39,20	1,00	2,86
17	Cu ln_3, 2m 35	3,67	0,77	29,71	1,35	2,77
18	Cu ln_3, 3m 10	5,07	1,61	78,70	1,87	5,32
19	Cu ln_3, 3m 35	2,63	0,49	21,26	2,17	1,63
20	Cu ln_3, 3m A	0,73	1,08	8,00	1,82	0,93
21	Cu ln_4, 1m 10	4,01	2,25	57,08	2,09	5,61
22	Cu ln_4, 1m 35	3,34	1,14	35,34	1,24	2,94
23	Cu ln_4, 2m 10	2,61	1,76	64,57	1,57	4,90
24	Cu ln_4, 2m 35	5,39	1,54	47,53	1,94	5,16
25	Cu ln_4, 3m 10	3,57	1,63	57,61	1,64	4,23
26	Cu ln_4, 3m 35	1,90	0,53	14,83	0,82	1,56
27	Cu ln_4, 3m A	1,28	0,30	6,30	1,49	1,15
28	Cu ln_5, 1m 10	1,94	1,25	28,58	2,13	2,66
29	Cu ln_5, 1m 35	1,26	0,68	17,83	1,44	2,47
30	Cu ln_5, 1m A	0,39	0,23	5,51	1,59	0,73
31	Cu ln_5, 2m 10	0,98	0,59	10,40	1,53	1,53
32	Cu ln_5, 2m 35	2,67	0,71	18,75	1,82	1,68
33	Cu ln_5, 3m 10	1,47	1,11	26,24	1,68	2,86

Appendix 14 (continued): Fine roots K, P, Ca, Na and Mg (mg/g) of the study trees at different depths (cm) and distances (m), Cu = C. lusitanica, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus*, *ln* = *sampling lines*

		Macronutrient				
No.	**Species and sampling position**	**K**	**P**	**Ca**	**Na**	**Mg**
34	Cu ln_5, 3m 35	4,81	0,57	18,90	1,76	1,51
35	Cu ln_5, 3m A	2,43	0,50	13,25	1,20	1,80
36	Cu ln_6, 1m 10	1,65	0,78	27,34	0,99	2,13
37	Cu ln_6, 1m 35	2,46	0,78	16,80	2,07	2,45
38	Cu ln_6, 1m A	1,95	0,57	9,32	1,09	2,05
39	Cu ln_6, 2m 10	1,49	1,11	37,28	1,45	2,87
40	Cu ln_6, 2m 35	3,41	0,91	25,28	2,23	2,80
41	Cu ln_6, 2m A	2,10	0,77	9,88	1,88	2,01
42	Cu ln_6, 3m 10	1,22	0,79	27,66	1,97	1,92
43	Cu ln_6, 3m 35	8,35	0,68	22,32	1,65	2,52
44	Po ln_1, 1m 10	2,01	0,76	56,96	2,04	3,73
45	Po ln_1, 1m 35	3,14	0,75	32,15	1,57	3,57
46	Po ln_1, 1m A	1,48	0,64	42,21	1,47	4,73
47	Po ln_1, 2m 10	1,58	1,18	35,64	1,58	3,83
48	Po ln_1, 2m 35	3,61	0,69	33,06	8,69	4,06
49	Po ln_1, 2m A	2,18	0,49	28,69	1,27	16,17
50	Po ln_1, 3m 10	2,28	1,16	48,01	2,26	4,78
51	Po ln_1, 3m 35	1,17	0,59	49,90	1,93	14,28
52	Po ln_1, 3m A	1,69	0,74	24,46	1,76	3,66
53	Po ln_2, 1m 10	4,59	0,79	51,71	1,65	3,88
54	Po ln_2, 1m 35	0,99	0,49	30,17	0,92	2,93
55	Po ln_2, 1m A	1,13	0,52	20,54	1,54	2,64
56	Po ln_2, 2m 35	3,45	0,53	29,75	1,80	3,34
57	Po ln_2, 2m A	0,81	0,56	22,37	1,59	3,02
58	Po ln_2, 3m 10	2,49	0,65	17,88	0,86	5,36
59	Po ln_2, 3m 35	1,45	0,83	24,99	1,84	3,31
60	Po ln_2, 3m A	2,39	0,48	20,98	0,83	2,66
61	Po ln_3, 1m 10	2,00	1,13	35,06	1,77	3,60
62	Po ln_3, 1m 35	1,08	0,56	38,67	1,39	3,22
63	Po ln_3, 1m A	1,02	0,47	26,54	1,81	2,40
64	Po ln_3, 2m 10	2,07	0,80	49,99	1,66	5,76
65	Po ln_3, 2m 35	2,30	0,42	17,82	1,85	3,52
66	Po ln_3, 2m A	1,07	0,43	12,55	1,67	2,88
67	Po ln_3, 3m 10	2,02	0,56	23,28	2,03	4,96
68	Po ln_3, 3m 35	2,04	0,85	33,95	1,93	4,96

Appendix 14 (continued): Fine roots K, P, Ca, Na and Mg (mg/g) of the study trees at different depths (cm) and distances (m), Cu = C. lusitanica, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus*, *ln* = *sampling lines*

		Macronutrient				
No.	**Species and sampling position**	**K**	**P**	**Ca**	**Na**	**Mg**
69	Po ln_3, 3m A	2,36	0,52	14,61	1,73	3,11
70	Po ln_4, 1m 10	2,12	0,59	33,08	1,04	2,35
71	Po ln_4, 1m 35	1,45	0,54	50,51	1,75	2,96
72	Po ln_4, 1m A	1,39	0,40	35,62	1,78	3,12
73	Po ln_4, 2m 10	3,04	0,76	32,43	1,47	3,76
74	Po ln_4, 2m 35	2,84	0,48	29,02	1,45	4,56
75	Po ln_4, 2m A	2,65	0,44	24,76	1,51	3,31
76	Po ln_4, 3m 10	2,79	0,59	41,09	1,40	2,74
77	Po ln_4, 3m 35	1,96	0,42	30,02	1,21	3,67
78	Po ln_4, 3m A	2,93	0,48	15,03	1,55	3,33
79	Po ln_5, 1m 10	1,34	0,87	37,84	1,64	3,26
80	Po ln_5, 1m 35	2,88	0,53	34,77	1,68	3,83
81	Po ln_5, 1m A	2,16	0,57	21,46	2,45	3,19
82	Po ln_5, 2m 10	1,42	0,85	43,24	1,76	3,05
83	Po ln_5, 2m 35	2,67	0,56	28,02	1,59	3,10
84	Po ln_5, 2m A	2,32	0,63	23,55	1,69	3,41
85	Po ln_5, 3m 10	2,59	1,07	20,84	2,14	3,35
86	Po ln_5, 3m 35	2,33	0,63	16,38	1,76	3,57
87	Po ln_5, 3m A	2,71	0,50	21,57	1,68	3,08
88	Po ln_6, 1m 10	1,57	0,71	35,89	1,61	3,71
89	Po ln_6, 1m 35	1,98	0,41	34,77	1,63	2,95
90	Po ln_6, 1m A	2,00	0,46	21,25	1,94	2,88
91	Po ln_6, 2m 10	1,96	0,83	55,75	1,87	3,71
92	Eu ln_4, 1m 10	1,72	0,75	43,88	2,48	2,68
93	Eu ln_5, 1m 35	3,11	0,92	34,94	1,82	3,74
94	Cr ln_2, 3m 35	2,52	0,37	9,59	1,06	1,47
95	Cr ln_5, 2°	0,99	0,21	6,01	0,62	1,04
96	Cr ln_6, 3A	9,31	1,18	9,61	1,08	3,54
97	Eu ln_1, 3m 10	3,59	0,85	33,89	1,18	3,45
98	Eu ln_2, 3m 35	2,69	0,76	37,11	1,58	2,90
99	Eu ln_5, 1m 10	2,87	1,04	32,60	1,52	3,11
100	Cr ln_2, 1m A	1,84	0,66	8,72	2,02	1,86
111	Cr ln_4, 2m 10	3,24	0,86	15,33	1,41	3,64
112	Cr ln_5, 2m 35	2,06	0,27	11,66	2,05	1,42
113	Cr ln_6, 3m 35	5,55	0,91	26,17	1,85	3,89

Appendix 14 (continued): Fine roots K, P, Ca, Na and Mg (mg/g) of the study trees at different depths (cm) and distances (m), Cu = C. lusitanica, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus*, *ln* = *sampling lines*

		Macronutrient				
No.	**Species and sampling position**	**K**	**P**	**Ca**	**Na**	**Mg**
114	Eu ln_2, 3m 10	2,12	1,04	35,66	2,77	2,84
115	Eu ln_3, 3m 35	1,88	0,75	30,55	1,79	2,55
116	Eu ln_4, 3m A	3,60	1,23	48,99	1,93	3,12
117	Eu ln_6, 1m 10	2,64	0,94	27,66	1,37	3,59
118	Cr ln_5, 2m 10	5,89	1,35	35,29	1,05	4,48
119	Eu ln_1, 2m 10	3,31	1,04	36,07	1,40	3,30
120	Eu ln_2, 2m 85	2,33	0,80	20,42	1,35	2,25
121	Eu ln_3, 3m 10	3,34	1,20	34,53	1,38	3,54
122	Cr ln_2, 1m 10	5,30	1,49	33,38	1,14	3,79
123	Eu ln_1, 1m A	1,03	0,50	13,30	1,72	1,35
124	Eu ln_2, 2m 35	3,99	1,07	46,56	1,81	4,20
125	Eu ln_3, 2m A	0,58	0,17	9,81	1,28	0,90
126	Eu ln_4, 3m 10	1,59	0,74	43,66	1,32	2,37
127	Eu ln_5, 3m 35	3,39	0,97	40,53	1,14	2,54
128	Cr ln_1, 1m 10	7,49	1,25	66,98	1,62	7,17
129	Cr ln_4, 1m 10	4,51	1,09	29,76	1,50	4,12
130	Cr ln_5, 1m 35	4,86	1,40	32,87	1,11	3,04
131	Cr ln_6, 2m 10	6,47	0,82	17,41	0,97	4,06
132	Eu ln_2, 2m 10	4,50	1,17	34,39	1,63	3,31
133	Eu ln_3, 2m 35	1,25	0,83	18,78	1,40	1,54
134	Eu ln_4, 2m A	2,69	0,72	23,92	0,59	2,14
135	Eu ln_5, 3m 10	1,91	1,15	48,26	1,63	2,95
136	Eu ln_6, 3m A	0,64	0,19	8,42	1,50	0,87
137	Cr ln_5, 1m 10	5,19	1,69	45,10	1,41	5,53
138	Cr ln_6, 1m A	1,14	0,16	3,53	1,58	0,93
139	Eu ln_1, 1m 10	3,35	1,51	66,82	1,83	4,72
141	Eu ln_2, 1m A	3,32	0,82	22,77	1,31	3,50
141	Eu ln_3, 2m 10	2,42	0,64	15,40	1,45	2,19
142	Eu ln_4, 2m 35	3,78	0,94	29,77	2,29	4,05
143	Eu ln_6, 3m 35	2,37	0,74	45,93	1,69	3,58
144	Cr ln_4, 3m A	4,41	0,67	19,51	1,04	2,88
145	Cr ln_6, 1m 35	4,07	1,24	29,99	1,41	2,92
146	Po ln_6, 3m A	2,19	0,45	27,90	1,98	4,10
147	Eu ln_2, 1m 35	5,87	0,93	31,18	1,58	3,73
148	Eu ln_3, 1m A	3,27	1,17	36,96	2,11	3,20

Appendix 14 (continued): Fine roots K, P, Ca, Na and Mg (mg/g) of the study trees at different depths (cm) and distances (m), Cu = C. lusitanica, Cr = *C. macrostachys*, Eu = *E. globulus*, Po = *P. falcatus, ln = sampling lines*

		Macronutrient				
No.	**Species and sampling position**	**K**	**P**	**Ca**	**Na**	**Mg**
149	Eu ln_4, 2m 10	3,00	1,37	33,09	2,52	4,20
150	Eu ln_5, 2m 35	3,60	0,99	41,99	2,17	4,25
151	Eu ln_6, 3m 10	2,50	1,01	43,08	1,44	3,88
152	Cr ln_3, 2m 10	1,94	0,49	14,05	1,61	1,78
153	Cr ln_4, 3m 35	5,16	0,80	23,76	1,78	3,61
154	Cr ln_6, 1m 10	3,06	0,69	20,48	1,31	2,57
155	Po ln_6, 3m 35	1,80	0,41	42,72	1,47	3,85
156	Eu ln_2, 1m 10	3,44	1,24	36,45	2,14	4,20
157	Eu ln_3, 1m 35	4,15	1,13	38,83	1,43	2,78
158	Eu ln_5, 2m 10	0,97	1,06	27,76	1,25	2,80
159	Eu ln_6, 2m A	0,92	0,33	12,58	1,14	1,51
160	Cr ln_3, 1m 35	6,05	1,56	38,28	1,03	3,71
161	Cr ln_4, 3m 10	2,80	1,08	18,51	1,42	4,83
162	Cr ln_5, 3m 35	3,08	0,55	14,89	1,54	2,32
163	Po ln_6, 3m 10	1,23	0,90	49,93	1,44	3,75
164	Eu ln_3, 1m 10	2,98	1,06	42,95	1,98	3,06
165	Eu ln_4, 1m 35	4,80	1,52	18,14	2,06	4,15
166	Eu ln_6, 2m 10	3,20	1,00	39,70	2,01	3,41
167	Cr ln_3, 1m 10	7,53	1,26	38,84	1,58	4,77
168	Cr ln_4, 2m A	1,29	0,36	5,67	1,27	1,49
169	Cu ln_4, 3m, 10	2,39	0,48	16,73	0,62	1,16

7 Declaration / Erklärung

Hiermit erkläre ich, dass ich die Arbeit selbständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe.

Ferner erkläre ich, dass ich anderweitig mit oder ohne Erfolg nicht versucht habe, diese Dissertation einzureichen. Ich habe keine gleichartige Doktorprüfung an einer anderen Hochschule endgültig nicht bestanden.

Bayreuth, den 11 Februar 2004

(Asferachew Abate)