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The potential of oil palm and forest plantations for carbon  
sequestration on degraded land in Indonesia

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## ABSTRACT

Terrestrial ecosystems play an important role in regulating the abundance of atmospheric carbon dioxide (CO<sub>2</sub>). Plantations of trees and perennial crops on degraded and marginal lands are an effective way of enhancing the build up of the terrestrial carbon (C) pool. The aim of this study is to quantify the potential of C sequestration through the conversion of *Imperata cylindrica* grasslands into oil palm and *Acacia mangium* plantations. Research was conducted in Sumatra and East Kalimantan (Indonesia). Total C stored in the systems (both below- and aboveground) was determined with destructive sampling techniques and the rate of C sequestration estimated with the false-time-series approach. *Imperata cylindrica* grasslands produce only a relatively small amount of biomass C (5.9-7.6 Mg ha<sup>-1</sup>) and have shallow roots (maximum depth 1.8 m) and, therefore, only a low level of soil carbon storage can be expected in this system. Biomass and biomass C of both oil palm and *A. mangium* plantations increase with age to a level much higher than that of *I. cylindrica* grassland. In the oil palm plantations, rates are 84.4 and 76.8 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in biomass and soil, respectively, while in *A. mangium* plantations 78.5 and 157.7 Mg C ha<sup>-1</sup> 5 m<sup>-1</sup>, respectively, can be achieved. Furthermore, the deep penetration of the roots (to a depth of 5 m) in these plantations promotes a substantial amount of C sequestration in the deeper soils. Soil C storage increases with plantation age to almost twice that of *I. cylindrica* grassland, suggesting that the establishment of plantations is beneficial not only in terms of C sequestration but also in terms of land rehabilitation. Although the magnitude of biomass C in the plantations is quite comparable, due to the longer period for the sequestration (plantation cycle of 9 and 30 years for the *A. mangium* and oil palm plantations, respectively), the rate of C sequestration in the biomass of the oil palm plantation is much lower (3.4 and 9.3 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the oil palm and *A. mangium* plantations, respectively). However, there is a significant difference in the soil-C sequestration in these plantations (17.5 and 2.6 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> yr<sup>-1</sup> for the *A. mangium* and oil palm plantations, respectively). Of the C stored in the systems, 81.2 and 76.9% of the total C of the *A. mangium* and oil palm plantations, respectively, is assigned to the belowground C pool (soil and belowground biomass C) to a depth of 5 m. In *I. cylindrica* grassland, this value is 98.0%. Regardless of the difference in magnitude and distribution of the C sink, it is evident that oil palm and *A. mangium* plantations can play an important role in sequestering atmospheric CO<sub>2</sub>. The conversion of marginal land (mainly *I. cylindrica* grasslands) into such plantations should thus be encouraged.

# Das Potential von Ölpalmen- und Waldplantagen zur Kohlenstoffspeicherung auf degradierten Böden in Indonesien

## KURZFASSUNG

Terrestrische Ökosysteme spielen eine wichtige Rolle bei der Regulierung der Menge von atmosphärischem CO<sub>2</sub>. Baumplantagen und der Anbau von Dauerkulturen auf degradierten Böden oder Marginalland sind wirksame Möglichkeiten, den terrestrischen C-Pool zu erhöhen. Die Studie in Sumatra und Ost-Kalimantan quantifiziert das Potential der C-Speicherung durch die Umwandlung von *Imperata cylindrica*-Grasland in Ölpalmen- und *Acacia mangium*-Plantagen. Der Gesamtkohlenstoff im System (unter- und oberirdisch) wurde mit destruktiven Beprobungsmethoden und die C-Speicherungsrate in einer ‚falschen Zeitreihe‘ bestimmt. *Imperata cylindrica*-Grasland produziert nur eine geringe Menge Biomasse-C (5.9-7.6 Mg ha<sup>-1</sup>). Aufgrund der relativ flachen Durchwurzelung (maximale Tiefe 1.8 m) ist in diesem System nur eine geringe Boden-C-Speicherung zu erwarten. Biomasse und Biomasse-C von Ölpalmen- bzw. *A. mangium*-Plantagen nehmen mit deren Alter auf ein Vielfaches der Menge in *I. cylindrica*-Grasland zu. In Ölpalmenplantagen erreichen die Werte 84.4 bzw. 76.8 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in Biomasse bzw. Boden und in *A. mangium*-Plantagen 78.5 bzw. 157.7 Mg C ha<sup>-1</sup> 5 m<sup>-1</sup>. Außerdem führt das tiefe Wurzelwerk dieser Plantagen zu einer deutlichen Erhöhung der C-Speicherung in den tieferen Bodenschichten. Der Boden-C-Gehalt erreicht mit zunehmendem Alter der Plantage fast das Doppelte der Menge im *I. cylindrica*-Grasland, was darauf hindeutet, dass Plantagen nicht nur hinsichtlich der C-Speicherung sondern auch im Hinblick auf Landrehabilitation vorteilhaft sind. Obwohl der in der Biomasse gespeicherte Kohlenstoff in beiden Plantagensystemen vergleichbar ist, ergibt die längere Rotationszeit (30 Jahre bei der Ölpalmenplantage gegenüber 9 Jahre für die *A. mangium*-Plantage) eine erheblich niedrigere C-Speicherungsrate in der Ölpalmenplantage (3.4 bzw. 9.3 Mg ha<sup>-1</sup> Jahr<sup>-1</sup> für Ölpalmen- bzw. *Acacia mangium*-Plantage). Der Unterschied in der C-Speicherung im Boden ist beträchtlich: 17.5 und 2.6 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> Jahr<sup>-1</sup> für die *A. mangium*- bzw. Ölpalmenplantagen). Von dem Gesamtkohlenstoff der Plantagensysteme werden 81.2 (*A. mangium*) bzw. 76.9% (Ölpalmen) im unterirdischen C-Pool (Boden und unterirdische Biomasse) bis zu einer Bodentiefe von 5 m gespeichert. In *I. cylindrica*-Grasland sind es 98.0%. Unabhängig vom Unterschied in der Menge und Verteilung der C-Speicherung wird deutlich, dass Ölpalmen- und *Acacia mangium*-Plantagen einen Beitrag zur Festlegung von atmosphärischem CO<sub>2</sub> leisten könnten. Die Umwandlung von Marginalland (hauptsächlich *I. cylindrica*-Grasland) in derartige Plantagen sollte daher gefördert werden.

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## 1 INTRODUCTION

Climate change and global warming are among the most challenging environmental, economic and social issues worldwide. Global temperatures have increased by 0.3-0.6 °C over the past 100 years and are expected to increase by a further 1-3.5 °C by 2100, accompanied by changes in precipitation, storm patterns, and drought frequency and intensity (Santer *et al.* 1996; Kattenberg *et al.* 1996). Global warming, which has been associated with an unprecedented increase in atmospheric greenhouse gas concentrations, is expected to lead to negative impacts on valuable ecosystems, increased intensity and frequency of heat waves, and other climatic-related disasters as well as crop failures and freshwater scarcity.

One of the most prominent anthropogenic-induced greenhouse gases is carbon dioxide (CO<sub>2</sub>), contributing to more than 51% of the global warming. The level of atmospheric CO<sub>2</sub> has increased from 280 ppm in 1800 to a present more than 360 ppm. The atmosphere now contains about 760 Pg of carbon (C) as CO<sub>2</sub>. The annual global CO<sub>2</sub> emission in the 1990s was 6.3 ±0.4 Pg C yr<sup>-1</sup> (1 Pg = 10<sup>15</sup> g). While most was derived from the burning of fossil fuel (IPCC 2001), land-use change, mainly tropical deforestation, also contributed an estimated 1.6 Pg C yr<sup>-1</sup> (Houghton 1999). However, atmospheric C represents less than 30% of the C in terrestrial ecosystems. Vegetation contains nearly 500 Pg C, while soils contain another 2000 Pg C in form of organic matter and detritus (Schimel 1995; WBGU 1998; IPCC 2000).

Terrestrial ecosystems play an important role in regulating the abundance of atmospheric CO<sub>2</sub>. Of the 406 Pg of C emitted during the period 1850 to 1998, 270 Pg C were derived from fossil fuel combustion and cement production, and 136 Pg C were emitted through land-use activities (IPCC 2000). Of these emissions, roughly 110 Pg C were absorbed back into terrestrial ecosystem sinks and about 120 Pg C were absorbed by oceans. The rest (176 Pg C) accumulated in the atmosphere. Thus, it is evident that there is a need to reduce atmospheric CO<sub>2</sub>, and other greenhouse gases (GHGs) and that policy measures must take into account the role of terrestrial ecosystems (IPCC 2000).

There are great opportunities in forestry, agriculture, and other sectors for mitigating further increases in the atmospheric C pool. The options vary by social and economic conditions. Slowing or halting deforestation, improved natural forest

management practices, afforestation, and reforestation of degraded forests and wastelands are the most attractive opportunities in the forestry sector (IPCC 2001). All activities leading to the preservation or enhancement of the existing terrestrial C pools, or to the prevention of an increase in atmospheric C pools such as the use of biomass to offset fossil fuel use should be the main focus of GHG mitigation projects. Some practical examples of mitigation strategies include fire or insect control, forest conservation, establishing fast-growing stands, changing silvicultural practices, planting trees in urban areas, ameliorating waste management practices, managing agricultural lands to store more C in soils, improving management of grazing lands, and replanting grasses or trees on cultivated lands (IPCC 2001).

In the case of terrestrial C sinks, a forest ecosystem transforms atmospheric CO<sub>2</sub> into C stock components (trees, roots, other vegetation, litter, and soil organic matter). Even though C stored in forests may ultimately be released through natural or anthropogenic disturbances, forest-C sequestration has been identified as one of the most promising options to reduce the build-up of atmospheric CO<sub>2</sub> (Dixon et al. 1993; Sampson and Sedjo 1997; Marland and Schlamadinger 1999). IPCC (1996) estimated that 700 Mha of forestland might be globally available for C conservation. Of that, 138 Mha might be available for slowed tropical deforestation, 217 Mha for regeneration of tropical forests, and 345 Mha for plantations and agroforestry. By 2050, a cumulative mitigation impact of 60 to 87 Pg C due to improved forest management could be expected, 45 to 72 Pg C of this is likely to occur in the tropics. Towards the end of this time interval, the mitigation impact could approach a maximum rate of 2.2 Pg C/yr (IPCC 2001).

Notwithstanding the debate as to whether global forests are sources or sinks of greenhouse gases (Pelley 2003; Harmon 2001; Metting *et al.* 2001; Schimel *et al.* 2001; Lal and Singh, 2000; Ravindranath *et al.* 1997), managed fast-growing forests may enhance C sequestration (Lee *et al.* 2002; Ney *et al.* 2002; Metting *et al.* 2001; Papadopol 2000). Silvicultural strategies aiming at accelerating the stand growth are likely to increase the rate of C sequestration of the respective forests (Lee *et al.* 2002; Chen *et al.* 2000; Montagnin and Porras 1998).

Plantation of trees and perennial crops on degraded and marginal lands is likely to be an effective way to enhance the build-up of terrestrial C pools. These

plantations promote C sequestration not only in the biomass but also in deep soils. However, there is little information on the potential C sink that could be attained by conversion of degraded lands (such as *Imperata cylindrica* grasslands) into specific tree plantations such as *Acacia mangium* and oil palm.

About 7.5-8.5 million ha of *I. cylindrica* grasslands are distributed on various islands in Indonesia (Garrity *et al.* 1997; Soekardi *et al.* 1993), an area that has been identified to have low economic and ecological values. In line with the extensive expansion of oil palm and forestry plantations (mainly in Sumatra and Kalimantan) planned by the government, conversion of these lands into plantations would be a promising option.

The oil palm as a perennial crop has become important in Indonesia, firstly, as a major source of oils and fats for human food, secondly, as animal feeds, and thirdly, for the manufacture of many domestic products such as cosmetics, soap and detergents. The establishment of large-scale monoculture oil palm plantations in Indonesia began in 1985 over an area of about 600.000 ha. In 1999, the area had expanded to about 3 million ha (Glastra *et al.* 2002; Wakker 2000).

Plantations of fast-growing species have been rapidly increasing in Asia in recent years (Cossalter and Pye-Smith, 2003). *Acacia mangium* is one of the most common fast-growing species in the humid tropics. *Acacia mangium* used to be planted primarily for site rehabilitation; however, due to its rapid growth and tolerance of very poor soils, this species is playing an increasingly important role in efforts to sustain commercial supplies of tree products while reducing pressure on natural forest ecosystems. Its quick growth and dense shade make the tree an effective tool in reforesting *Imperata* grass swards and reducing fire risk (Nitrogen Fixing Tree Association, 1987). It has been reported that this species has a great potential with regard to unproductive and degraded lands such as those infested by *I. cylindrica* (Otsamo 2002; Hardiyanto *et al.* 1999; Otsamo *et al.* 1997).

The main goal of this study is to evaluate the potential C sink that could be achieved by conversion of *I. cylindrica* grasslands into plantations (*Acacia mangium* and oil palm). Furthermore, this study aims at quantifying the C pool and distribution of the plantation systems (*Acacia mangium* and oil palm) and *I. cylindrica* grasslands. The

rate of biomass and C accumulation of the plantations was estimated from a false time series sampling.

Field experiments were conducted on two islands in Indonesia (Sumatra and Kalimantan) between 2002 and 2004. In Sumatra, observation was conducted in the provinces North Sumatra and Jambi and in the province East Kalimantan in Kalimantan.

The thesis consists of seven chapters. Following the introduction in Chapter 1, Chapter 2 provides the site description, and chapters 3, 4 and 5 present the analyses of biomass and C distribution of *I. cylindrica* grassland, *Acacia mangium* and oil palm plantations, respectively. A general discussion on the biomass and C stored in the two plantation systems and *I. cylindrica* grasslands is presented in Chapter 6, and the overall conclusions and recommendations are given in Chapter 7.



## 2 SITE DESCRIPTION

The study was conducted on the two Indonesian islands of Sumatra and Kalimantan. The sites were selected based on the abundance of the *I. cylindrica* grasslands and the plan for the establishment of plantations in these regions.

### 2.1 Sumatra

The study was carried out in two provinces of Sumatra, i.e., North Sumatra for the 20- and 30-year-old oil palm plantations and Jambi in south Sumatra for the 3- and 10-year-old oil palm plantations. North Sumatra is located between 0° 04' and 4° 11' north latitude and 97° 53' and 100° 13' east longitude, and Jambi 0° 45' and 2° 25' south latitude and 101° 10' and 104° 55' east longitude (Anonymous 1997).

Altitudes in North Sumatra and Jambi range from 0-250 m asl near the coast to more than 1500 m asl inland. The geomorphology of these regions is flat to undulating near the coast and rolling to mountainous in the upland of the Bukit Barisan mountains. The geomorphology of these regions affects the rainfall pattern, leading to high local variation in rainfall distribution. Based on the Schmidt and Ferguson classification, climate types A to E are found, with annual rainfall ranging from less than 1500 mm to more than 4500 mm. The plots in the study area were all located in climate type A.

The climate of the island of Sumatra is humid tropical, being classified as Af according to the Köppen classification (Köppen 1931) or as humid forest according to the FAO (2001). In the lowlands, the annual average temperatures are 26-27° C. Daily maxima range from 30° C to 36° C and daily minima are around 22° C. However, the more specific climate of the study region is classified according to Köppen as Aafw – a tropical rainy isothermal climate with hot summers (hottest month more than 22°C), without a dry season (mean precipitation in driest month more than 60 mm) and two rainfall maxima (February-April and October-December). Monthly rainfall and temperature distribution of this site are presented in Figure 2.1.

The soils of Sumatra have developed under year-round high temperatures and precipitation and are highly weathered and leached. These soils have low cation-exchange-capacities, high acidity and shallow top-soils. However, in areas with volcanic ash or alluvial deposits, soils of higher fertility are found. Most of the soils in

the lowland areas are fine textured and are well drained and highly weathered (BPN 1993). In some cases, these soils are derived from acid volcanic tuff sediments and have high Al saturation. Kaolinitic clay minerals dominate the clay fraction of the soils.

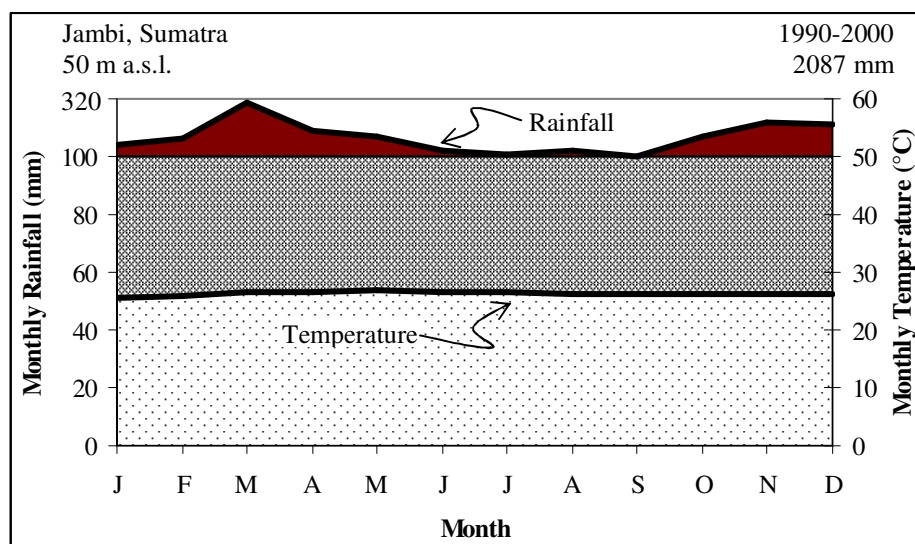


Figure 2.1: Monthly rainfall and temperature curves of study sites in Jambi, south Sumatra

The soils of the study site are Typic Hapludults, characterized by low fertility, clay loam and silty clay texture for the upper and lower soils, respectively. The drainage of the soils is moderately good (slightly slow) to good, the effective soil depth of 50-100 cm and solum depth more than 1 m (PMP-SMART 2001).

## 2.2 East Kalimantan

East Kalimantan lies between 115°26'28" - 117°36'43" east longitude and 1°28'21" north latitude - 1°08'06" south latitude. Similar to the Sumatra sites, the climate in East Kalimantan is classified as Aafw (Bremen et al., 1990; Ohta *et al.* 1992), i.e., a tropical rainy isothermal climate with hot summers (hottest month more than 22°C), without a dry season (mean precipitation in driest month more than 60 mm) and two rainfall maxima (April-May and December-January). The mean annual rainfall ranges between approximately 2000 mm in the north and 2500 mm in the south (Voss 1982). Mean monthly temperature is 27°C (RePPPProT 1987). Highest daytime temperatures of 35°C

and lowest nighttime temperatures of 19°C have been recorded (Voss 1979). Mean monthly temperature and rainfall are depicted in Figure 2.2.

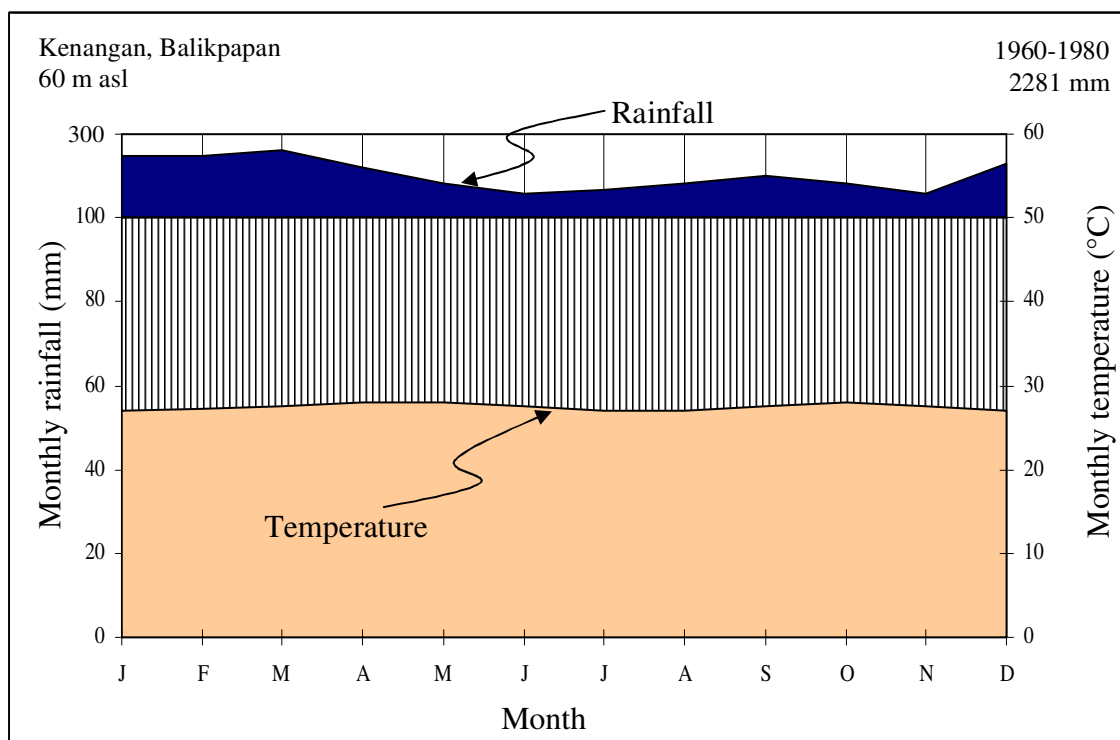


Figure 2.2: Temperature and rainfall curves of East Kalimantan

The eastern part of the province belongs mainly to the physiographic region of the Kutai Valley and Ridge Fold Belt. This region is dominated by systems of high, rugged, strongly folded and faulted mountains, hogbacks and cuestas, piedmont areas, low mountains and rugged hills, and undulating plains (Voss 1982; and Ohta 1992). However, the physiography of the western part of this province is rather smooth with altitude ranging between 50 and 1500 m asl.

The soils in this region have developed from the middle-late Miocene and early Miocene rocks dominate the geology of the province. These rocks have a thickness of approximately 2100 m to 8000 m. The middle-late Miocene rock consists mainly of muddy sandstone and mudstone. Coal layers are also abundant. Early Miocene rocks are largely calcareous mudstones with interbedded limestone, coaly sandstones and occasional tuff beds (Voss 1983; and Ohta *et al.* 1992).

Typic Paleudults and Typic Hapludults are the major soils in the region (Bremen *et al.* 1990 and Ohta *et al.* 1990). However, besides Entisols, Inceptisols and

## Site description

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Spodosols, Aquic Paleudults and Aquic Hapludults can also be found (Bremen *et al.* 1990 and IHM 1989)

The Ultisols have a mixed clay mineralogy consisting of kaolinite, chlorite/vermiculite and oxides of aluminum and iron. Small amounts of mica are reported by Kawana (1976). Sand and silt fractions are dominated by quartz Ruyiat (1989). Soil properties of the Sumatra and East Kalimantan are presented in Table 2.1.

Table 2.1: Soil properties of top- and subsoil in study sites in Sumatra and East Kalimantan, Indonesia

Parameter	Sumatra		East Kalimantan	
	Topsoil	Subsoil	Topsoil	Subsoil
Soil type (USDA)	Typic Paleudults		Typic Paleudults	
Soil texture (pipette)	SL-SiCL	SC-C	SL-SiCL	CL-C
pH (H <sub>2</sub> O)	4.3	4.4	4.3	4.4
Organic C (mg g <sup>-1</sup> , dry combustion)	15.4	3.9	16.0	6.0
Total N (mg g <sup>-1</sup> , dry combustion)	1.4	0.4	1.6	0.9
Available P (mg kg <sup>-1</sup> , Bray II)	5.8	3.4	7.6	2.6

### 3 **IMPERATA CYLINDRICA GRASSLANDS: BIOMASS AND CARBON DISTRIBUTION**

#### 3.1 **Introduction**

Low income, inappropriate technology, low input and poor understanding regarding land management have led to huge areas of deforested land in the tropics. In many cases, farmers with land adjacent to forest zones cleared the forests and converted the land into agricultural land to meet their subsistence needs. Due inappropriate land management systems, much of this area has been abandoned and invaded by *I. cylindrica*, the most common weed in the tropics. Today, *I. cylindrica* covers an area of more than 8.5 million ha in Indonesia alone (Garrity *et al.* 1997; Soekardi *et al.* 1993).

*Imperata cylindrica* is a perennial, rhizomatous grass and reproduces from seed and rhizomes; however, flowering is rare and generally occurs only after human disturbance or stress (Sajise 1972). The plant is stemless, growing in loose to compact tufts with slender, flat, linear-lanceolate leaves from the rhizomes (Hubbard *et al.* 1944). It is a serious pest throughout the tropical and subtropical regions and ranked as the seventh most troublesome weed worldwide (Holm *et al.* 1977). *Imperata cylindrica* has been reported to compete for nutrients, light, and water, and cause physical injury to neighboring plants through rhizomes penetrating the roots of these plants (Boonitee and Ritdhit 1984; Eussen and Soerjani 1975; Jagoe 1938). Furthermore, *I. cylindrica* has low nutritional values due to the high C/N ratio, and high lignin and polyphenol contents (Hartemink and O'Sullivan 2001).

The persistent and aggressive rhizomes of *I. cylindrica* are the main mechanism for survival and local spread, which makes the weed difficult to control. *I. cylindrica* is able to invade areas that will not support other vegetation, as it can tolerate a wide range of soil and climatic conditions (Hubbard *et al.* 1944; Eussen and Wirjahardja 1973).

Shade, repeated herbicide application, and mechanical control have all been used to control *I. cylindrica* (Macdicken *et al.* 1997 Terry *et al.* 1997). Mechanical control is, however, very labor intensive and the use of herbicide (Glyphosate) is costly and open to environmental risks. There is the potential of using *Mucuna* in the fallow

period to control this grass (Carsky 2001; Akobundu 2000). Nevertheless, because of no direct additional product, acceptance by the farmers in south east Asia is low.

*Imperata cylindrica* grass is usually found on soils with low pH, fertility, and organic matter content and soils that are highly leached (Sajise 1980; Wilcut *et al.* 1988). However, recent studies report that this grass grows fast in a wide range of soils and climatic zones (Snelder 2001; Garrity *et al.* 1997; Santoso *et al.* 1997) creating a vast area of unproductive grassland. This is unfavorable from both ecological and economical points of view: low biomass (Otsamo 2002), C accumulation, and biodiversity, enhanced soil degradation and compaction (Ohta 1990); the grass also has a very limited use. Moreover, this grassland is susceptible to fire that may extend to the forests in the vicinity of this grassland, resulting in an increased coverage. Thus, *I. cylindrica* grasslands emerge as fire-climax vegetation in areas where periodic fires hold back the natural secondary succession of forest (Eussen and Wirjahardja 1973). As a consequence of the unfavorable environmental conditions created by grass competition, allelopathy, fire susceptibility, soil degradation and compaction (Ohta 1990; Dela Cruz 1986; Soerianegara 1980), such grasslands are difficult to reforest or use for agricultural purposes, unless intensive land preparation and management are employed (Otsamo 2002; Otsamo *et al.* 1997). Land preparation for tree or crop plantations is very labor intensive and may require 200 man days ha<sup>-1</sup> (Van Noordwijk *et al.* 1997) or 800-1000 hours ha<sup>-1</sup> (Ruthenberg 1976).

However, this grass is susceptible to shade (Otsamo 2002; Brook 1989; Eussen 1981) resulting in reduced carbohydrate storage, rhizome and tuber-bulb production, shoot dry weight, increased susceptibility to competition and herbicides, and decreased vigor and regeneration (Macdicken *et al.* 1997). Plantations of fast growing trees are, therefore, effective in suppressing and elimination of this grass (Otsamo *et al.* 1997; Turvey 1996). Fast growing tree plantations may ameliorate the strongly fluctuating microclimate conditions and reverse soil degradation by enhancing soil microbiological activities through increased litter production and nitrogen fixation (Fisher 1995; Ohta 1990; Dela Cruz 1986), thus facilitating the reinvasion of native species (Otsamo 2000; Lugo 1997; Parrotta *et al.* 1997).

The potential use of agroforestry for the reclamation of *I. cylindrica* grassland has also been reported (de Foresta and Michon 1997; Santoso *et al.* 1997).

While the distribution of *I. cylindrica* grassland, its effect on soil properties and its reclamation potential have been intensively studied, data on the above- and belowground biomass and C distribution of this grassland system are still scarce. Such data are important for determining the base line of C storage of the system, which can be used in greenhouse-gas mitigation projects such as planting trees in marginal lands. The focus of this study is, therefore, to quantify the biomass and C stock of the system, both above- and belowground, as well as soil-C distribution.

### **3.2 Methodology**

Observation and sampling for the determination of biomass and C storage of *I. cylindrica* grassland were conducted at both the Sumatra and East Kalimantan sites. Three 3 m x 3 m plots were established on each site. Each plot consisted of three 1 m x 1 m sub-plots. All above ground biomass of *I. cylindrica* inside the sub-plots was harvested and weighed. Sub-samples were dried to a constant weight at 60°C and dry weight was determined. Thereafter, the samples were ground to pass a 0.2 mm sieve and stored for further chemical analyses.

Root biomass was sampled and collected at 16 drilling points in each plot to a depth of 3 m (using an 8-cm-diameter root auger in 15-cm increments) distributed on a systematical sampling basis (Figure 3.1). In some cases a less-weathered parent material layer was found at 3 m depth, presenting a physical barrier and preventing sampling for deeper soil layers. Roots were separated from the soil core by water saturation and flushing: soil cores were watered in small flasks overnight for soil suspension. In the case of heavy clayey soils (common for soil layers deeper than 50 cm), calgon (sodium polyphosphate) was added to the suspension to enhance the dispersion capacity of the soils. Hereafter, the suspension was rinsed under a medium pressure water tap and the roots were collected with 2-mm and 65- $\mu$ m sieves. The samples were processed following the same procedure as for aboveground biomass samples.

Soil samples for chemical analysis were drawn in line with the procedure of root biomass sampling. A small portion of the soil mass sample was drawn from each soil core of the root sampling. Samples were then mixed to six depth classes, 0-15, 15-30, 30-50, 50-100, 100-200 and 200-300 cm, air dried and ground to pass a 2-mm sieve.

A soil profile was established nearby one of the three plots on each site for observation of soil morphological characteristics and sampling of soil bulk density. Soil

bulk density was sampled at depths of 0-15, 15-50, 50-100, 100-200 and 200-300 cm. Three to six soil core samples were drawn at each depth depending on the range of the soil depth and its presumed variation (3, 4, 5, 6 and 6 core samples for the depths 0-15, 15-50, 50-100, 100-200 and 200-300 cm, respectively).

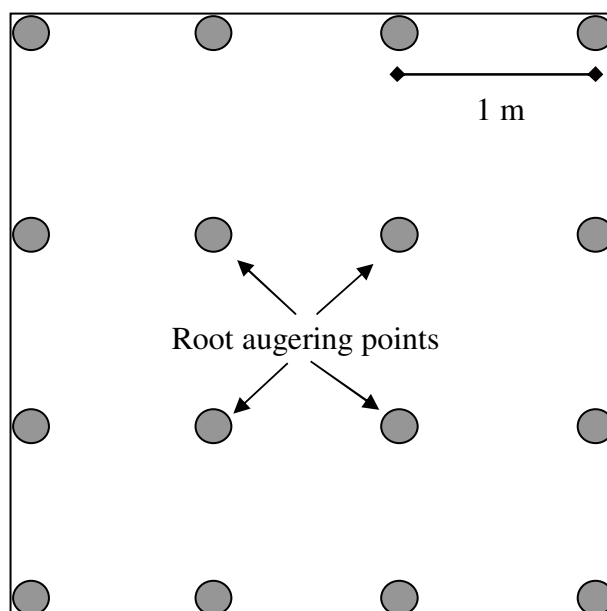


Figure 3.1: Layout of root sampling of *Imperata cylindrica* grassland at the study sites in Sumatra and East Kalimantan, Indonesia

Carbon and nitrogen (N) content of the samples was determined on the basis of dry combustion with a CNS (C, N, Sulfur) analyzer. Total C of the system was calculated based on C content and mass of each compartment of the system.

The data were analyzed with analysis of variance (ANOVA) and means were compared with the Least Significant Different (LSD) test procedure.

### 3.3 Results and discussion

Above- and belowground biomass of *I. cylindrica* grasslands varied within and among sites (Table 3.1). However, the difference was not significant at  $\alpha = 0.05$ . The aboveground biomass ranged from 6.0 to 10.1 Mg ha<sup>-1</sup>, which is close to the 11.4 Mg ha<sup>-1</sup> in *I. cylindrica* grasslands in South Kalimantan reported by Otsamo (2002). Although not significant, both above- and belowground biomass of the systems in East Kalimantan site were higher than in Sumatra. This difference may be the result of genetics, environment or seasonal variations of the systems. Nevertheless, since the data



were consistent with the organic C of the soils, the results reflect the difference in soil resources. Belowground biomass was higher than aboveground biomass by a factor of 1.5 for the systems in East Kalimantan and by a factor of 1.3 for those in Sumatra.

Table 3.1: Above- and belowground biomass of *Imperata cylindrica* grassland at the study sites in Sumatra and East Kalimantan, Indonesia

Site	Biomass (Mg ha <sup>-1</sup> )			Below-/ aboveground ratio
	Aboveground	Belowground <sup>1</sup>	Total	
East Kalimantan	<b>8.8±1.2</b>	<b>13.1±1.2</b>	<b>21.9±2.4</b>	<b>1.5±0.1</b>
Sumatra	<b>7.4±2.3</b>	<b>9.5±1.9</b>	<b>16.9±4.2</b>	<b>1.3±0.1</b>
	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>

<sup>1</sup> Down to 3 m soil depth; ns not significantly different at  $\alpha = 0.05$ ; three replications

Root biomass of *I. cylindrica* grasslands was distributed to a maximum depth of 180 cm. However, most of the roots were confined to the top soil layer (Table 3.2), i.e., 79.5% of the root biomass was found in the top 15 cm and 90% in the upper 41 cm. This implies that the conventional and mechanical elimination of this grass will never succeed, because of the difficulty of removing of the deep rhizomes. Measures could be combined with a sound and environmentally friendly chemical application before shade-based (Macdicken *et al.* 1997) and soil fertility improvement measures (Santoso *et al.* 1997) could effectively control this grass. The magnitude of root biomass of 12.4 Mg ha<sup>-1</sup> was in the range of that of cool-season grass and switch grass of riparian buffers of 10.9-16.8 Mg ha<sup>-1</sup> (Tufekcioglu *et al.* 2003; 1999). Although the biomass of *I. cylindrica* grassland systems is comparable to that the above systems, the distribution in *I. cylindrica* grassland was more concentrated in the upper soil layers: 88.4% of the roots was found in the top 35 cm, while this was 83.0 and 81.0% for the cool-season grass and switch grass systems, respectively (Tufekcioglu *et al.* 2003; 1999).

Bulk density of soils developed under *I. cylindrica* grasslands ranged from 1.1 to 1.5 depending on site and soil depth (Table 2). The soil bulk density of the East Kalimantan site was slightly lower than that of the Sumatra site. This difference may relate to past land-use history, parent material and the development of respective soils. Bulk density of the soils in East Kalimantan increased with depth, which can be attributed the decreasing biological activities. At the Sumatra site, bulk density peaked at the depth of 50-100 cm (maximum illuviation horizon) and declined to a depth of 300 cm. However, at both sites, bulk density of the top soils characterized by the dense

root biomass (Soepardi 1980; Soerjatna and McIntosh 1980) was significantly lower ( $\alpha = 0.05$ ) than that of deeper soils.

Table 3.2: Root biomass and bulk density of soils in *Imperata cylindrica* grasslands at the study sites in Sumatra and East Kalimantan, Indonesia, by depth

Depth (cm)	Root biomass (Mg ha <sup>-1</sup> )		Bulk density	
	East Kalimantan	Sumatra	East Kalimantan	Sumatra
0-15	9.9a	7.3a	1.08a	1.11a
15-50	1.5b	1.1b	1.29b	1.36b
50-100	0.9c	0.5c	1.34b	1.50b
100-200	0.2d	0.2d	1.35b	1.43b
200-300	0.0e	0.0e	1.39b	1.37b

Values followed with the same letters are not significantly different at  $\alpha = 0.05$ .

Even though the bulk density of soils developed under *I. cylindrica* grassland was higher than that of primary forests of 1.0 (top soil) and 1.3 (sub-soil) (Ruhayat 1989), the bulk density of topsoil of plantations of 1.1 to 1.2 and subsoil of 1.3 to 1.4 (Bremen *et al.* 1990; Ruhayat 1989) is comparable to that of under *I. cylindrica* grassland. However, compared to the values reported by Bremen *et al.* (1990) and Ruhayat (1989), the increase in soil bulk density from the top- to subsoils of *I. cylindrica* was much more distinct.

Carbon and N content of the aboveground biomass of *I. cylindrica* ( $40.7\% \pm 0.7\%$  and  $0.62\% \pm 0.06\%$ , respectively) was higher than that of belowground biomass ( $30.7\% \pm 2.2\%$  and  $0.56\% \pm 0.05\%$ , respectively) but only the C content was significant ( $p$  of  $< 0.001$  and  $0.13$ , respectively). These values are based on six replications for the aboveground biomass and three replications for the belowground biomass. The C content of *I. cylindrica* leaves of  $42.6\%$  reported by Hartemink and O'Sullivan (2001) was quite comparable to that of the aboveground biomass of the present study. This concentration did not much differ compared to that of *Piper aduncum* and *Gliricidia sepium* ( $40.4$  and  $43.8\%$ , respectively) reported by Hartemink and O'Sullivan (2001).

The average C:N ratio of the belowground biomass (55) was lower than that of aboveground biomass (66). However, the values were considerably lower than the 110 reported by Hartemink and O'Sullivan (2001). Compared to that of *Piper aduncum* and *Gliricidia sepium* of 26 and 18, respectively (Hartemink and O'Sullivan 2001), the C:N ratios of *I. cylindrica* were much higher. The rate of decomposition of *I. cylindrica*

leaves was much slower than that of *Piper aduncum* and *Gliricidia sepium*, which could not be explained by the C:N ratio alone; the process is also influenced by the lignin plus polyphenol over N ratio (Hartemink and O'Sullivan 2001).

On average, the biomass C of the *I. cylindrica* grassland systems in the East Kalimantan and Sumatra sites was 3.6 and 3.0 Mg ha<sup>-1</sup> (aboveground), 4.0 and 2.9 Mg ha<sup>-1</sup> (belowground) and 7.6 and 5.9 Mg ha<sup>-1</sup> (total), respectively (Table 3.3). This magnitude is in the range of the biomass C of cool-season grass and switch grass of riparian buffers reported by Tufekcioglu *et al.* (2003). Compared to aboveground biomass C of *I. cylindrica* grassland of 1.7-1.9 Mg ha<sup>-1</sup> reported by Ginting (2000) and Lachica-Lustica (1997), the results are somewhat higher, but lower than the 8.5 Mg ha<sup>-1</sup> reported by Lasco *et al.* (1999). Although belowground biomass was significantly higher than aboveground biomass ( $p = 0.027$ ), due to the lower C content of the belowground biomass (30.7% and 40.7% for the below- and aboveground biomass, respectively), the belowground and aboveground biomass C did not differ much. The ratio of below- to aboveground biomass C was 1.0 and 1.1 in Sumatra and East Kalimantan, respectively. A similar ratio was reported by Tufekcioglu *et al.* (2003) for the cool-season and switch grasslands of riparian buffers in Iowa.

Table 3.3: Above- and belowground biomass C of *Imperata cylindrica* grassland at the study sites in Sumatra and East Kalimantan, Indonesia

Site	Biomass C (Mg ha <sup>-1</sup> )		
	Aboveground	Belowground	Total
East Kalimantan	<b>3.6±0.5</b>	<b>4.0±0.4</b>	<b>7.6±0.9</b>
Sumatra	<b>3.0±0.9</b>	<b>2.9±0.6</b>	<b>5.9±1.5</b>
	<b>ns</b>	<b>*</b>	<b>ns</b>

*ns* = not significantly different at  $\alpha = 0.05$ ; \* significantly different at  $\alpha = 0.05$ ; three replications

Soil organic C and nitrogen are the main limiting factors in grassland productivity and are affected by biomass removal (periodic burning), low input of organic matter and loss of organic matter by surface erosion (Snelder 2001). Soil C content of soils at both sites decreased persistently with depth (Table 3.4). Values were 1.27 and 1.08% in the top 15-cm depth dropping to 0.15 and 0.10% at the 200-300-cm depth for East Kalimantan and Sumatra, respectively. There was a sharp decrease in the first 15-cm depth to the second 15 cm, after which the C content declined gradually to a depth of 300 cm.

Table 3.4: Carbon content and storage of soils in *Imperata cylindrica* grasslands at the study sites in Sumatra and East Kalimantan, Indonesia

Soil Depth (cm)	Site			
	East Kalimantan		Sumatra	
	C content (%)	C storage (Mg ha <sup>-1</sup> )	C content (%)	C storage (Mg ha <sup>-1</sup> )
0-15	1.27a	20.6	1.08a	18.1
15-30	0.88a	17.1	0.70b	14.3
30-50	0.75a	19.3	0.57b	15.5
50-100	0.53a	35.7	0.44b	32.7
100-200	0.27a	36.6	0.18b	25.7
200-300	0.15a	21.4	0.10b	14.0
0-300	-	150.6	-	120.3

Values followed by the same letters are not significantly different at  $\alpha = 0.05$ .

*Imperata cylindrica* grassland systems have a dense mat of rhizomes near the surface, which is a positive factor with respect to erosion control and a source of organic material (Soepardi 1980; Soerjatna and McIntosh 1980). It plays a positive role on sloping lands in reducing soil movement and as a vegetative filter for run-off carrying sediments. The relatively high C content of the top 15-cm soil could be due to the abundance of root mass. However, compared to the C content of the topsoil of plantation systems of 1.6 to 2.3% (Mackensen 1998; Syahrudin 1997; Bremen *et al.* 1990), the C content of the soils under *I. cylindrica* grasslands is even lower. This is in agreement with the previous finding that the C content of the soils in regularly burnt *I. cylindrica* grasslands tends to decline (Van Noordwijk *et al.* 1997; Ohta 1990). Furthermore, even though without fire a reasonable soil organic matter level might be maintained, litter quality and subsequent N mineralization are low (Hartemink and O'Sullivan 2001; Van Noordwijk *et al.* 1997).

With the exception of the 0-15-cm layer, the C content of the soils at the East Kalimantan site was significantly higher than that of at the Sumatra site ( $p < 0.001$ ). Since there was no evidence of differences in fire events at these sites, the difference suggests that there was already a difference in the level of soil C content prior to the invasion of *I. cylindrica*.

Distribution of the C storage of soils developed under *I. cylindrica* grassland is presented in Table 3.4. The results show that the top 50-cm soil depth contributed less than 40% of the total soil C storage to a depth of 3 m, and the contribution of the top 100-cm soil was 61.5-67.0%. This suggests that contribution of the C storage in the

deep soils is significant and, due to its high variability, must be assessed. The C storage to a depth of 3 m in this study is quite comparable to that in oxisols of secondary and primary Brazilian forests and traditional crops (130.0-145.0 Mg ha<sup>-1</sup>), but higher than that of oil palm and passion fruit plantations (108.0 and 125.0 Mg ha<sup>-1</sup>, respectively) (Sommer *et al.*, 2000). Little information exists on the C storage in deep soils in the study region; however, the 47.9-56.9 Mg ha<sup>-1</sup> in the top 50-cm soil are still in the range of values for forest plantations (42.1-67.5 Mg ha<sup>-1</sup>) (Mackensen 1998; Syahrudin 1997; Bremen *et al.* 1990; Ruhiyat 1989). Nevertheless, compared to secondary and primary forests (57.7-69.9 Mg ha<sup>-1</sup>) (Ruhiyat 1989), the soil C storage of *I. cylindrica* grassland systems is lower.

Of the total 126.2-158.2 Mg ha<sup>-1</sup> C, only 2.3-2.4% were stored in aboveground biomass. Compared to forest ecosystems, contribution of aboveground biomass C to the total C storage of grassland systems is generally much lower (Sharrow and Ismail 2004).

### **3.4 Conclusions**

*Imperata cylindrica* grassland stored only a relatively small amount of biomass C (5.9-7.6 Mg ha<sup>-1</sup>) implying that conversion into a more C-rich tree-based system would be promising tool to enhance C sequestration. Moreover, the roots of *I. cylindrica* extended to a maximum depth of only 180 cm. With most of these roots being confined to the topsoil, little organic material is deposited in deeper layers. Despite the dense mat of rhizomes, the extent of C stored in the top soils was modest. As sequestration is of global concern, the conversion of this grassland into systems with higher biomass accumulation and deeper root penetration is required.

Soil C content at both study sites decreased significantly with depth from the top 15 cm to the 3-m depth and was considerably higher in East Kalimantan than in Sumatra. With similar land-use history, the differences in soil C are likely to be related to the level prior to the invasion.

## 4 ACACIA MANGIUM PLANTATIONS

### 4.1 Introduction

Tropical forests play an important role in the global C budget, and some evidence suggests that tropical forests may sequester atmospheric CO<sub>2</sub> (Sataye *et al.* 2001; Grace *et al.* 1995). However, Cox *et al.* (2000) and White *et al.* (2000) estimated that a substantial amount of C could be released from tropical forests if temperatures increase due to global climate change.

Studies on the sequestration and dynamics of C in tropical soils have recently gained importance. These are mainly driven by the fact that the changes in the magnitude of C held in soil organic matter may significantly change the levels of atmospheric CO<sub>2</sub> (Schlesinger 1991). Estimates for the quantity of organic C in the upper meters of soil world-wide range from 1220 Gt to 1550 Gt (Eswaran 1995; Post *et al.* 1982; Schlesinger 1977; Schlesinger 1984), which is nearly twice the aboveground biomass of 560-835 Gt (Sombroek *et al.* 1993). Soils, in particular those in the tropics, could be large sinks of atmospheric C if well managed (Lugo and Brown 1993). The transformation of forestland into agricultural land leads to substantial losses of aboveground biomass, but the effect on soil C stocks remains poorly understood. It is commonly assumed that after conversion to agricultural use the soil becomes impoverished in C, which is reversed during the fallow period (Cerri *et al.* 1991; Greenland and Nye 1959; Lugo and Brown 1993; Raich 1983).

The sequestration of C into vegetation and soil sinks is one of the mechanisms for reducing net greenhouse gas emissions. Conservation strategies, which sequester C, include converting marginal lands to compatible land-use systems, restoring degraded soils, and adopting best management practices. Notwithstanding the debate as to whether global forests are sources or sinks of greenhouse gases (Pelley 2003; Harmon 2001; Metting *et al.* 2001; Schimel *et al.* 2001; Lal and Singh, 2000; Ravindranath *et al.* 1997), managed fast growing forests may enhance C sequestration (Lee *et al.* 2002; Ney *et al.* 2002; Metting *et al.* 2001; Papadopol 2000). Silvicultural strategies aiming at accelerating stand growth are likely to increase the rate of C sequestration of the respective forests (Lee *et al.* 2002; Chen *et al.* 2000; Montagnin and Porras 1998).

Plantations of fast-growing species have been rapidly increasing in Asia in recent years (Cossalter and Pye-Smith, 2003). *Acacia mangium* is one of the most common fast growing species planted in the humid tropics. Plantations of *A. mangium* have been established at many secondary forest and grassland sites across the region, covering about  $20 \times 10^6$  ha (ca. 9.4% of the total forested area) in ASEAN countries in the year 2000 (FAO 2003). *A. mangium* used to be planted primarily for site rehabilitation; however, due to its rapid growth and tolerance of very poor soils, this species is playing an increasingly important role in efforts to sustain commercial supplies of tree products while reducing pressure on natural forest ecosystems. Its quick growth and dense shade make the tree an effective tool in reforesting *Imperata* grass swards and reducing fire risk (Nitrogen Fixing Tree Association 1987). It has been reported that this species has a great potential with regard to unproductive and degraded lands such as those infested by *I. cylindrica* (Otsamo 2002; Hardiyanto *et al.* 1999; Otsamo *et al.* 1997). The establishment of plantations with this species in areas for forestry-based C offset projects is, therefore, promising.

There are about 7.5-8.5 million ha of *I. cylindrica* grasslands distributed in various islands in Indonesia, an area that would be large enough to support the extensive expansion of oil palm and forestry plantations planned by the government. These plantations have high potential to be promoted in the world-C trade and they may, therefore, increase the foreign exchange earnings of the country. However, the question as to how much CO<sub>2</sub> equivalent can be sunk by converting *I. cylindrica* grassland into plantation is still open. To answer this question, studies on the biomass and C storage of both *I. cylindrica* grasslands and man-made forests are of utmost importance.

In this study, efforts are devoted to quantifying the biomass and C accumulated in *A. mangium* plantations of different ages and biomass and C distribution.

## **4.2 Methodology**

Plots for the determination of biomass and C storage of an *A. mangium* plantation were established at the East Kalimantan site. Three 0.05-ha circular plots (r = 12.6 m, consisting of 55 trees of a full standing stock plantation with a planting space of 3 m x 3 m) were established in a 1-, 4-, and 9-year-old *A. mangium* plantation. Extreme

variation in stand density, undergrowth coverage and land slope was avoided. Thus, 9 plots were established (3 stand ages, 3 replications). To minimize errors induced by the variation of soil type, all observation plots were established in loamy to clayey Ultisols, considering that this is the most common soil in the region.

The diameters of the trees in each plot were measured and the data used to estimate the total biomass of the respective stand. For this, the data was combined with the results of the tree biomass sampling to build an allometric equation. Twenty trees were harvested and uprooted. Total biomass of the harvested trees was weighed, and samples were drawn from the different components (root, stem, branch, twig and leaf) and weighed. Samples were dried to constant weight at 60°C. Thereafter, samples were ground to pass a 0.2-mm sieve for chemical analysis.

Three 5 m x 5 m subplots were established to assess the biomass of woody undergrowth occupying the respective plot. All woody undergrowth in these sub-plots was harvested and uprooted. Total biomass was weighed and the samples were sorted into roots (medium and coarse), stems, branches and twigs, and leaves. Thereafter, the procedure as for the trees was carried out. To estimate the total biomass and C stored in the herbaceous undergrowth, three 1 m x 1 m sub-plots were established, and the herbaceous undergrowth in these sub-plots was harvested and weighed to calculate the total fresh weight. Samples were drawn representatively for total dry weight assessment. Thereafter, the same procedure as for the tree samples was followed.

Only litter in the L and F layers of the soil was considered as litter standing stock in this work, because the H layer was incorporated into the soil sample. In each main plot, three 0.5 m x 0.5 m subplots were established to collect the litter. The litter in these subplots was collected, sorted into woody and non-woody components and weighed (fresh and air dry). A small sample of each component was drawn and processed following the same procedure as for the tree samples.

To complete the biomass determination, three subplots 3 m x 3 m in accordance with the planting space of the *A. mangium* plantations were established in each main circular plot. Fine root and soil samples were drawn at 17 drilling points to a depth of 3 m (using an 8-cm-diameter soil core auger in 15 cm increments) distributed in a systematical sampling system on the basis of the distance to the closest trunk: 10 cm (A), 50 cm (B), 100 cm (C), 150 cm (D) and 212 cm (E) (Figure 4.1). Roots were



separated from the soil core by water saturation and flushing as described in Section 3.2.

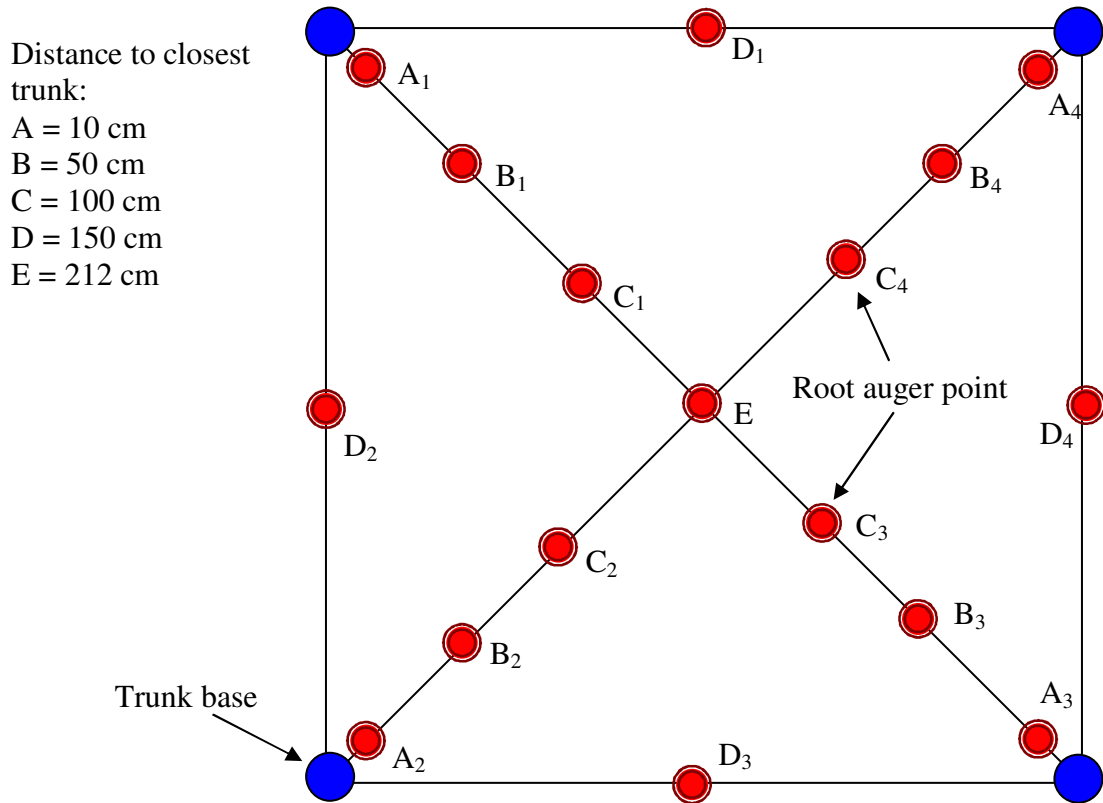


Figure 4.1: Layout of root and soil sampling in *Acacia mangium* stand in East Kalimantan, Indonesia

A soil profile was established near the center of one of the three plots of each plantation age for observation of the soil morphological characteristics and sampling of soil bulk density. Soil sampling and analysis were carried out following the procedure described in Section 3.2.

Data were analyzed with analysis of variance (ANOVA) and means compared with the Least Significant Different (LSD) test procedure.

### 4.3 Results and discussion

#### 4.3.1 Biomass distribution

The biomass of the *A. mangium* plantations was assessed using an allometric equation based on the results of the destructive sampling of the trees. Six allometric equations were developed; all are at  $p < 0.001$ .

$$Y = 0.0065X^{2.7601}, \quad r^2 = 0.9452 \text{ for root biomass (excluding fine root biomass)}$$

$$Y = 0.034X^{2.7166}, \quad r^2 = 0.9442 \text{ for stem biomass}$$

$$Y = 0.0608X^{2.0034}, \quad r^2 = 0.9470 \text{ for branch biomass}$$

$$Y = 0.0399X^{1.9189}, \quad r^2 = 0.8711 \text{ for leaf biomass}$$

$$Y = 0.2518X^{2.1679}, \quad r^2 = 0.9205 \text{ for aboveground biomass}$$

$$Y = 0.1027X^{2.4942}, \quad r^2 = 0.9628 \text{ for total biomass}$$

Y = expected biomass of the tree compartment

X = tree diameter at breast height.

Allometric equations developed to estimate biomass and volume of the stands in most of the previous studies are based on the diameter and height of trees (Yantasath *et al.* 1992; Halenda 1989; Ruhayat 1989; Bustomi 1988). However, the results in this study show that estimations of tree biomass based on diameter alone can provide accurate and reliable results. Since tree height is to a large extent dependent on tree diameter and the relation of tree diameter, and since height is likely species specific, estimations of tree biomass and volume based on tree diameter can be quite reliable, especially when the stand consists of mono species. Furthermore, measurement of the height of the standing trees is difficult in the field and may, therefore, be subject to errors, thus estimation of the stand yield (biomass or volume) based on tree diameter alone is recommended.

Most allometric equations in former studies are developed from a single stand age (Syahrudin 1997; Halenda 1989; Ruhayat 1989; Lim 1988, 1986), mainly supported by the assumption that tree form may change with stand age. In contrast to this assumption, the results in this study show that the established allometric equations are applicable for a very wide range of stand ages (1- to 9-year-old stands). This implies that the equations can be employed for similar plantations elsewhere, regardless of the age of the stand. Soemarna and Bustomi (1986) developed an allometric equation fitted for 3- to 7-year-old *A. mangium* stands. Hiratsuka *et al.* (2003) found that the allometric equations of aboveground biomass of 6-year-old stands of *A. mangium* in Benakat, Indonesia and Sonbe, Vietnam, 7-year-old stands in Madang, Papua New Guinea (PNG), and 8-year-old stands in Benakat and Bogor, Indonesia, were not site dependent. The equation developed in this study confirms their finding ( $r^2 = 0.99$ ,  $p < 0.001$ ) that the allometric equation for *A. mangium* plantations is not site specific and that the

equation can be applied for any plantation of this species, regardless of stand age and site conditions.

Biomass distribution of the plantations is presented in Table 4.1. The diameter distribution of the 4- and 9-year-old stands is comparable to that of the so-called site index 18.0 m of 15.3 and 20.5 cm, respectively, reported by Newaz and Millat-E-Mustafa (2004). Nevertheless, the results on the diameter distribution of the 1-year-old stands of 5.6 cm in this study are higher than their finding of 3.2 cm. The average diameter of 1-year-old *A. mangium* stands ranged widely from 1.8 to 8.8 cm (Yanthasath *et al.* 1986; Paudyal and Nik Muhamad 1990), depending on site conditions, planting space and material, and plantation management.

Table 4.1: Stand density, diameter and biomass distribution in *Acacia mangium* plantation system in East Kalimantan, Indonesia

Stand age (year)	Stand density (trees ha <sup>-1</sup> )	Diameter of trees (DBH) (cm)	Biomass (Mg ha <sup>-1</sup> )				Total biomass (%)			
			BGB	AGB	Litter	Total biomass	RBGB	RWUG	RHU	
1	Mean	1580	5.6	11.3	16.8	1.6	29.7	38.1	5.0	14.3
	SD	121.7	1.2	2.7	1.9	0.3	4.6	2.7	4.4	7.9
	n	3	237	3	3	3	3	3	3	3
4	Mean	626.7	15.0	18.7	64.8	9.3	92.8	20.1	13.4	1.0
	SD	30.6	3.4	4.4	1.5	1.8	7.05	3.2	1.2	0.2
	n	3	94	3	3	3	3	3	3	3
9	Mean	713.3	20.7	36.3	139.2	5.9	181.4	20.0	0.4	0.1
	SD	83.3	5.7	4.9	18.5	0.8	23.3	1	0.1	0.03
	n	3	107	3	3	3	3	3	3	3

*SD* = standard deviation, *DBH* = diameter at breast height, *BGB* = belowground biomass, *AGB* = aboveground biomass, *RBGB* = relative belowground biomass to total biomass, *RWUG* = relative woody undergrowth biomass to total biomass, *RHU* = relative herbaceous undergrowth to total biomass.

There was an increase in stand diameter variation in line with age of the plantation. Since it is assumed that the stand is genetically homogeneous, this may reflect the increase in the effect of the environmental factors such as differences in micro relief, access to soil nutrients and water, as well as symbiosis with certain *Rhizobium* strains (Martin-Laurent *et al.* 1999; Galiana *et al.* 1995; 1998).

Total biomass accumulation increased from only 25.4 Mg ha<sup>-1</sup> in the first year of the plantation to 181.2 Mg ha<sup>-1</sup> in the ninth year. It is obvious that the biomass of the *A. mangium* stands already surpassed that of *I. cylindrica* of 21.9 Mg ha<sup>-1</sup> in the very early stage of the plantation. This implies that establishment of *A. mangium* plantations

is a promising tool if the biomass is the concern, especially in marginal and degraded lands (Otsamo, 2002, Otsamo *et al.* 1997).

Aboveground biomass of the 4-year-old stands (52.6 Mg ha<sup>-1</sup>) (Table 4.2) in this study was in the range of that of 5- to 7-year-old *Eucalyptus deglupta* stands (45.7-81.2 Mg ha<sup>-1</sup>) (Syahrudin 1997; Ruhayat 1989). Compared to the biomass of 4-year-old *Gmelina arborea* stands (3.7 – 10.9 Mg ha<sup>-1</sup>) studied by Swamy *et al.* (2003), this value is higher. However, the contribution of belowground biomass of 17.5-40.2% (Swamy *et al.* 2003) is in agreement with the results of the present study of 20.0-38.1%. It is important to notice that the accumulation rate of belowground biomass was quite high in the first years (almost similar to that of aboveground biomass) and declined with plantation age.

Table 4.2: Biomass distribution of *Acacia mangium* plantation system in East Kalimantan, Indonesia

Stand age (year)		Fine root	Coarse root	Stem	Branch	Leaf	AGB	BGB	Total biomass
		(Mg ha <sup>-1</sup> )							
1	Mean	9.5	1.3	6.5	3.2	1.8	11.5	10.8	22.3
	SD	2.7	0.3	1.4	0.6	0.3	2.3	3.0	5.3
4	Mean	9.5	8.0	37.2	10.7	4.7	52.6	17.5	70.1
	SD	4.3	0.3	1.5	0.4	0.2	1.9	4.2	4.2
9	Mean	12.3	23.9	108.7	19.6	10.2	138.4	36.2	174.7
	SD	2.2	3.5	15.5	1.9	1.2	18.5	4.9	23.1

*SD* = standard deviation, *GB* = belowground biomass, *AGB* = aboveground biomass; three replications of each stand age; fine roots were defined to depth of 3 m.

Information on the biomass of young plantations (less than 3 years old) is scarce. Compared to the aboveground biomass of 1-year-old *Eucalyptus deglupta* plantations of 3.1 Mg ha<sup>-1</sup> (Syahrudin 1997), the results in this study are much higher. Aboveground biomass of *A. mangium* plantations ranges widely depending on factors such as planting space (tree density), site quality, silvicultural practices and plant material characteristics. However, in general, the magnitude of aboveground biomass in this study is still in range of that reported in previous studies (Table 4.3).

Biomass of all compartments of the stands increased with stand age. There is, however, no significant difference in fine root biomass across plantation age. Belowground biomass of the 4- and 9-year-old stands is in the range of that of

Amazonian primary forest and secondary vegetation (22.0 – 34.0 ton ha<sup>-1</sup> 6 m<sup>-1</sup>) (Sommer *et al.* 2000).

Table 4.3: Stand density and aboveground biomass of *Acacia mangium* plantations of different ages and sites

Stand age (year)	Stand density (trees ha <sup>-1</sup> )	Aboveground biomass (Mg ha <sup>-1</sup> )	Site	Reference
1	1580	11.5	East Kalimantan, Indonesia	This work
3.5	1089	54.4	Sarawak, Malaysia	Lim and Hamzah 1985
3.5	625	64.1	Malaysia	Lim 1985
4	626.7	52.6	East Kalimantan, Indonesia	This work
4	2500	48.0	Thailand	Yantasath 1992
4	10000	128.0	Thailand	Yantasath 1992
4	1566	90.4	Malaysia	Lim 1988
4.5	1089	86.9	Sarawak, Malaysia	Lim 1986
5	600	58.9	East Kalimantan, Indonesia	Ruhiyat 1989
6	696	67.5	East Kalimantan, Indonesia	Ruhiyat 1989
6	1289	122.4	Sonbe, Vietnam	Hiratsuka <i>et al.</i> 2003
6	822	132.6	Benakat, Indonesia	Hiratsuka <i>et al.</i> 2003
6	1369	157.5	Benakat, Indonesia	Hiratsuka <i>et al.</i> 2003
6	787	133.2	Benakat, Indonesia	Hiratsuka <i>et al.</i> 2003
6	877	172.8	Benakat, Indonesia	Hiratsuka <i>et al.</i> 2003
6	903	143.5	Benakat, Indonesia	Hiratsuka <i>et al.</i> 2003
6.8	730	123.2	Malaysia	Halenda 1989
7	708	96.6	East Kalimantan, Indonesia	Ruhiyat 1989
7	506	99.7	Madang, PNG	Hiratsuka, <i>et al.</i> 2003
9	713.3	138.4	East Kalimantan, Indonesia	This work
9	1382	189.5	South Sumatra, Indonesia	Hardiyanto, <i>et al.</i> 1999

Information on the undergrowth biomass of forest plantations is very scarce, and reports on the importance and contribution of undergrowth in tropical forest plantations are even rarer. Biomass distribution of litter standing stock and undergrowth is presented in Table 4.4. Total biomass of woody undergrowth of the 4-year-old stands was notably higher than that of the 1- and 9-year-old stands. In the first year of the plantation, there was intensive undergrowth management controlling the development of the undergrowth. This management was less intensive in the second year and only occasional during the consecutive years, since the canopy closure became well developed (Syahrudin 1997). Nevertheless, tree mortality in the 4-year-old stand was rather high (this is a common case for plantations established in degraded lands, e.g., *I. cylindrica* grassland, if there is no intensive management) (Soerianegara 1980; Otsamo *et al.* 1997). A stand density of 626 trees ha<sup>-1</sup> allowed vigorous development of woody undergrowth.

Table 4.4: Biomass of undergrowth (above- and belowground) and litter standing stock in *Acacia mangium* stands of different ages in East Kalimantan, Indonesia

Stand age (year)		Belowground biomass	Aboveground biomass			Litter standing stock
			WU	HU (Mg ha <sup>-1</sup> )	Total	
1	Mean	0.45	1.04	4.25	5.29	1.64
	SD	0.39	0.58	1.51	1.73	0.63
	n	6	6	9	6	9
4	Mean	1.15	11.31	0.91	12.22	9.27
	SD	0.40	3.62	0.38	1.24	3.71
	n	6	6	9	6	9
9	Mean	0.11	0.60	0.17	0.78	5.96
	SD	0.04	0.19	0.13	0.17	1.58
	n	3	3	9	3	8

*SD* = standard deviation, *WU* = woody undergrowth, *HU* = herbaceous undergrowth.

In line with the undergrowth biomass, the litter standing stock of the 4-year-old stands was highest. This may relate not only to the dense undergrowth, but also to the growth physiology of the stand, i.e., litter production is normally highest in the early fast growing period of the stand and then declines as the stand gets close to maturity (Lugo et al., 2004). A 9-year-old stand is possibly very close to the mature state for the *A. mangium* stands. The litter standing stock in this study is, however, in agreement with that of former studies (7.0-19.6 Mg ha<sup>-1</sup>) (Syahrudin 1997; Ruhiyat 1989).

#### 4.3.2 Root distribution

Roots are important for anchorage, water and nutrient uptake, storage of carbohydrates and synthesis of growth regulators. Fine roots represent a small portion of the total biomass of the ecosystem (De Agelis *et al.* 1981), typically less than 5 % (Jackson *et al.* 1997; Vogt *et al.* 1996), but play a significant role in determining the functioning of the system. A significant part of the net primary production of both native and managed ecosystems is in some cases allocated to the fine root production (Harris *et al.* 1977; Buyanovsky *et al.* 1987). A magnitude of 30% to 50% of the C cycled annually in forest ecosystems is probably allocated to fine root production (Grier *et al.* 1981; Vogt *et al.* 1996). Of the global primary production, roots consume about 30% (Jackson *et al.* 1997).

Fine root biomass of the *A. mangium* plantation system ranged from 9.5 Mg ha<sup>-1</sup> 3 m<sup>-1</sup> (in the first and fourth year) to 12.3 Mg ha<sup>-1</sup> 3 m<sup>-1</sup> (in the ninth year). This is

quite comparable to the root biomass of *I. cylindrica* of 12.4 Mg ha<sup>-1</sup> 3 m<sup>-1</sup>. However, the vertical distribution of the root biomass of *I. cylindrica* grassland was restricted to the topsoil (Figure 4.2). The results of this study are in agreement with those of previous works (Curt and Prévosto 2003; Makkonen and Helmisaari 1999; Hendricks and Bianchi 1995; Vogt *et al.* 1996). Curt *et al.* (2001) reported estimates of fine root biomass of Douglas fir in the upper 30 cm soil of 17.3-28.4 Mg ha<sup>-1</sup>. These values are clearly higher than those in this study, which are, however, quite comparable to those reported by Santantonio *et al.* (1977) studying fine root biomass (<5 mm) in the upper soil in Douglas-fir forests of Oregon ranging from 8.5 to 10.1 Mg ha<sup>-1</sup>. The values in this study are also in agreement with those for plantations in Michigan and Oregon reported by Fogel (1983) (about 8.0 to 24.1 Mg ha<sup>-1</sup>).

Generally, fine root biomass contributes only a small portion of the total biomass of the system, typically less than 5% (Jackson *et al.* 1997; Vogt *et al.* 1996). The results in this study are, nevertheless considerably higher, especially for the younger stands (1- and 4-year-old stands) with averages of 37.35, 10.33 and 6.81% for the 1-, 4- and 9-year old stands, respectively. It seems that the fine root system of the plantation developed early from the beginning of the plantation to a required level, thereafter being maintained in a narrow dynamic range.

In line with the results of previous works (Swamy *et al.* 2003; Tufekcioglu *et al.* 2003; Curt *et al.* 2001; Dhyani and Tripathi 2000; Sommer *et al.* 2000), the fine roots of the *A. mangium* plantation systems were concentrated in the top centimeters of the soil profile. In the 3 m-deep soil profile, more than 50% of the fine root biomass was found in the top 30 cm. However, compared to *I. cylindrica* grassland, the fine roots of *A. mangium* penetrated much deeper to a depth of 3 m. This is much deeper than the 1.8 m in *I. cylindrica* grassland. Moreover, 90% of the root biomass of *I. cylindrica* grassland confined to a depth of 41 cm was clearly much shallower than for *A. mangium* plantation systems, where values were of 157 cm, 167 cm and 170 cm for the 1-, 4- and 9-year-old stands, respectively.

Fine root biomass showed a continuous decrease with soil depth, thus being in accordance with many previous studies (Curt and Prévosto 2003; Curt *et al.* 2001; Tufekcioglu *et al.* 1999; Nie *et al.* 1997), which indicate that this root profile usually corresponds to a vertical decrease in nutrients, porosity, and water storage capacity in

the soil profiles (Sainju and Good 1993). Fine roots proliferate in the A-horizon of most soils due to the accumulation of organic matter, higher CEC and organic C, N, P and K concentration (Bowen 1984; Kalisz *et al.* 1987; Pritchett and Fisher 1987; Sainju and Good 1993). A rapid vertical decrease in fine root density was observed in a highly acidic soil under spruce stands (Jentschke *et al.* 2001).

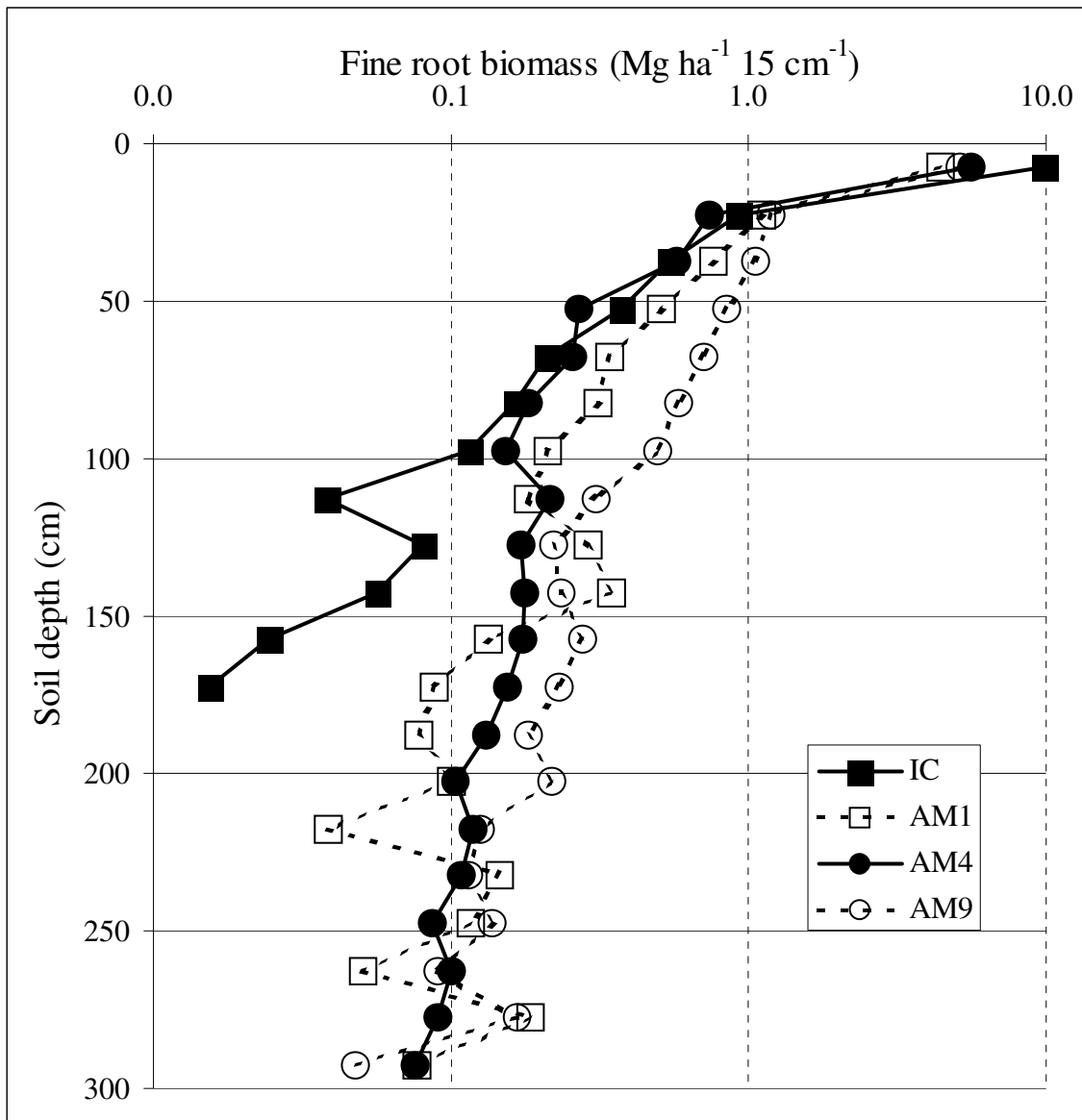


Figure 4.2: Vertical distribution of fine root biomass of the *Acacia mangium* plantation system (AM) and *Imperata cylindrica* grassland (IC) in East Kalimantan, Indonesia (1, 4 and 9 = 1-, 4- and 9-year-old stand)

The vertical distribution of fine roots indicates the rooting strategy of trees and is species specific and genetically inherited (Curt and Prévosto 2003; Polomski and



Kuhn 1998; Brown 1992). There are very few reports on the root distribution in *A. mangium* plantation systems. However, the results of this study show that the distribution of the fine root biomass of the plantations was similar regardless of age. This high fine root biomass accumulation in the top few centimeters of the soil is typical for many pioneer trees (Polomski and Kuhn 1998; Perala and Alm 1990; Grime 1979). This shallow concentrated rooting strategy may allow an efficient use of the topsoil resources (Crabtree and Berntson 1994).

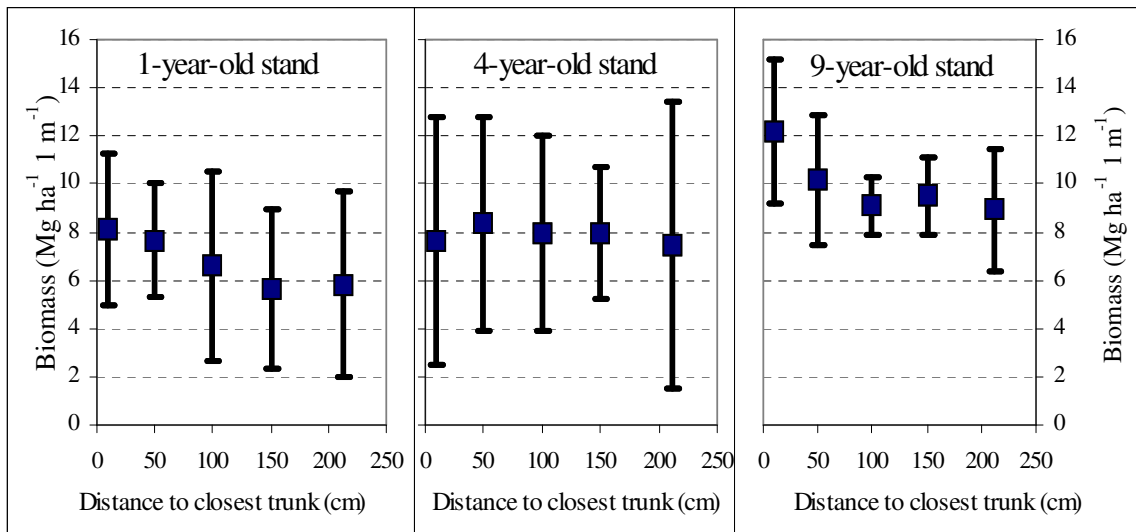


Figure 4.3: Horizontal distribution of fine root biomass of *Acacia mangium* plantation system in East Kalimantan, Indonesia; rectangles are means and stake bars are standard deviations

The lateral extent of woody roots may exhibit a high degree of plasticity and depend on environmental conditions (Millikin and Bledsoe 1999; Belsky 1994). In line with previous findings (Purbopuspito and Van Rees 2002; Jose *et al.* 2001; Peter and Lehmann 2000; Jones *et al.* 1998), although not significant, there was a slight decrease in the horizontal distribution of the fine root biomass with distance to the tree base in 1- and 9-year-old stands (Figure 4.3). Such a decrease could not be observed in the 4-year-old stand. This may relate to the dense undergrowth occupying the sites of this stand. However, Millikin and Bledsoe (1999) reported that distance from tree did not significantly affect fine root biomass of blue oak.

Root distribution is highly variable and is constrained by the microsite spatial variability created by the soil environment or by the different plant species existing on each site (Roy and Singh 1995; Vogt *et al.* 1995). The present results show that the

distribution of the fine root biomass in the *A. mangium* plantations was highly heterogeneous, with coefficients of variation ranging from 41.3-216.2% and 5.6-153.7% for within and among sites, respectively. The variability within sites was much higher than that among sites, on average by a factor of 2 (coefficient of variation of  $108.0 \pm 21.0\%$  and  $57.1 \pm 22.3\%$  for within and among sites, respectively). A considerable variability of Douglas-fir root biomass within microsite has also been observed (Curt *et al.* 2001). This high variability of fine root biomass within sites may reflect a high micro-spatial variability of the soil resources of the system. It could, therefore, be of interest to determine to what extent soil and microsite patches can modify fine root biomass, architecture, and seasonal turnover, thus conditioning the exploitation of soil resources (Drexhage and Gruber 1998; Fitter 1994; Pritchett and Fisher 1987).

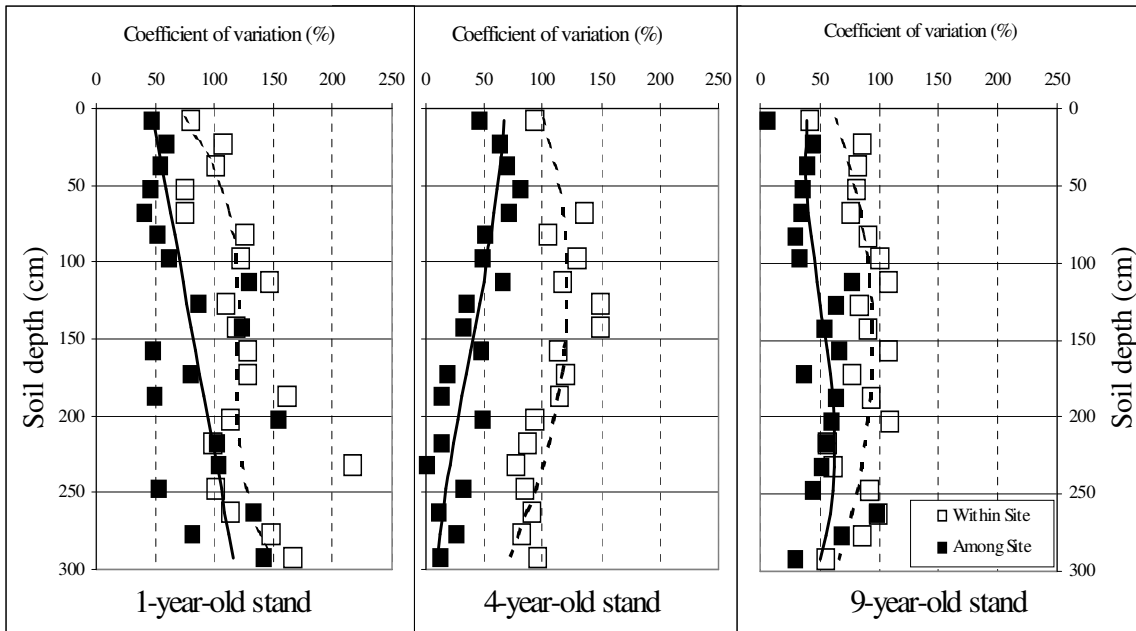


Figure 4.4: Variability of vertical fine root biomass distribution within and among sites of *Acacia mangium* plantation systems in East Kalimantan, Indonesia

Details on the variability of the vertical fine root biomass distribution of the system are depicted in Figure 4.4. In general, the variability was considerably low in the first 15 cm of the soils, followed by an increase to a depth of 120-165 cm. Thereafter, variability decreased to the depth of 3 m. However, there were some exceptions to this general trend. The 1-year-old stands exhibited a persistent increase in the variability of vertical fine root biomass distribution to a depth of 3 m. It is the question whether this

increase is the result of the insufficient sample size or whether it illustrates the real variability of the distribution.

In the first 1 m depth of the soil, the same sample size was applied in determining the fine root biomass distribution in all stand ages (153 root auger points). However, for the second and third 1-m depth, a more intensive sampling was undertaken for the 4-year-old stand, i.e., a sample size of 65 and 45 root auger points, respectively. The sample size for the respective depth of the 1- and 9-year-old stands was only 20 and 15. Based on the variability of the fine root biomass of the defined soil profile (to depth of 3 m) and the sample size, it was observed that the variability of the fine root biomass was not significantly affected by the sample size. Compared to the deeper part of the soil profile (second and third 1-m depth) where a 15-65 sample size was used, employing a 153 sample size in the first 1-m depth did not significantly reduce the variability. It is also evident that increasing the sample size from 15 to 45 auger points and from 20 to 65 auger points for the third and second 1-m depth, respectively, did not result in a significant reduction in the variability. This implies that employing the core sampling method does not give a precise result in the assessment of the fine root parameters of a system, especially if a small sample size is applied.

The variability of the fine root biomass was, to some extent, defined by the soil bulk density of the sites (Figure 4.5). Generally, there was a positive non-linear correlation between soil bulk density and coefficient of variation of fine root biomass. It was observed that the correlation between soil bulk density and coefficient of variation of fine root biomass followed the Modified Exponential model ( $y = ae^{b/x}$ ,  $r = 0.75$ ,  $p < 0.001$ ,  $a = 1086.26$ ,  $b = -3.45$ ). This is in line with the finding of Curt *et al.* (2001) reporting that the soil physical characteristics may alter the root system of Douglas fir. Nevertheless, it is interesting that the coefficients of variation of fine root biomass of the 9-year-old *A. mangium* stand were distributed below the expectation line of the equation. This may reflect that the older plantations have a somewhat better ability to manipulate the detrimental environment, thus allowing an optimal exploitation of the soil resources.

Compared to that of *I. cylindrica* grassland (coefficient of variation ranged from 34.65 to 94.85%) in the vicinity of the plantation systems, the variability of the fine root biomass of *A. mangium* was higher. However, the vertical trend of the

variability of the root biomass distribution in the *I. cylindrica* grassland system was rather similar to that of 1-year-old *A. mangium* plantations. On the one hand, this high variability may be beneficial, if it reflects the ability of the system to adapt to the unfavorable environment so that the optimal utilization of resources may still be maintained. On the other hand, it may be disadvantageous, if this variability has resulted from the disability of the system to manipulate its environment.

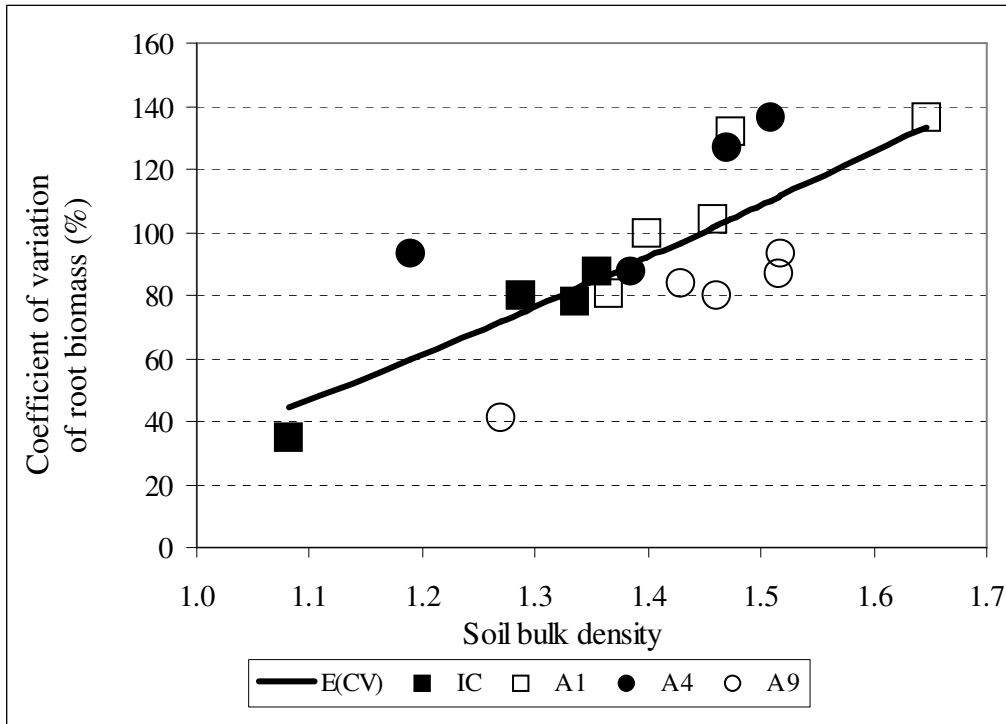


Figure 4.5: Relationship between soil bulk density and variability of fine root biomass of *Acacia mangium* plantation system (A) and *Imperata cylindrica* grassland (IC) in East Kalimantan, Indonesia; 1, 4 and 9 = 1-, 4- and 9-year old stands; E(CV) = expected coefficient of variation of the systems

### 4.3.3 Biomass carbon distribution

Carbon content of the stand biomass varied from 27.9% to 45.6% (Table 4.5) depending on the tree compartment. These figures are slightly lower than the assumption of 50% proposed by Brown and Lugo (1984) and Hamburg (2000). Compared to the root biomass of secondary and primary forests (43.9-46.6%) (Sommer *et al.* 2000), C content of the root biomass in this study (excluding those of fine root biomass) was quite comparable. Among those compartments, C content variability of fine root and

leaf biomass was the highest, ranging from 27.9-34.2% and 39.1-43.9% (coefficient variation of 10.9 and 7.7%) for the fine root and leaf biomass, respectively. The variability of the C content in other compartments was considerably low (coefficient variation ranging from 0.7 to 2.8%).

Excluding the C content of the fine root biomass, the C content among tree compartments was not significantly different. This implies that sampling of tree compartments is only important in determining the dry matter of each compartment of the stand, and sampling in different compartments to determine their C content is not necessary.

Contrary to expectation, there was no significant difference in C content of the tree compartments across plantation age. This also implies that sampling for different stand ages to determine their C content is unnecessary.

Table 4.5: Carbon content of tree compartments of different ages of *Acacia mangium* stands in East Kalimantan, Indonesia

Stand age (year)	Root		Stem (%)	Branch	Leaf
	Fine	Coarse			
1	29.7	43.8	44.6	45.6	39.1
4	34.2	43.6	45.1	44.3	43.9
9	27.9	44.9	45.1	43.8	42.9
<b>Mean</b>	<b>30.6a</b>	<b>44.0b</b>	<b>44.9b</b>	<b>44.5b</b>	<b>42.4b</b>
SD	3.3	0.9	0.3	1.3	3.3
n	9	7	6	7	8

*SD = standard deviation, mean values followed by the same letters are not significantly different at  $\alpha = 0.05$ .*

The C content of undergrowth biomass in the studied stands ranged from 37.3 to 41.6% (Table 4.6). Average C content of the woody undergrowth biomass was 40.9, 40.7, 39.3, and 38.9 for the root, stem, branch, leaves compartment of the woody undergrowth, respectively and 38.8% for the herbaceous undergrowth. Nevertheless, there were no significant differences in C content among the compartments. The variability of C content within compartments was considerably low (coefficient of variation of 2.1, 2.9, 5.4, 3.3, and 4.6% for the root, stem, branch, leaves compartment of the woody undergrowth and herbaceous undergrowth, respectively).

Table 4.6: Carbon content of undergrowth and litter standing stock under different ages of *Acacia mangium* stands in East Kalimantan, Indonesia

Stand age (year)	Woody undergrowth				Herbaceous undergrowth	Litter standing stock
	Roots	Stems	Branches	Leaves		
1	38.0	41.6	nd	38.8	40.8	35.4
4	41.5	41.2	39.3	38.4	37.3	34.4
9	40.5	39.5	nd	39.5	38.3	37.8
<b>Mean</b>	<b>40.9a</b>	<b>40.7a</b>	<b>39.3a</b>	<b>38.9a</b>	<b>38.8a</b>	<b>35.8b</b>
SD	0.9	1.2	-	1.3	1.8	4.9
n	6	6	2	6	6	6

SD = standard deviation, nd = not determined; mean values followed by the same letters are not significantly different at  $\alpha = 0.05$ .

Compared to that of trees and undergrowth, the C content of litter standing stock biomass was, however, slightly lower (average of 35.8%), but the variability was higher (coefficient variation of 13.6%). This implies that a larger number of samples is required for a better assessment of the C content of the litter standing stock.

Table 4.7: Total C distribution of different ages of *Acacia mangium* plantation system in East Kalimantan, Indonesia

Stand age (year)		BGB	AGB	Litter	Total	RBGB	RWUG	RHU
		(Mg ha <sup>-1</sup> )				(%)		
1	Mean	3.6	7.2	0.6	11.4	31.5	5.3	15.2
	SD	0.8	0.9	0.1	1.7	7.3	2.9	4.7
4	Mean	7.2	28.5	3.2	38.9	18.6	13.1	0.9
	SD	1.5	0.7	0.6	2.5	3.8	1.3	0.2
9	Mean	14.2	62.1	2.2	78.6	18.1	0.4	0.1
	SD	1.9	8.3	0.3	10.3	0.7	0.1	0.02

SD = standard deviation, BGB = belowground biomass C, AGB = aboveground biomass C, RBGB = relative belowground biomass C to total, RWUG = relative woody undergrowth biomass C to total C of the system, RHU = relative herbaceous undergrowth to total biomass C to total C of the system.

Total biomass C distribution of the *A. mangium* plantation system is presented in Table 4.7. Both below- and aboveground biomass C increased persistently in line with age of the plantation. It was 3.6 and 5.5 Mg ha<sup>-1</sup> in the 1-year-old plantation and 14.2 and 62.1 Mg ha<sup>-1</sup> in the 9-year-old plantation, respectively.

Total C stored in the plantation system increased from 9.6 Mg ha<sup>-1</sup> in the 1-year-old plantation to 78.6 Mg ha<sup>-1</sup> in the 9-year-old plantation. Compared to *I. cylindrica* grassland, where values were 7.5, 4.0, 3.6 Mg ha<sup>-1</sup> for the total, below- and aboveground biomass C, respectively, it is clear that the total biomass C accumulated in

the plantation system has surpassed that of *I. cylindrica* grassland early in the beginning of the plantation. However, the curve of the annual rate of C sequestered by the system is quite flat across plantation age (Figure 4.6). This implies that when C sequestration is the concern, plantation management for more than 9 years (harvesting expectation for pulp production) seems to be beneficial. Furthermore, if the C of the stems as the harvested component is the concern, harvesting of a 9-year-old *A. mangium* stand is considered too early, because it would not have reached the peak of its economic cycle.

The average annual C sequestration in the biomass of the system of  $9.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  was remarkably higher than that of riparian planted poplars of  $2.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  (Tufekcioglu *et al.* 2003).

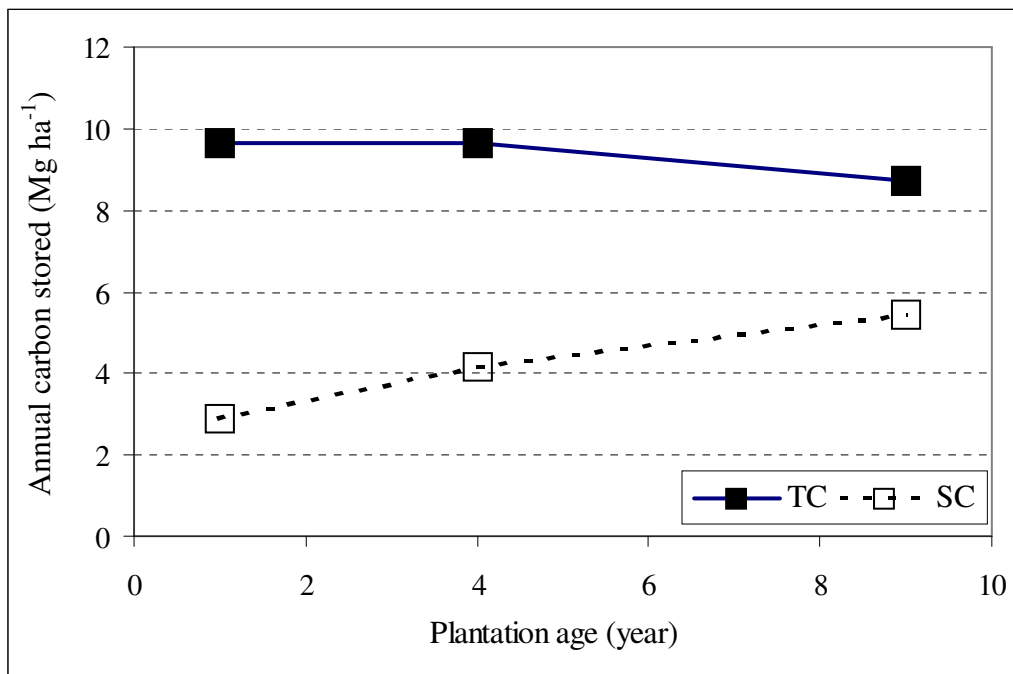


Figure 4.6: Annual carbon storage in biomass of *Acacia mangium* plantation system in East Kalimantan, Indonesia; TC = total biomass carbon, SC = stem biomass carbon

With regard to the practical implication of the measurement of biomass C of *A. mangium* in forestry-based C offset projects, a simple and reliable method should be established. The results in this study show that estimation of the biomass of *A. mangium* stands from tree diameters is sufficiently accurate and reliable. Both aboveground and belowground biomass C of the stand could be well estimated with this method (Table 4.8). However, there is no parameter for simplifying the measurement of the biomass C

of undergrowth, litter standing stock and fine roots of the plantation. There is a wide range of biomass values of undergrowth and litter standing stock in *A. mangium* plantations, and they should, therefore, be measured directly in each specific stand. Among of the biomass compartments, measurement of fine root biomass is the most time consuming and labor intensive. The results show that there was a small variation of fine root biomass and biomass C among plantation ages, but the variation within sites was considerably high (see Figure 4.5). This implies that estimation of fine root biomass and biomass C with a small sampling size is subject to high errors. Applying a sample size of 153 auger points resulted in coefficients of variation of  $108.0 \pm 21.0\%$  and  $57.1 \pm 22.3\%$  for within and among sites, respectively. However, fine root biomass C ranged from 2.8 to 3.4 Mg ha<sup>-1</sup>, producing less than 5% of the total biomass C of the mature plantation system. Therefore, estimations of fine root biomass C of *A. mangium* plantation systems with a factor of 4% of the total biomass C of the system for the mature plantations or adopting a magnitude of 3.0 Mg ha<sup>-1</sup> for the young plantations would be sufficient and is recommended.

Table 4.8: Allometric equations for biomass C (Mg ha<sup>-1</sup>) estimation of *Acacia mangium* plantations in East Kalimantan, Indonesia, based on tree diameter (DBH, cm)

Dependent Variable	a	b	r <sup>2</sup>	p
Coarse and medium roots C	0.0051	2.6198	0.9669	< 0.001
Stem C	0.0599	2.2971	0.9111	< 0.001
Branch C	0.0752	1.6512	0.9428	< 0.001
Leaf C	0.0265	1.8208	0.8941	< 0.001
Aboveground biomass C	0.1188	2.1546	0.9258	< 0.001
Total biomass C	0.1143	2.2219	0.9441	< 0.001

Regression model:  $Y = a * DBH^b$

There is little information on the total biomass and C storage of plantations in the tropics. Most publications deal with aboveground biomass of stands (excluding biomass of undergrowth and litter standing stock, an exception to studies of Syahrinudin 1997 and Ruhiyat 1989) and information on belowground biomass and C stock is very scarce. Based on available data on aboveground biomass of *A. mangium* plantations presented in Table 4.3 and the assumption of a C content of 43.3% (overall average of C



content of *A. mangium* plantations in this study), a general rate of C accumulated in this plantation system was constructed (Figure 4.7).

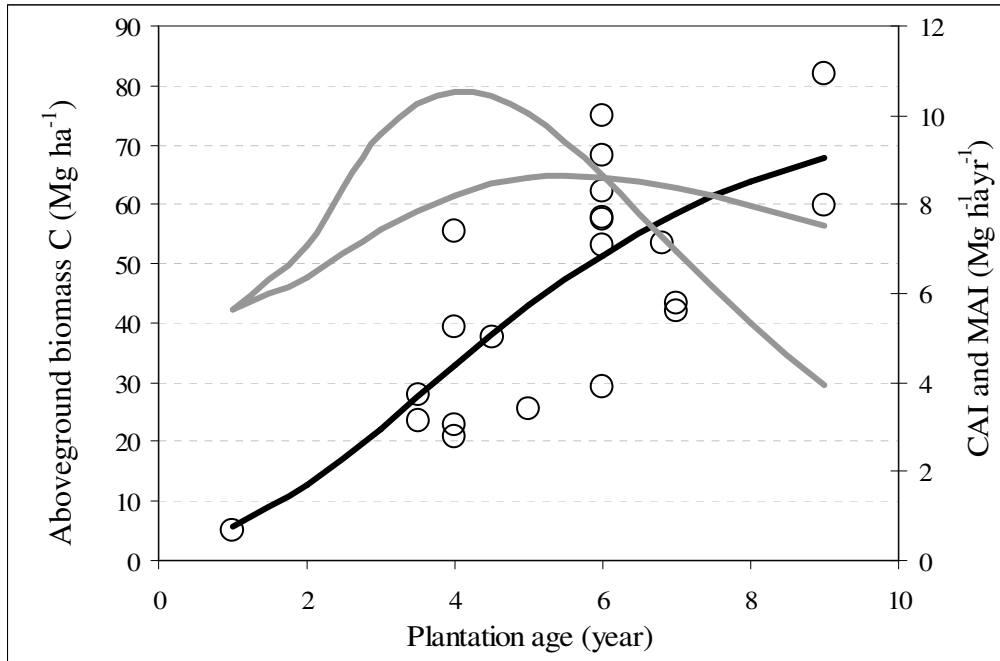


Figure 4.7: General rate of carbon sink in *Acacia mangium* plantation system; references see Table 4.3

Figure 4.7 shows that general accumulation of C in aboveground biomass of *A. mangium* stands follows the Gompertz Relation ( $Y = a \cdot \exp(-\exp(b-cx))$ ),  $a = 75.18$ ,  $b = 1.38$ ,  $c = 0.39$ ,  $r^2 = 0.58$  and  $p < 0.001$ ). Calculation of the general rate of C sink in the aboveground biomass of the stands gave an average of  $8.0 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ , which is slightly higher than the calculation based on the data in the present study of  $6.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ . These figures are, however, lower than the estimation by ISME (1999) of  $12.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ . Compared to the total biomass C sink in this study of  $9.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ , aboveground biomass C of the stand produced 70% of the total C accumulated in the system. Applying this value, the general rate of total C sink of *A. mangium* plantation system of  $11.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  was calculated. With regard to timber production, if there is no requirement for a minimum tree dimension and the price for the timber is flat across tree dimension and age, the best cutting cycle would be at the age of 6 years (Figure 4.8), because at this point of time, the CAI (Current Annual Increment) crosses the MAI

(Mean Annual Increment) indicating the highest stand growth rate and revenue for the plantation.

In contrast to the persistent increase of the belowground biomass, the relative contribution of belowground biomass C to total biomass C decreased in the older stages of the plantation. However, the contribution of belowground biomass C of the 4-year-old stands was quite comparable to that of the 9-year-old stands. This suggests that the contribution of the belowground biomass C in the older stands is fairly stable (average  $18.4\% \pm 2.7\%$ ). As sampling of the belowground biomass C is time and labor consuming, this figure could be adopted for estimation of the belowground biomass C of similar plantation systems elsewhere.

The ratio of belowground to aboveground biomass (root/shoot ratio) of forest systems is strongly influenced by stand age and site characteristics (Cairns *et al.* 1997). However, the results show that the range of this ratio is relatively narrow for the older plantations (4- and 9-year-old stands) (0.23-0.27). These values are in the range of those of temperate forests of 0.15-0.40 reported by (Cairns *et al.* 1997).

In general, relative contribution of both woody and herbaceous undergrowth biomass C decreased with plantation age. The contribution of woody and herbaceous undergrowth biomass C dropped from 6.7 and 18.9% in the first year to 0.36 and 0.08% in the ninth year, respectively. This drop relates to the canopy development of the stand, since well established *A. mangium* stands have a dense canopy, and there is little available light for the development of undergrowth. Nevertheless, due to the high mortality rate of the stands, contribution of woody undergrowth in the 4-year-old stands was remarkably high (13.2%).

The distribution of total biomass C in *A. mangium* stands is presented in Table 4.9. Excluding that of the fine root compartment, total biomass C of all compartments of the stand increased in line with the plantation age. Of those compartments, the stem compartment stored the largest amount of biomass C, followed by the branch, coarse root and leaf compartments. However, the biomass C in the coarse root compartment in the 9-year-old stand was higher than that in the branch compartment. It is interesting to note that the ratio between the biomass C of the coarse root and stem compartment seemed to be maintained in the specific narrow range. It was 20.5%, 20.9% and 21.9%

for the 1-, 4-, and 9-year-old stands, respectively. This strongly implies that estimates of coarse root biomass C from that of the stem compartment are quite credible.

Table 4.9: Total C distribution in *Acacia mangium* stands of different ages in East Kalimantan, Indonesia

Stand age (year)		Fine root	Coarse root	Stem	Branch	Leaf	AGB	BGB	Total
1	Mean	2.8	0.6	2.9	1.5	0.7	5.0	3.4	8.5
	SD	0.8	0.1	0.6	0.3	0.1	1.0	0.9	1.9
4	Mean	3.2	3.5	16.8	4.7	2.1	23.6	6.7	30.3
	SD	1.5	0.1	0.7	0.2	0.1	0.9	1.4	1.5
9	Mean	3.4	10.7	49.0	8.6	4.4	61.9	14.2	76.1
	SD	0.6	1.6	7.0	0.8	0.5	8.3	1.9	10.1

*SD* = standard deviation, *BGB* = belowground biomass C, *AGB* = aboveground biomass C; three replications of each stand age; fine roots were defined to depth of 3 m.

Total fine root biomass C of the *A. mangium* plantation system ranged from 2.8 Mg ha<sup>-1</sup> in the first year to 3.4 Mg ha<sup>-1</sup> in the ninth year. However, there was no significant difference in fine root biomass C among the plantation ages. The overall average of total fine root biomass C was 3.2±0.9 Mg ha<sup>-1</sup>.

Table 4.10: Total C distribution of litter standing stock and undergrowth in *Acacia mangium* stands in East Kalimantan, Indonesia

Stand age (year)		Belowground biomass C	Aboveground biomass C			Litter standing stock C
			WU	HU	Total	
(Mg ha <sup>-1</sup> )						
1	Mean	0.17	0.43	1.73	2.16	0.58
	SD	0.13	0.20	0.53	0.73	0.12
	n	6	6	9	3	9
4	Mean	0.47	4.61	0.34	4.95	3.19
	SD	0.10	0.57	0.05	0.61	0.62
	n	6	6	9	3	9
9	Mean	0.04	0.24	0.07	0.30	2.21
	SD	0.01	0.08	0.03	0.10	0.30
	n	6	6	9	3	9

*WU*= woody undergrowth, *HU* = herbaceous undergrowth

Although undergrowth biomass C played only a minor contribution to the total biomass C of the system, it may have an important role in litter production of the system, which in turn may benefit the enrichment of the soil C of the system. Since undergrowth grows fast and has a short life cycle, a considerable amount of litter may

have been contributed. This hypothesis is supported by the data (Table 4.10) showing that a large amount of litter standing stock C was found in the 4-year-old stand, which had a considerably high amount of undergrowth biomass C. However, litter production of a plantation system does not solely rely on the presence of undergrowth but to some extent also depends on the physiological characteristics of the stands.

#### **4.3.4 Soil carbon distribution**

The patterns of soil C distribution vary highly with soil age, soil texture, rainfall and temperature patterns, and vegetation type. The vertical distribution in both *I. cylindrica* grassland and *A. mangium* plantation systems was quite similar to that in previous studies reported by Syahrudin (1997) and Ruhayat (1989) in soils in the same region. Soil C content decreased in line with the soil depth (Figure 4.9) and was highly depth dependent ( $r^2$  ranged from 0.97 to 0.99). The slope of the decrease in the soil C content is steep in the upper 50 cm of the soils and more gentle in the deeper soils. Nevertheless, a distinct difference in the vertical soil C distribution can be observed between *I. cylindrica* grassland and *A. mangium* plantation systems. Compared to that of the *A. mangium* plantation system, the slope of the decrease in *I. cylindrica* grassland was less steep in the upper 50 cm but steeper for the lower part of the soil profile (see Figure 4.8). This demonstrates the strong influence of fine root biomass on soil C content. Although the vertical distribution of soil C is determined by soil depth, spatial variation seems to be dictated by the fine root biomass distribution ( $r^2$  of 0.83-0.99).

Soil C content is the result of litter (above- and belowground) production defined by vegetation type and development stage, and soil respiration controlled by root respiration and by decomposition of litter and soil organic matter. Soil physical properties such as texture and structure may control the respiration of the soils (De Jong and Schappert 1972). Soil temperature and moisture are the most important factors regulating soil respiration (Kicklighter *et al.* 1994; Lloyd and Taylor 1994; Howard and Howard 1993). However, the results in this study do not show a significant difference in soil C content in the upper part of the soil (top 50 cm), which is the layer affected most strongly in terms of soil temperature by the conversion of *I. cylindrica* grassland into *A. mangium* plantation. It seems that the influence of the plantation on soil temperature and moisture was offset by the effect of belowground litter production. In the upper 50

cm soil, the fine root biomass of *I. cylindrica* grassland ( $2.5 \text{ kg dm}^{-3}$ ) was much higher than that of *A. mangium* ( $1.4\text{-}1.6 \text{ Mg dm}^{-3}$ ). However, the roots of *I. cylindrica* grassland, which were confined to a shallow top layer of the soil (1.8 m) may explain the lower soil C content in the deeper soils in contrast to the fine roots of *A. mangium*, which extend to a depth of 3 m.

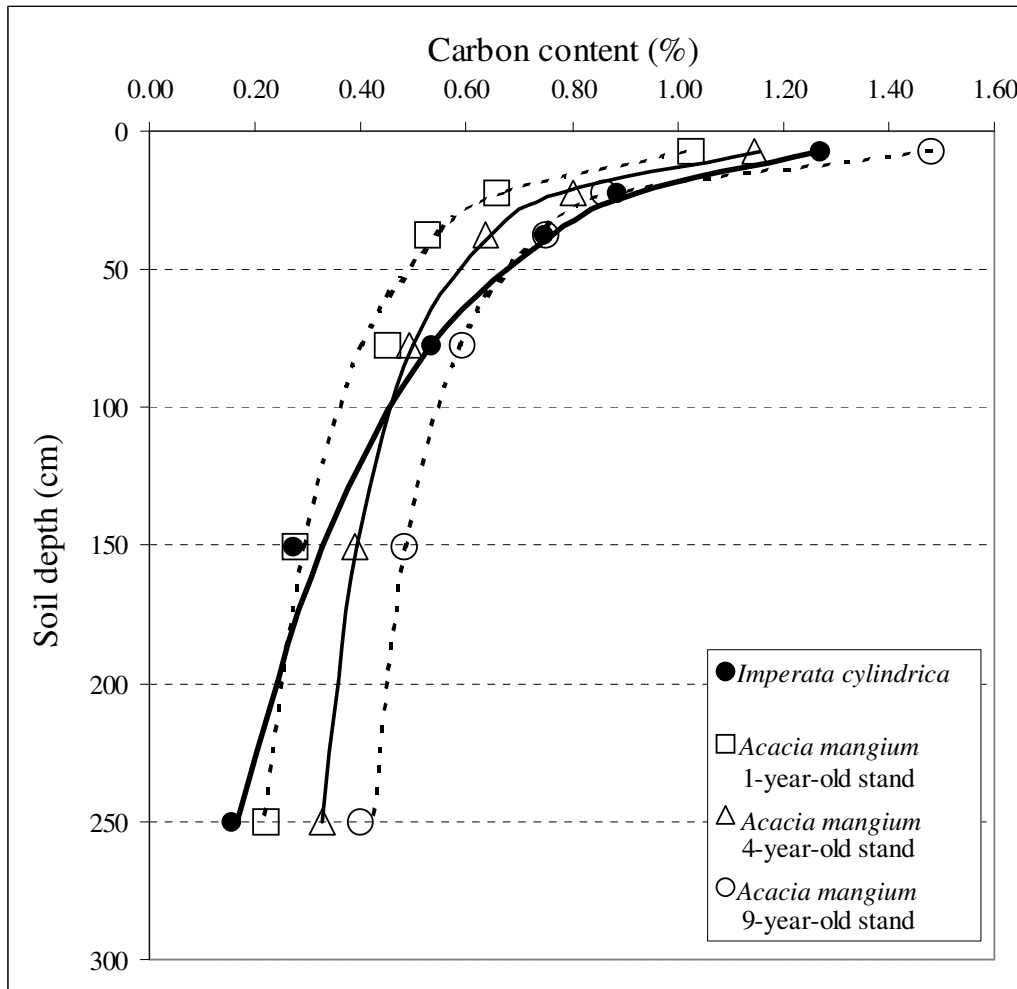


Figure 4.8: Vertical distribution of soil C content (%) in different ages of *Acacia mangium* stands in East Kalimantan, Indonesia

Soil C storage in this study is in the range of that reported in previous studies (Mackensen 1998; Syahrudin 1997; Bremen *et al.* 1990; Ruhayat 1989). Total C stored in the soils in *A. mangium* plantation systems ranged from  $158.6 - 246.2 \text{ Mg ha}^{-1} 3 \text{ m}^{-1}$  (Figure 4.9). These values are somewhat higher than the values of primary and secondary forests of  $130.0 - 145.0 \text{ Mg ha}^{-1} 3 \text{ m}^{-1}$  reported by Sommer *et al.* (2000). The C values in the soils in the *I. cylindrica* grassland ranged widely (from  $120.3 \text{ Mg ha}^{-1} 3$

m<sup>-1</sup> in Sumatra to 150.6 Mg ha<sup>-1</sup> 3 m<sup>-1</sup> in East Kalimantan). However, since the *A. mangium* plantations are located in East Kalimantan, the base line for all calculations of the soil C sink of the plantations is the soil C storage of *I. cylindrica* in East Kalimantan.

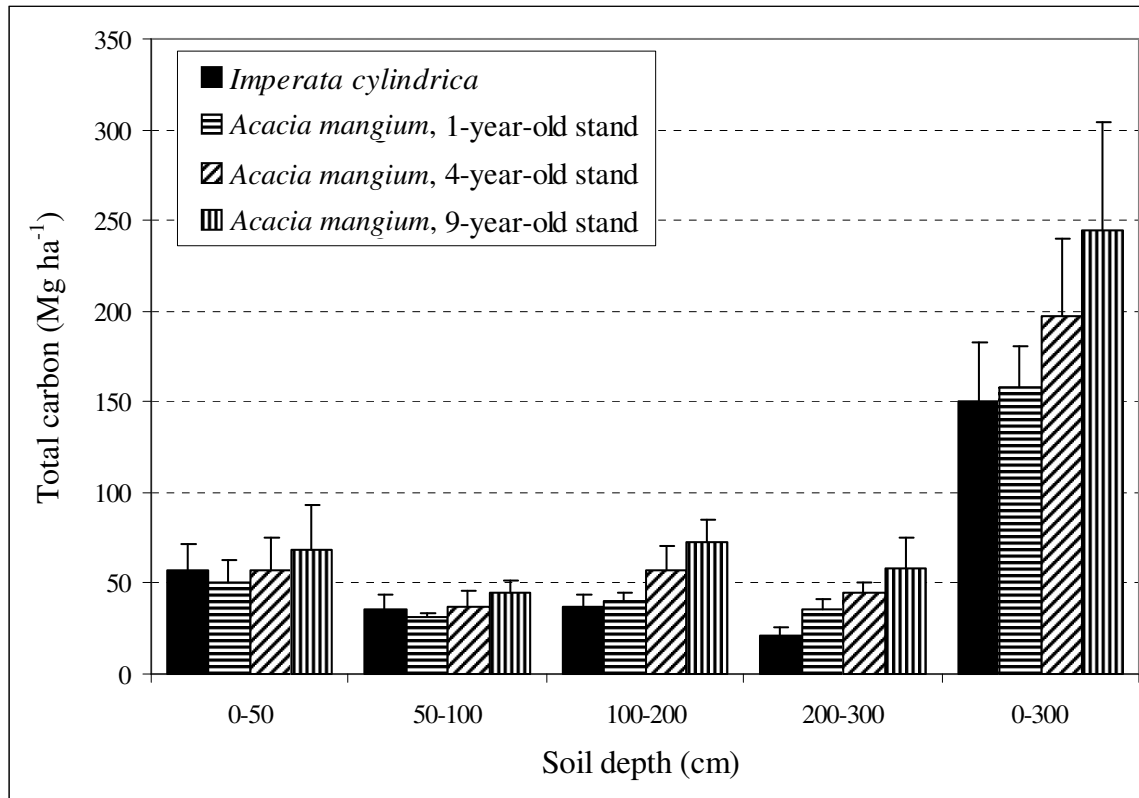


Figure 4.9: Soil C storage in *Imperata cylindrica* grassland and *Acacia mangium* plantation systems in East Kalimantan, Indonesia

Soil C storage is largely dependent on environmental, biogeochemical and land management factors. Different land use and management practices influence soil properties such as soil temperature, moisture, microbial biomass, organic matter and fine root biomass, which in turn affect the magnitude of soil respiration (Lee and Jose 2003; Raich and Tufekcioglu 2000; Kelting *et al.* 1998) and soil C dynamics. Trees can substantially increase the organic matter input into the system through the turnover of leaves and roots (Jose *et al.* 2000). The results in this study show that the conversion of *I. cylindrica* grassland into *A. mangium* plantation considerably increased the soil C storage. The rate of soil C accumulation was 1.7 – 3.0, 3.4 – 4.6 and 3.5 – 4.9 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the first, second and third 1-m-depth, respectively. There was a slight decrease

at a depth of 0-50 and 50-100 cm during the early stages of plantation establishment, which may be related to the lower litter production. However, the deeper soils experienced an increase in C storage from the beginning of the plantations (Figure 4.9). An increase in soil C accumulation (0-100 cm) from 0.66 to 1.17 Mg ha<sup>-1</sup> yr<sup>-1</sup> by incorporating legume trees in a grass pasture was reported by Tarré *et al.* (2001). Sataye *et al.* (2001) estimated an increase in soil C of 0.5 to 3.0 Mg ha<sup>-1</sup> yr<sup>-1</sup> in forest plantations in the tropics. A magnitude of soil organic matter sink of 1.1 Mg ha<sup>-1</sup> yr<sup>-1</sup> was reported by Lugo *et al.* (2004) in restored neotropical forest systems in Puerto Rico.

The most important finding of this study is that the conversion of *I. cylindrica* grassland into *A. mangium* plantation led to a much higher C sequestration in deep soils than in the upper soil layers. This finding is in contrast to the proposed soil C change measurement in forestry offset projects to a depth of only 1 m (Hamburg 2000). While most previous soil C studies concentrate on the upper soil layers down to a maximum depth of 2 m (Tufekcioglu *et al.* 2003; Tarré *et al.* 2001; Brown and Lugo 1990; Fisher *et al.* 1994; Moraes *et al.* 1995), the results of this study confirm the finding of Sommer *et al.* (2000), Trumbore *et al.* (1995) and Nepstad *et al.* (1994) showing the importance of root penetration in deep soil layers for C sequestration. Moreover, the C sequestered in deep soils could be more beneficial than that sequestered in shallow soils, because soil organic matter of deep soils is more resistant to decomposition and thus has a longer resident time (Gaudinski *et al.* 2000; Van Dam *et al.* 1997). The overall rate of soil C sequestration by this conversion was 8.6 – 12.7 Mg ha<sup>-1</sup> yr<sup>-1</sup>. These figures are indeed much higher than those reported in former studies. With a rate of biomass C accumulation of 9.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>, an aboveground litter production of 3.2 Mg ha<sup>-1</sup> yr<sup>-1</sup>, and a fine root biomass production ranging from 66 –70% of net primary production (Fogel 1985; Grier *et al.* 1981), a magnitude of 41.7 Mg C ha<sup>-1</sup> yr<sup>-1</sup> could be allocated for fine root production. This suggests that the above values of soil C sequestration are still reasonable. Furthermore, it should be taken into account that most of the sequestration (more than 75%) is assigned to the deeper part of the soils (1-3 m depth). If the plantations are harvested after 9 years (expected harvesting age for pulp production), a soil C sink of 77.4 – 113.9 Mg ha<sup>-1</sup> could be expected. These values are higher than for C sequestered in the biomass of the plantation system amounting to only 78.6 Mg ha<sup>-1</sup>.

#### 4.3.5 Carbon distribution in *Acacia mangium* plantation system

Carbon content of the stand biomass of the *A. mangium* plantation varied from 27.9% to 45.6% depending on the tree compartment. Variability was highest in fine root and leaf biomass, ranging from 27.9-34.2% and 39.1-43.8% (coefficient variation of 10.9 and 7.7%), respectively. Variability in other compartments was considerably low, with coefficient variations ranging from 0.7 to 2.8%. The C content of undergrowth biomass of 37.3 to 41.6% was quite comparable to that of stand biomass. Compared to that of trees and undergrowth, the C content of litter standing stock biomass was, however, slightly lower (average of 35.8%), but variability was higher (coefficient variation of 13.6%).

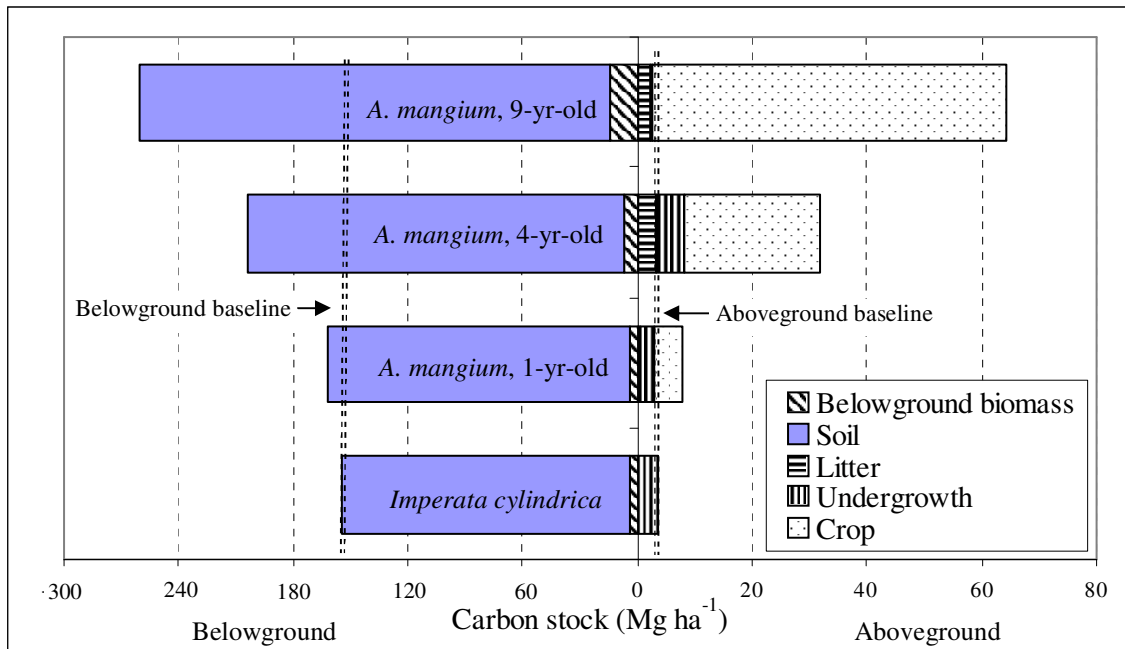


Figure 4.10: Carbon distribution of *Imperata cylindrica* grassland and *Acacia mangium* plantation systems in East Kalimantan, Indonesia; belowground C stock was defined to depth of 3 m; values for the above- and belowground C of the *Imperata cylindrica* grassland were considered as the baseline for the plantations

Below- (to depth of 3 m) and aboveground C stocks increased substantially from 162.2 and 7.8 Mg ha<sup>-1</sup> for the 1-year-old plantation to 260.4 and 64.4 Mg ha<sup>-1</sup> for the 9-year-old plantation, respectively (Figure 4.10). Compared to *I. cylindrica* grassland with 154.6 and 3.6 for the below- and aboveground C stocks, respectively, it is clear that the level of C stocks of the *A. mangium* plantation was higher than that of the *I. cylindrica* grassland since the early stages of the plantation. Of the C stored in the



biomass of the plantation systems, 18% (4- and 9-year-old stands) to 32% (1-year-old stand) was allocated to the belowground biomass. The rate of C accumulation in the biomass of the *A. mangium* plantation systems averaged 9.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>.

Soil C content of the systems decreased in line with soil depth and was highly depth dependent ( $r^2$  ranged from 0.97 to 0.99 and  $p$  of < 0.001). However, spatial variation seems to be dictated by the fine root biomass distribution in the system ( $r^2$  = 0.83-0.99 and  $p$  < 0.001).

Conversion of *I. cylindrica* grassland into *A. mangium* plantation led to a much higher C sequestration in the deep soils. The rate was 1.7-3.0, 3.4-4.6 and 3.5-4.9 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the depths 0-1, 1-2 and 2-3 m, respectively. A potential soil C sink of 77.4-113.9 Mg ha<sup>-1</sup> could be expected by this conversion. More than 75% of this amount was allocated to the deep soils (100-300 cm soil depth). Together with the C sequestered in the biomass of the plantations, C sequestration of 156.0-192.5 Mg ha<sup>-1</sup> could be achieved.

It is interesting that most of the C stored in the plantation system was allocated to the belowground stock (soil and belowground biomass C), a fact that has been ignored in most previous works, due probably to the difficulty in the assessment of this component. The results show that belowground C contributed to more than 95% in the early stages of the plantation (1-year-old) and then declined with age to only 80% in the 9-year-old plantation (Table 4.11). However, the relative contribution of the belowground C stock of the *A. mangium* plantations was lower than that of the *I. cylindrica* grassland system (98%).

Table 4.11: Below- and aboveground C stock distribution of *Imperata cylindrica* grassland and *Acacia mangium* plantation systems in East Kalimantan, Indonesia

System	Belowground		Aboveground biomass	Belowground / total (%)
	Soil	Biomass (Mg ha <sup>-1</sup> )		
<i>Imperata cylindrica</i>	150.6	4.0	3.6	97.7
<i>Acacia mangium</i>	1-year-old	158.6	3.6	7.8
	4-year-old	196.9	7.2	31.7
	9-year-old	246.2	14.2	64.4

*Belowground C stock was defined to depth of 3 m*

#### 4.4 Conclusions

Biomass and biomass C of the *A. mangium* plantation system increased with age to a level much higher than that of *I. cylindrica* grassland, implying that the conversion of marginal lands into plantations should be encouraged. In term of greenhouse gas mitigation, these plantations may lower the magnitude of atmospheric CO<sub>2</sub> not only through sequestration, but also by preventing an increase in atmospheric CO<sub>2</sub> through the use of the biomass produced in this plantation for bio-fuel replacing the use of fossil fuel.

The deep penetration of the roots in *A. mangium* plantations likely has important implications for C sequestration in the deeper soils. Soil C storage increased with plantation age to almost twice that of *I. cylindrica* grassland, suggesting that the establishment of plantations is beneficial not only in terms of C sequestration but also in terms of land rehabilitation, as a considerable amount of nutrients may associate with C stored in the system. Furthermore, an increase in soil C storage may improve soil physical properties such as stability of soil structure and water holding capacity, and soil chemical properties such as nutrient availability. It could also increase CEC and thus decrease the risk of toxicity through certain elements, e.g., Al, which in turn would increase the fertility status of the respective soils.

Conversion of *I. cylindrica* grassland into *A. mangium* plantations could sequester 78.4 Mg C ha<sup>-1</sup> in the plantation biomass during a period of 9 years. The average rate of C accumulation in the biomass of the plantation was 9.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>. Compared to total C stored in the biomass of *I. cylindrica* grassland of 7.6 Mg ha<sup>-1</sup>, an additional 70.8 Mg C ha<sup>-1</sup> could be expected in the biomass alone. Together with that sequestered in the soil (to a depth of 3 m) of 95.7 Mg ha<sup>-1</sup>, a magnitude of C sequestration of 166.5 Mg ha<sup>-1</sup> could be achieved.

## 5 OIL PALM PLANTATIONS

### 5.1 Introduction

There is an increasing interest in the importance of the role of terrestrial ecosystems in the global C budget. Tropical forests store a large amount of C (428 Pg in soil and vegetation, Watson *et al.* 2000) and serve as both a sink for and source of atmospheric C. Land-use change and forestry activities, primarily deforestation of the tropical forests, are a significant source of CO<sub>2</sub> emissions, representing 1.6 Pg yr<sup>-1</sup> of the total anthropogenic emission of 6.3 Pg yr<sup>-1</sup> (Watson *et al.* 2000; Houghton *et al.* 1995).

Plantations, either forests or woody perennial crops, have led to a decrease in the C pool to a magnitude of 50% lower than the original forest stock (Lasco 2002). Oil palm plantations are becoming the center of environmental controversies with regard to deforestation in the tropics. They have been made responsible for most of the deforestation in South East Asia. Nevertheless, this would not be the case if the plantations were established in degraded lands or in unproductive forests. It is obvious that whether such plantations facilitate the sink or emission of CO<sub>2</sub> depends on the initial condition of the land on which the plantations are established.

The oil palm as a perennial crop has become important, firstly, as a major source of oils and fats for human food, secondly, as animal feeds, and, thirdly, for manufacture of many domestic products such as cosmetics, soaps and detergents (Khalid *et al.* 1999). The establishment of large-scale monoculture oil palm plantations in Indonesia began in 1985, when they covered about 600.000 ha. In 1999, the area had expanded to about 3 million ha (Glastra *et al.* 2002; Wakker 2000).

Production and trade in oil palm commodities has expanded rapidly in response to an increasing world population and improved living standards. The global production of palm oil has increased very rapidly, more than doubling between 1970 and 1980. In 1980, palm oil became the world's second most important vegetable oil after soybean.

Oil palm is currently one of the major sources of vegetable oil in the world. The crop ranks second among the world oil production crops and first in the international market of vegetable oils and fats. This crop is grown in lowlands of the humid tropics (15° N - 15° S) with an evenly distributed rainfall of 1,800-5,000

mm/year and is well adaptable to a wide range of soils and to low pH, but sensitive to high pH (above 7.5) and to stagnant water (Wichmann 2001).

These plantations show a very high productivity (Lamade and Setyo 2002) and there is evidence of the success of plantations in degraded land such as *I. cylindrica* grasslands in Sumatra and Kalimantan. There are about 7.5-8.5 million ha of *I. cylindrica* grassland distributed over many islands in Indonesia, an area which would be sufficient for the extensive expansion of oil palm and forestry plantations planned by the government. These plantations have a high potential to be promoted in the world C trade and may, therefore, increase the foreign exchange earnings of the country. However, the question as to how much CO<sub>2</sub> can be sunk by converting *I. cylindrica* grassland into plantations is still open. To answer this question, studies on the biomass and C storage of oil palm plantations compared to those of *I. cylindrica* grassland are of utmost importance.

In this study, efforts are focused on quantifying the biomass and C accumulated in the oil palm plantations at different ages, as well as biomass and C distribution in the plantations.

### **5.2 Methodology**

Sampling for the biomass and C storage inventory of oil palm plantations was carried out on sites in Sumatra and East Kalimantan. However, due to the time and labor constraints, sampling for aboveground biomass and C stock was conducted for plantations in Sumatra alone. Three 0.05 ha circular plots ( $r = 12.6$  m, consisting of 7 oil palm trees; Figure 5.1) were established in 3-, 10-, 20- and 30-year-old oil palm plantations in Sumatra and 3- and 10-year-old plantations in East Kalimantan. Extreme variation in stand density, undergrowth coverage and land slope was avoided. Thus, 12 plots were established in Sumatra (4 stand ages, 3 replications) and 6 plots in East Kalimantan (2 stand ages, 3 replications). To minimize errors induced by the variation of soil type, all observation plots were established in loamy to clayey Ultisols, as this soil type is the most common in these regions.

For the biomass estimation, a palm tree from each crop age, with diameter and height approximately equivalent to the mean of the population, was harvested and uprooted. Total biomass of the harvested trees was weighed and samples were drawn

from the different components (trunk base, trunk, frond base, petiole, rachis, leaflet, spear, cabbage and inflorescence) and weighed. Samples were dried to a constant weight at 60°C to obtain the total dry weight of each component. Thereafter, samples were ground to pass a 0.2-mm sieve for chemical analysis. The trunk base was defined as the part of trunk developed belowground including roots developed underneath the trunk base to a depth of 1 m.

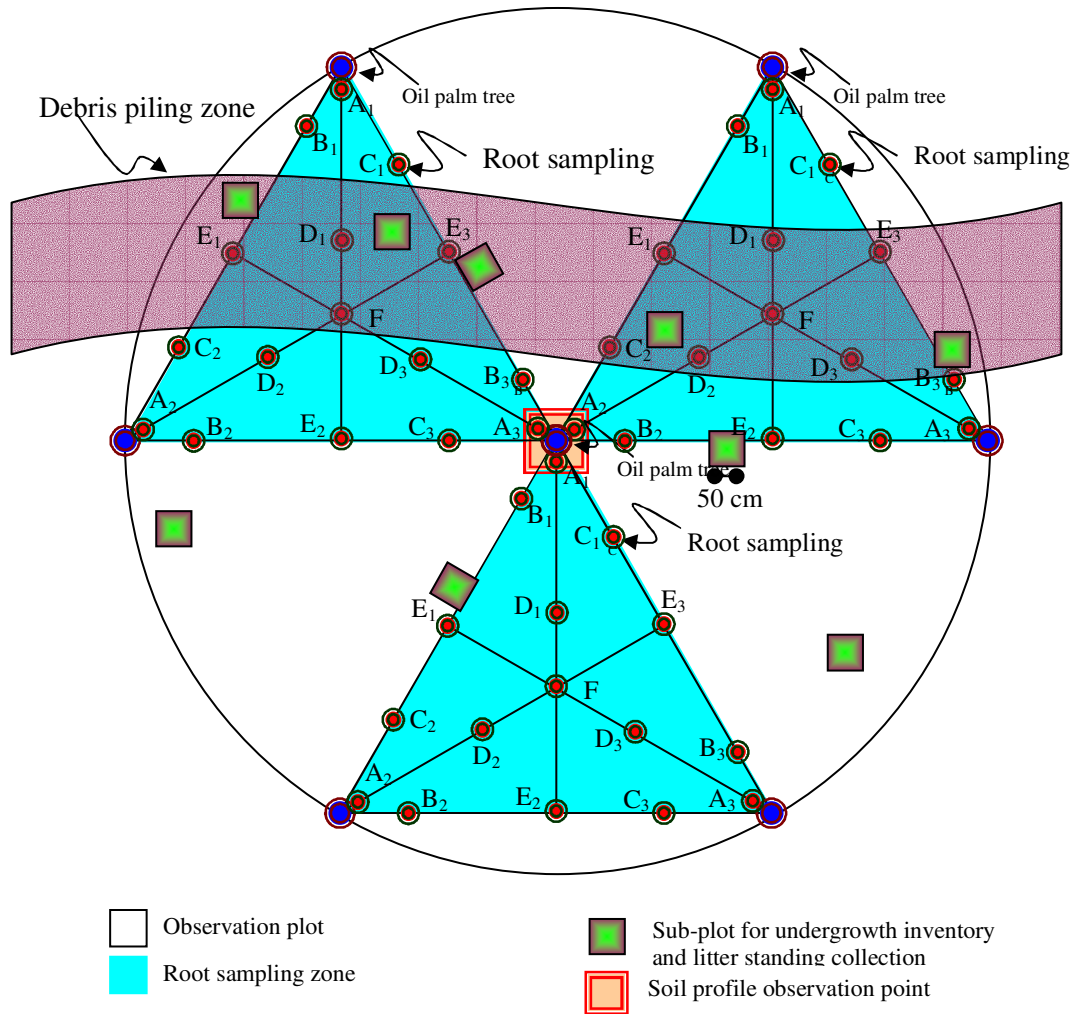


Figure 5.1: Layout for the biomass and carbon storage sampling on oil palm plantation in Sumatra and East Kalimantan, Indonesia

Nine 0.5 m x 0.5 m sub-plots were randomly established to assess the biomass of the herbaceous undergrowth occupying the respective plot. All undergrowth in these sub-plots was harvested and weighed to calculate the total fresh weight. Samples were

drawn representatively for the total dry weight assessment. Thereafter, the same procedure as for the tree samples was followed.

Litter standing stock was defined as the litter in the L and F layers of the soils, because the H layer was incorporated into the soil sample. Sampling for litter standing stock was carried out as for undergrowth sampling. All litter in the sub-plots was collected, sorted into woody and non-woody components and weighed (fresh and air dry). A small sample from each component was drawn and processed following the same procedure as for tree samples.

To estimate the total biomass of the system, root biomass was sampled and collected at 16 drilling points in each subplot (three subplots/plot) to a depth of 5 m (using an 8-cm-diameter root auger in 15 cm increments) distributed in a systematical sampling on the basis of the distance to the closest trunk – 10 cm (A), 100 cm (B), 200 cm (C), 300 cm (D), 450 (E) and 520 cm (F). Roots were separated from the soil core by means of water saturation and flushing.

A soil profile was established nearby the center of one of the three plots of each plantation age for observation of soil morphological characteristics and sampling of soil bulk density. Soil sampling and analyses were carried out following the procedure described in Section 3.2.

Data were analyzed with analysis of variance (ANOVA) and means were compared with the LSD-test procedure.

### **5.3 Results and discussions**

#### **5.3.1 Biomass distribution**

Both below- and aboveground biomass of the system increased persistently with plantation age. Total biomass of the system was 40.9, 117.9, 157.9 and 204.3 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations (Table 5.1), respectively. Compared to the total biomass of *I. cylindrica* grassland near the plantations of 16.9 Mg ha<sup>-1</sup>, the total biomass of the oil palm plantations already surpassed that of *I. cylindrica* in the very early stage of the plantation. This suggests that conversion of *I. cylindrica* grassland into oil palm plantation is beneficial if biomass and land rehabilitation is the concern. Of the compartments of the system (crop, undergrowth and litter standing stock), the crop contributed the highest amount of biomass, accounting for 85.6-94.3%. Undergrowth

contributed 1.4-2.9% of the total biomass and litter standing stock 4.3-11.5%. Despite the minor contribution of these compartments to the total biomass, they could play an important role in the functioning of the system such as controlling soil erosion and surface run-off, and promoting soil C and nutrient cycles as well as soil biological activities. The undergrowth dry matter of a 5-year-old oil palm plantation can range from 2-3 Mg ha<sup>-1</sup> to 7-8 Mg ha<sup>-1</sup> depending on the extent of weeding (Chen *et al.* 1991) and this could decline to between 0.5 and 1 Mg ha<sup>-1</sup> in the consecutive years. The values in this study ranging from 1.2 to 3.6 Mg ha<sup>-1</sup> are still in this range.

Table 5.1: Above- and belowground biomass distribution of different ages of oil palm plantation systems in Sumatra, Indonesia

Age (year)	Belowground biomass	Aboveground biomass			Total biomass	Relative belowground to total (%)
		Litter	Undergrowth (Mg ha <sup>-1</sup> )	Crop		
3	13.3	4.7	1.2	21.7	40.9	32.5
10	25.0	5.1	1.6	86.3	117.9	21.2
20	40.1	15.7	3.6	98.4	157.9	25.4
30	52.4	17.9	3.2	130.7	204.3	25.6

*Belowground biomass was defined to depth of 5 m.*

Aboveground crop biomass increased from 21.7 Mg ha<sup>-1</sup> in third year of the plantation to 130.7 Mg ha<sup>-1</sup> for the 30-year-old plantation. Aboveground biomass in previous studies varies widely from 68.9 to 86.0 Mg ha<sup>-1</sup> for a 25-year-old oil palm (Nordin 2002) and a 23-year-old plantation (Khalid *et al.* 1999) to about 192.0 to 202.0 Mg ha<sup>-1</sup> for the 14- and 19-year-old oil palm (Sitompul and Hairiah 2000), respectively. Rees and Tinker (1963) reported a magnitude of aboveground biomass in 7- to 22-year-old oil palm plantations of 26.2-84.4 Mg ha<sup>-1</sup>. It is obvious that the aboveground biomass of the plantation systems is variable and may be influenced by the inherent characteristics, pedoagroclic conditions and management.

Of the crop aboveground biomass, the trunk contributed 56.7 to 75.3%. These figures are considerably higher than those reported by (Khalid *et al.* 1999a) of 48% but are in agreement with those reported by Rees and Tinker (1963) of 7- to 22-year-old oil palm plantations of 42.8-73.0%. Trunk biomass in this study ranged between 13.1 and 94.3 Mg ha<sup>-1</sup> for the 3- and 30-year-old plantations, respectively (Table 5.2). Compared to the trunk biomass reported in previous studies of 36.7-46.8 Mg ha<sup>-1</sup> for 22- to 27.5-

year-old plantations (Khalid *et al.* 1999a; Corley *et al.* 1971; Tinker and Smilde 1963), the results are considerably higher. However, they are in agreement with the 88.5 Mg ha<sup>-1</sup> of a 15-year-old plantation reported by Ng *et al.* (1968).

Table 5.2: Biomass distribution of the oil palm trees of different ages in Sumatra, Indonesia

Age (year)	Belowground		Aboveground				
	Root	Trunk base	Trunk	FronD base	Rachis	Leaflet	Others
3	12.0	1.3	13.1	1.2	4.6	1.4	1.40
10	16.1	8.9	49.0	20.5	9.9	4.8	2.16
20	27.6	12.5	74.1	2.3	15.8	4.3	5.71
30	35.7	16.7	94.3	3.3	24.2	6.4	6.54

*Trunk base, defined as part of trunk developed belowground including roots developed underneath the trunk base to depth of 1 m; rachis, including petiole; others, including spear, cabbage and inflorescences; root biomass was defined to depth of 5 m.*

The biomass of the frond base increased substantially from 1.2 Mg ha<sup>-1</sup> in the 3-year-old plantation to 20.5 Mg ha<sup>-1</sup> in the 10-year-old plantation, then declined to only 2.3 and 3.4 Mg ha<sup>-1</sup> in the 20- and 30-year-old plantation, respectively. There was an increase in frond base biomass from 3- to 10-year-old plantations in line with the increase in the trunk dimension of the crops. However, due to the abscission of the frond base of the older plantations (in most cases, frond bases begin to be detached from the trunk at the plantation age of 13 to 18 years), the biomass of the frond base of the older plantations (20- and 30-year-old) was pronouncedly lower. Khalid *et al.* (1999a) reported a magnitude of frond base of a 23-year-old oil palm plantation of 129.1 kg palm<sup>-1</sup> equivalent to 17.6 Mg ha<sup>-1</sup>. This is quite comparable to the results in this study for the 10-year-old plantation (23.7%), which is in agreement with the 18-22% reported in the previous studies (Khalid *et al.* 1999a; Henson 1993).

Rachis biomass, including petioles, increased from 4.6 to 9.9, 15.8 and 24.2 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations, respectively. Compared to the values reported by Khalid *et al.* (1999a) for a 23-year-old oil palm plantation of 110.5 to 127.9 kg palm<sup>-1</sup> equivalent to 15.0-17.4 Mg ha<sup>-1</sup> and Rees and Tinker (1963) for 7- to 22-year-old oil palm plantations of 42.7-101.8 kg palm<sup>-1</sup> equivalent to 5.8-13.8 Mg ha<sup>-1</sup>,



the results in this study are still comparable. The relative contribution of the rachis was considerably high in the young plantation. It was 21.1% in the 3-year old plantation and dropped to only 11.4% in the 10-year-old plantation as the other compartments of the crop developed, especially trunk and frond base. Nevertheless, there was an increase in the contribution of rachis to the crop aboveground biomass of the older plantations. It was 16.1 and 18.5% for the 20- and 30-year-old plantations, respectively. Similar values (17.6-20.4%) in a 23-year-old oil palm plantation in Malaysia were reported by Khalid *et al.* (1999a) and (12.9-22.2%) in a 7- to 22-year-old plantation (Rees and Tinker 1963).

Leaflet biomass of the plantation system increased from only 1.42 Mg ha<sup>-1</sup> (3-year-old plantation) to 4.82 Mg ha<sup>-1</sup> (10-year-old plantation), then fluctuating between 4.34 Mg ha<sup>-1</sup> (20-year-old plantation) and 6.44 Mg ha<sup>-1</sup> (30-year-old plantation). These figures are still comparable to those of 7- to 22-year-old oil palm plantations (24.7-48.5 kg palm<sup>-1</sup> equivalent to 3.4-6.6 Mg ha<sup>-1</sup>) (Rees and Tinker 1963) and of a 23-year-old plantation (7.9 Mg ha<sup>-1</sup>) (Khalid *et al.* 1999a). However, the relative contribution of leaflet biomass was somewhat low, ranging from 4.4-6.5%. Compared to the values reported by Khalid *et al.* (1999a) of 9.3% of the crop aboveground biomass and by Rees and Tinker (1963) of 8.0-12.8%, these are somewhat lower.

Biomass of other components (spear, cabbage and inflorescences) increased from only 1.4 to 2.2, 5.7 and 6.5 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantation systems, respectively. The relative contribution of these components was rather high in the early stage of the plantations. It was 6.4% for the 3-year-old plantation, decreased to 2.5% for the 10-year-old plantation and to only 1.9% for the 20- and 30-year-old plantations. Khalid *et al.* (1999a) reported a slightly higher contribution of 3.2% in a 23-year-old oil palm plantation in Malaysia.

Root biomass of the system was 12.0, 16.1, 27.6 and 35.7 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations, respectively. Compared to the root biomass of a 23-year-old plantation of 16.00 Mg ha<sup>-1</sup> reported by Khalid *et al.* (1999b) and that of a 27.5-year-old of 17.8 Mg ha<sup>-1</sup> reported by Corley *et al.* (1971), the root biomass of mature oil palm in this study was considerably high. However, Khalid *et al.* (1999b) defined the root biomass to a depth of 60 cm and Corley *et al.* (1971) to a depth of 90 cm, while in this study the total depth was 5 m. Biomass to a depth of 90 cm was 7.7, 10.1, 18.2 and 24.2 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations,

respectively. These figures are quite comparable to the findings of Khalid *et al.* (1999b) and Corley *et al.* (1971). Sommer *et al.* (2000) reported a similar root biomass in a 9-year-old oil palm plantation in Eastern Amazon ( $14.0 \text{ Mg ha}^{-1} \text{ 6m}^{-1}$ ). Roots contributed 14.4-34.2%, and together with the trunk base produced 22.4-38.0% of the total crop biomass. These results are in agreement with those reported in previous studies (Khalid *et al.* 1999b; Corley *et al.* 1971).

There was a persistent increase in both below- and aboveground biomass of the oil palm plantation with age. However, the aboveground biomass was logarithmically correlated with age, while belowground biomass was linearly correlated (Figure 5.2). A similar trend in relation of oil palm biomass with plantation age in Malaysia was found by Nordin (2002).

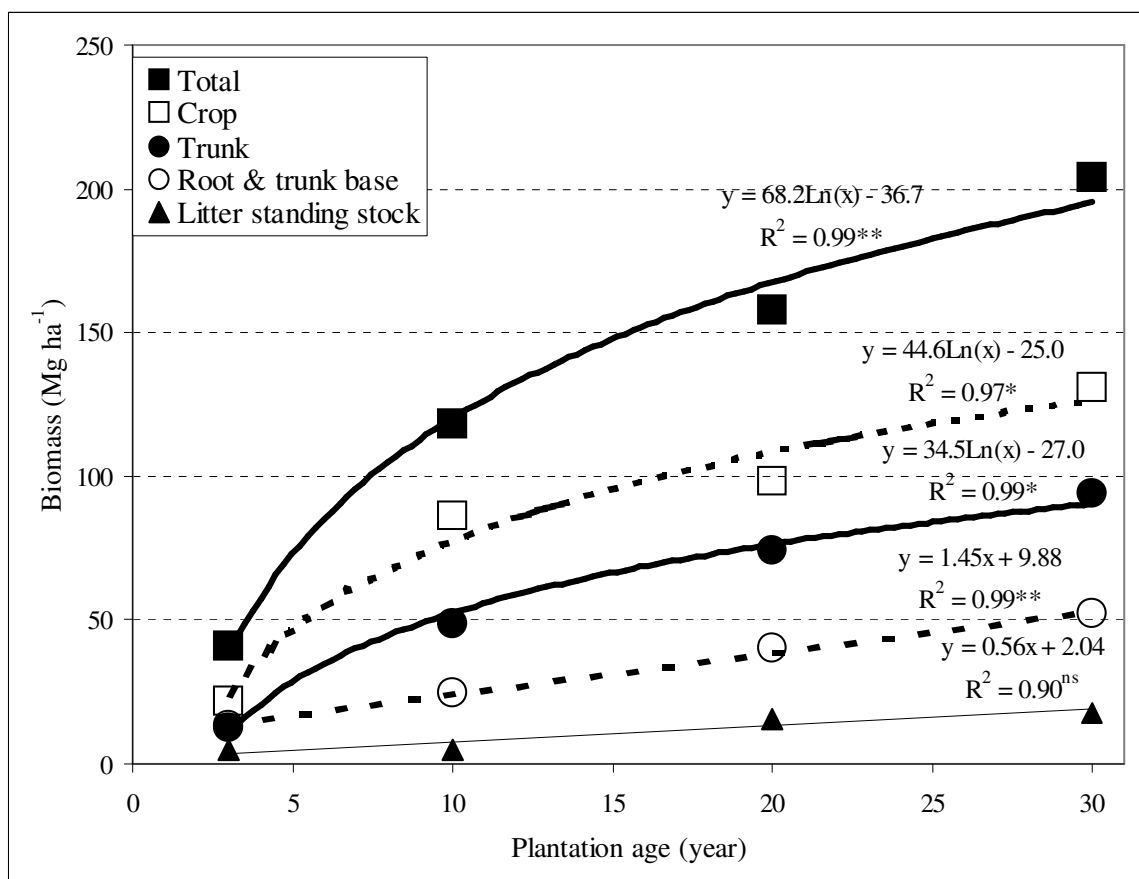


Figure 5.2: Trend of relation of biomass of oil palm compartments with age of plantation in Sumatra, Indonesia

The rate of biomass accumulation in the system was 13.6, 11.8, 7.9 and 6.8 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations and the overall weighed average was 8.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>. Compared to the 10.0 Mg ha<sup>-1</sup> yr<sup>-1</sup> reported by ISME (2000), the annual rate of biomass accumulation in this study is somewhat lower. However, depending on how this rate is calculated, without weighing, the annual rate of the biomass of the oil palm in this study reaches 10.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>.

### 5.3.2 Root distribution

There was a large difference in root biomass between the oil palm plantation in Sumatra and that in East Kalimantan (Table 5.3). The reasons will be elaborated in the following discussion. Root biomass in Sumatra ranged from 12.0 to 16.1, 27.6 and 35.7 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> for the 3-, 10, 20 and 30-year-old plantations, respectively. Compared to the values in East Kalimantan of 21.2 and 31.7 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> for the 3- and 10-year-old plantations, respectively, the root biomass in Sumatra was much lower. However, the root biomass in both sites was higher than that of *I. cylindrica* in the neighborhood of the respective sites, which was 8.7 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in Sumatra and 12.4 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in East Kalimantan. Moreover, the vertical distribution of the root biomass of *I. cylindrica* grassland was restricted to the top soil layer (Figure 5.3).

Table 5.3: Vertical root biomass distribution in oil palm plantation systems in East Kalimantan and Sumatra, Indonesia

Depth (m)	East Kalimantan		Sumatra			
	3-year-old	10-year-old	3-year-old	10-year-old	20-year-old	30-year-old
0-1	16.5	21.6	8.1	10.8	19.7	26.4
1-2	2.5	5.9	2.2	2.7	4.8	5.9
2-3	1.1	2.7	1.0	1.7	1.8	1.9
3-4	0.9	1.1	0.5	0.6	0.9	1.1
4-5	0.3	0.3	0.1	0.2	0.4	0.3
0-5	21.2	31.7	12.0	16.1	27.6	35.7

In the 5-m deep soil profile, more than 50% of the root biomass was found in the top 60 cm. However, compared to *I. cylindrica* grassland, the roots of the oil palm penetrated much deeper, i.e., to a depth of 5 m. This is much deeper than the *I.*

*cylindrica* grassland with a depth of only 1.8 m. Penetration of oil palm roots to a depth of 6 m was reported by Sommer *et al.* (2000).

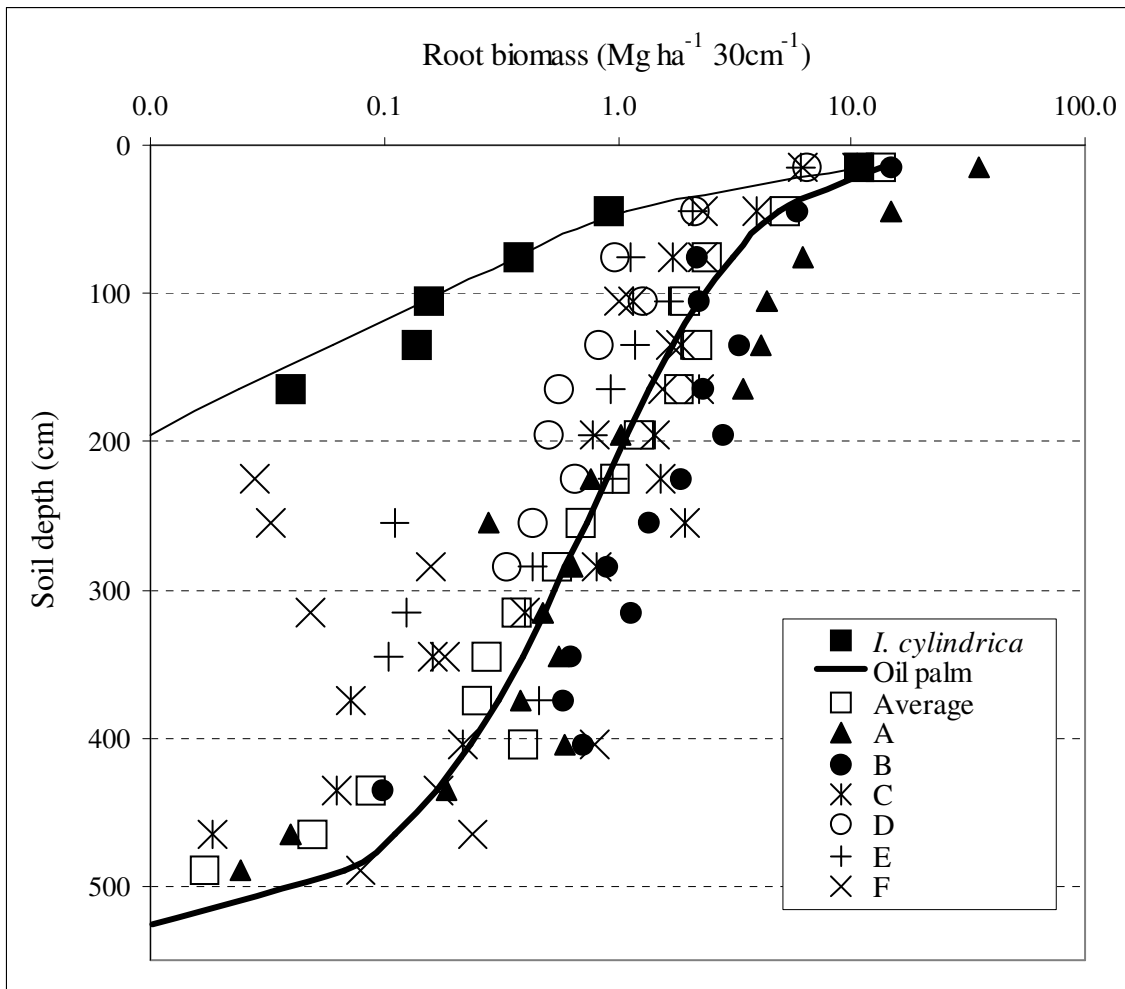


Figure 5.3: Vertical distribution of root biomass of a 10-year-old oil palm plantation and *Imperata cylindrica* grassland (IC) systems in East Kalimantan, Indonesia; A, B, C, D, E and F = 10, 100, 200, 300, 450 and 520 cm from the trunk base

Distribution of the roots of the oil palm plantation seems to be site and age dependent. It is interesting that although distribution of 50% of the root biomass of the oil palm plantation in East Kalimantan (31 and 41 cm depth for the 3- and 10-year-old plantations, respectively) was shallower than in Sumatra (46, 58, 58, and 59 cm depth for the 3-, 10-, 20- and 30-year-old, respectively), distribution of 90% of the root biomass in both sites was not significantly different: 90% of the root biomass in East Kalimantan was found to a depth of 244 and 223 cm in the 3- and 10-year-old plantations, respectively, and in Sumatra to depths of 228, 239, 207 and 219 cm in the

3-, 10-, 20- and 30-year-old plantations, respectively. The first 1-m depth produced 67-78% of the total root biomass (to depth of 5 m).

The root biomass consisted mainly of primary roots, which contributed 47, 70, 84 and 80% to total root biomass of the 3-, 10-, 20- and 30-year-old plantations, respectively. Secondary and tertiary (including quaternary) root biomass contributed 11-16% and 5-37%, respectively. Compared to the root biomass reported by Khalid *et al.* (1999b) of 50, 20 and 30% for the primary, secondary and tertiary roots, respectively, these results are still comparable. While the biomass of both primary and secondary roots increased continuously with age, the biomass of tertiary roots (including quaternary roots) fluctuated, which is probably the result of the physiological demands of the plant and environmental conditions (Figure 5.4).

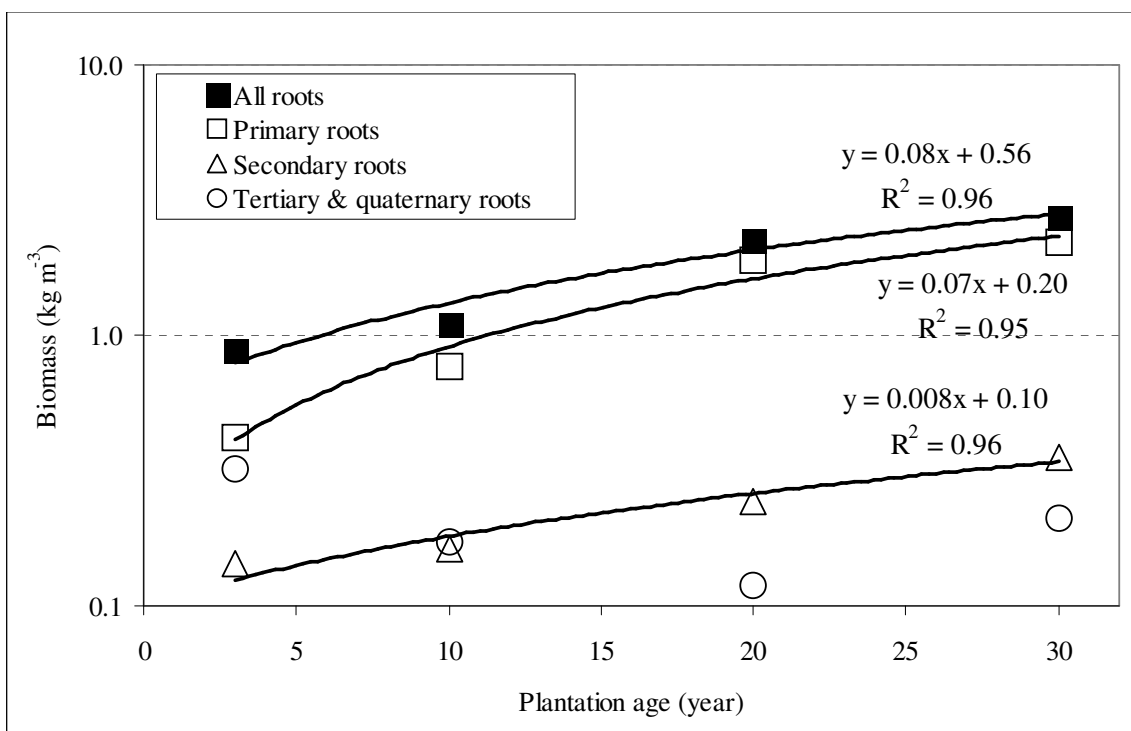


Figure 5.4: Biomass of primary, secondary and tertiary (including quaternary) roots of oil palm plantation systems in Sumatra, Indonesia

However, the contribution of tertiary and quaternary roots to the total root biomass was considerably high in the top 15 cm of soil, declining sharply in the deeper soils (77 to 22%, 41 to 11%, 27 to 4% and 44 to 8% for the 3-, 10-, 20- and 30-year-old plantations, respectively). A similar trend in a 23-year-old oil palm plantation in Malaysia was reported by Khalid *et al.* (1999b), who found that tertiary roots

contributed 53% in the top 15 cm and declined to only 25% of the total root biomass at the 15-30 cm soil depth. Wright (1951) reported that most of the tertiary roots of oil palm on deep acid sandy soils in West Africa were confined to a depth of 10 cm. Vertical distribution of fine roots indicates the rooting strategy of trees and is species specific and genetically inherited (Curt and Prévosto 2003; Polomski and Kuhn 1998; Brown 1992); this shallow concentrated rooting strategy may allow an efficient use of the topsoil resources (Crabtree and Berntson 1994). Fine-roots proliferated in the A-horizon of most soils, due to accumulation of organic matter, higher CEC and higher nutrient concentration in organic C, N, and K (Bowen 1984; Kalisz *et al.* 1987; Pritchett and Fisher 1987; Sainju and Good 1993).

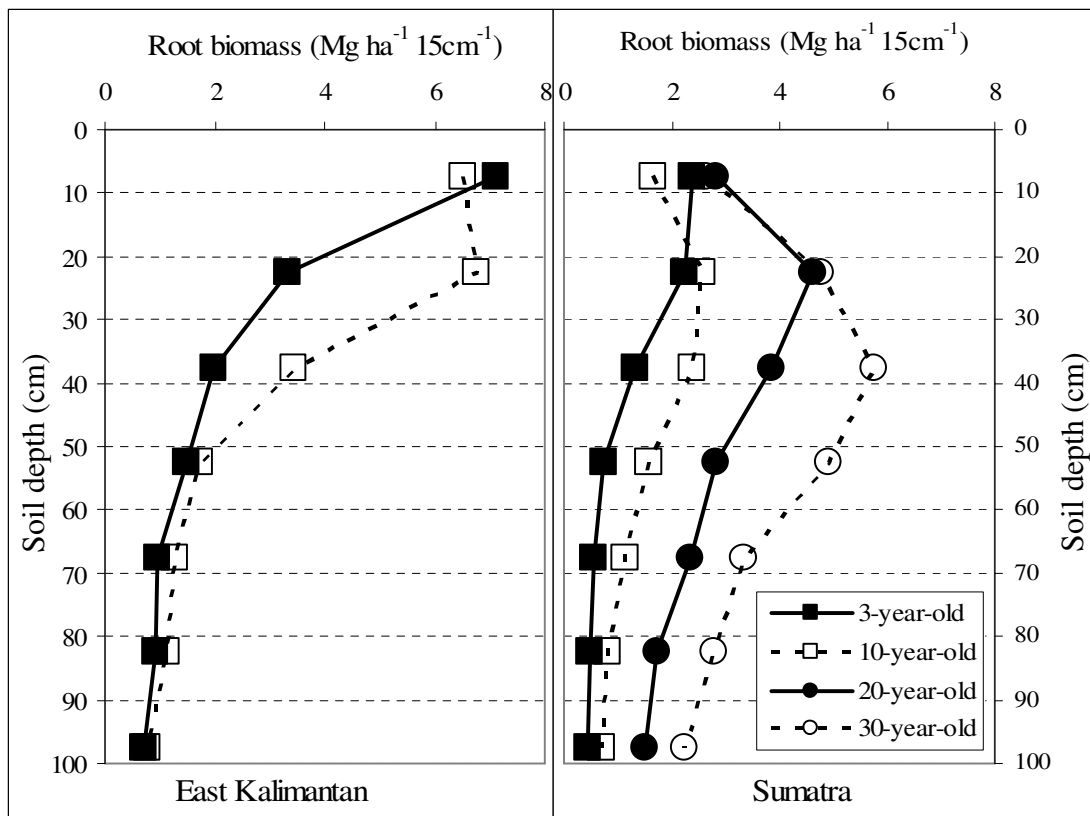


Figure 5.5: Vertical distribution of root biomass of oil palm plantations in Sumatra and East Kalimantan, Indonesia

Although roots of oil palm can penetrate deeper than 4 m, the majority have been found in the top 45 cm (Lambourne 1935). The largest magnitude of root biomass is to be found between a soil depth of 20 and 60 cm (Tailez 1971), but the exact depth

of the root concentration depends to large extent on the soil type (Chan 1977). Root biomass of the oil palm plantations at both sites showed a parallel trend of vertical root distribution. Most of the roots of the young plantations (3-year-old) were concentrated in the uppermost 15 cm and decreased with soil depth. However, the concentration of roots in the uppermost soils was more pronounced for the plantations at the East Kalimantan site (Figure 5.5).

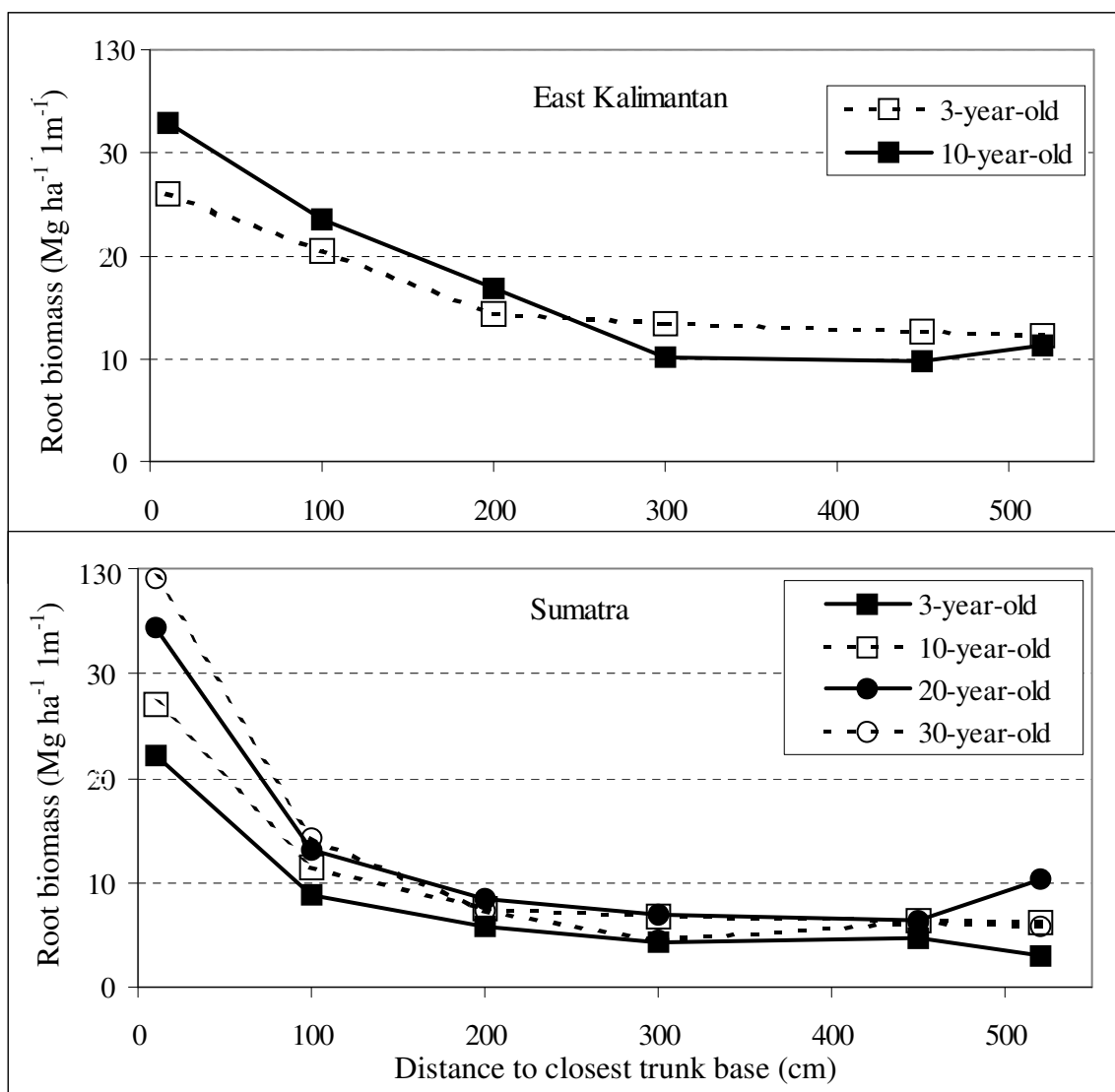


Figure 5.6: Lateral distribution of root biomass of different ages of oil palm plantations in Sumatra (below) and East Kalimantan (above), Indonesia

The vertical distribution of root biomass in the older plantations is in agreement with that reported by Khalid *et al.* (1999b) and Chan (1977). There was an

increase in root biomass at a depth of 15-30 cm for the 10- and 20-year-old plantations, and at a depth of 15-45 cm for the 30-year-old plantation. Thereafter, biomass declined with depth, but again at a depth of 0-45 cm, the magnitude of root biomass of the plantations in East Kalimantan was much higher.

The lateral extent of woody roots may exhibit a high degree of plasticity and depend on environmental conditions (Millikin and Bledsoe 1999; Belsky 1994). Roots of oil palm may grow laterally to a distance of more than 12 m (Wright 1951). However, Zaharah *et al.* (1989) reported that roots of mature oil palms can absorb nutrients as far as 36 m away from the base trunk. Feeding roots up to more than 6 m away from the trunk base and lateral roots of more than 20 m have also been observed (Lambourne 1935). Nevertheless, root density decreases with distance to the trunk base, and the majority of the absorbing roots of mature oil palms may extend to a radius of at least 3.5-4.5 m from the trunk base (Ruer 1967). A high root biomass was concentrated near the trunk base (10 cm from the trunk base), decreasing sharply at a distance of 1 m, then declining gradually to a distance of 3 m from the trunk base. Hereafter, it was more or less stable or fluctuated slightly to a distance of 5.2 m from the trunk base (Figure 5.6).

Khalid *et al.* (1999b) reported that the lateral distribution of the roots of a 23-year-old oil palm plantation in Malaysia was the same as in this study, which is also in agreement with that of a 14-year-old oil palm plantation in West Africa (Purvis 1956). A similar distribution in other systems has also been reported (Purbopuspito and Van Rees 2002; Jose *et al.* 2001; Peter and Lehmann 2000; Jones *et al.* 1998). The lateral and vertical trend of root biomass density in the 10-year-old oil palm plantation in East Kalimantan is depicted in Figure 5.7. There was a high concentration of root biomass close to the trunk base to a depth of less than 50 cm.

In general, root biomass density can be classified into 6 zones. The first zone constituted the highest concentration of root biomass, which reached more than 10 kg m<sup>-3</sup> in the 10-year-old oil palm plantation. This zone developed near the trunk base to a distance of less than 1 m and within a soil depth of 15 cm and 50 cm. However, this zone sometimes extended to a depth of more than 75 cm in the old plantation (30-year-old) without an increase in the lateral distance to the trunk base. The second zone developed directly in the outer of the first zone to a distance of rarely more than 2 m from the trunk base and to a depth of 50 cm, where the root biomass showed a density



of  $5\text{-}10 \text{ kg m}^{-3}$ . The third zone emerged in the outer area of the second zone, extending to a distance of 4 m from the trunk base close to the soil surface but confined to a shallow soil depth below the second root zone of less than 60 cm. The root biomass density of this zone ranged from  $3\text{-}5 \text{ kg m}^{-3}$ . The fourth root zone showed a biomass density of  $1\text{-}3 \text{ kg m}^{-3}$  and developed in the outer area of and below the third root zone to a distance of 5.2 m from the trunk base (planting space was a triangular  $9 \text{ m} \times 9 \text{ m} \times 9 \text{ m}$ ) to a depth of 40 cm at a distance of 5 m from the trunk base and of 160 cm near the trunk base. Below this zone, a root zone with a root biomass density of  $0.5\text{-}1 \text{ kg m}^{-3}$  was sometimes observed. This zone developed at depths of 40-150 cm to a distance of 5 m from the trunk base and of 160-280 cm near the trunk base with some discontinuousness. The final root zone developed below the fifth root zone, with a biomass density of less than  $0.5 \text{ kg m}^{-3}$ ; due to the high spatial variation, further zonation of this root biomass is not possible.

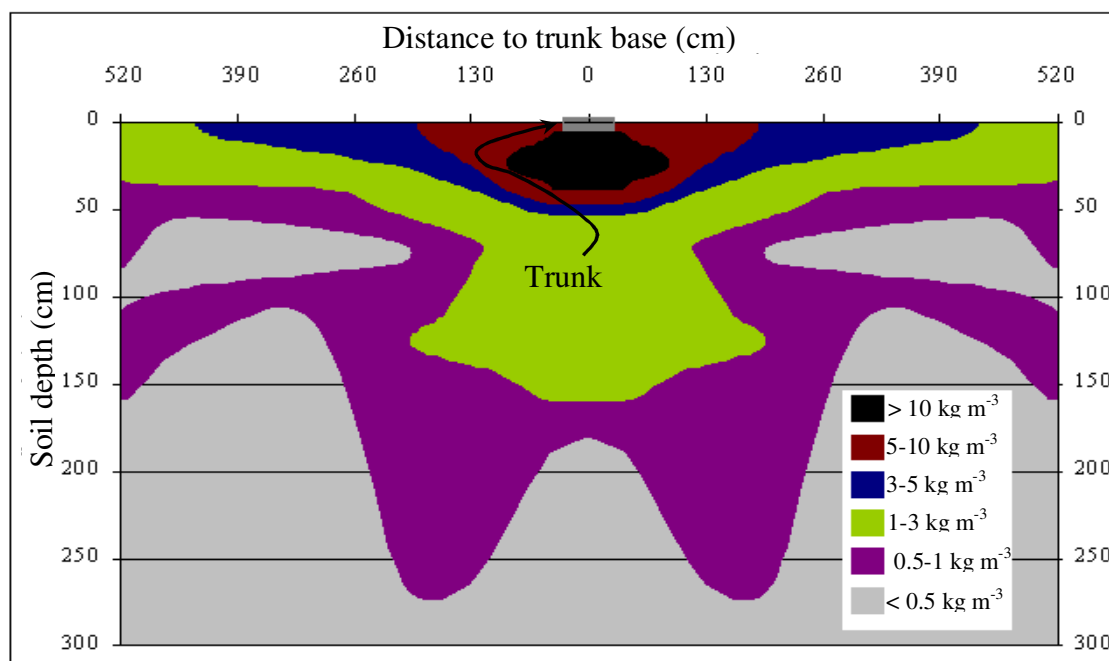


Figure 5.7: Vertical and lateral root biomass density of a 10-year-old oil palm plantation in East Kalimantan, Indonesia

It is important to bear in mind that this is not a static zonation. The zones may shrink and swell depending on numerous genetically inherited factors and the environmental conditions of the plantation. In some cases, it was observed that the second and third zones had developed in a very narrow lateral range of between 50 and

100 cm from the trunk base. An intensive sampling of roots near to the trunk base (0-100 cm) is, therefore, of utmost importance, if an accurate estimate is required.

### 5.3.3 Biomass carbon distribution

The C content of the compartments of the oil palm plantation systems ranged widely from 32.3 to 44.2% (Table 5.4). However, only leaf litter and tertiary roots (including quaternary roots) compartments had low C contents of 32.3 and 36.6%, respectively, while for the other compartments these values ranged from 39.4 to 44.2%. The average C content of 41.7, 38.4 and 40.3% for the crop aboveground biomass, non-crop aboveground biomass, and root and trunk base biomass, respectively, resulting in an overall average of 40.4%, was much lower than the assumed values of 50% applied for most of the previous studies. However, the average values have to be corrected with the relative biomass of each compartment. The calculations resulted in a weighed average of 41.3%, and the use of this value in converting biomass to C stock instead of the above-mentioned 50% is recommended.

Table 5.4: Carbon content of compartments of oil palm plantation systems in Sumatra and East Kalimantan, Indonesia

Compartment		Mean (%)	SD	n
Crop aboveground compartments	Spear	39.5 bcd	3.3	6
	Leaf	43.7 de	2.5	6
	Rachis	41.4 cd	1.1	10
	Fronde base	41.4 cde	0.9	6
	Trunk	42.6 de	1.6	6
	Average	41.7	1.0	-
Non crop compartments	Undergrowth	39.3 c	2.9	8
	Non-leaf litter	43.7 de	1.1	4
	Leaf litter	32.3 a	6.6	8
	Average	38.4	2.8	-
Trunk base and roots	Trunk base	44.2 e	1.8	12
	Primary root	41.1 cd	2.9	20
	Secondary root	39.4 c	3.9	20
	Tertiary root	36.6 b	4.4	20
	Average	40.3	1.2	-
Average		40.4	1.7	-

*SD = standard deviation; mean values followed by the same letter are not significantly different at  $\alpha = 0.05$*

The C content of the both the aboveground compartments and the trunk base of the oil palm plantations was not affected by plantation age. Although intensive root and soil sampling was performed in East Kalimantan, there was no sampling for aboveground biomass, so that it is not possible to compare C content and accumulation of the aboveground biomass. However, there is no difference in the C content of the non-crop biomass (litter and undergrowth).

Contrary to the aboveground biomass C content, site and plantation age had a significant effect on the C content of root biomass. In general, the values in East Kalimantan averaged 35.7%, which is significantly lower ( $\alpha = 0.05$ ) than the 40.7% in Sumatra. Plantation age may also have a significant effect on the C content of the root biomass (Table 2); younger plantations (3- and 10-year-old) showed a significantly lower C content than the older plantations (20- and 30-year-old). Root type was also a source of variation. Coarser roots (primary and secondary roots) show a higher C content than smaller roots (tertiary and quaternary roots). Nevertheless, in contrast to the younger plantations, the effect of root type on C content of the root biomass was less pronounced in the older plantations (Table 5.5).

Table 5.5: Carbon content of different root types of different ages of oil palm plantations in Sumatra and East Kalimantan, Indonesia

Plantation age (year)	Root type			Mean	SD	n
	Primary	Secondary	Tertiary (%)			
3	39.4	39.2	34.1	<b>37.6a</b>	3.4	18
10	40.9	36.7	34.5	<b>37.4a</b>	5.0	18
20	43.7	42.9	42.1	<b>42.9b</b>	1.0	9
30	42.0	41.4	40.0	<b>41.1b</b>	2.7	15
<b>Mean</b>	<b>41.1b</b>	<b>39.4b</b>	<b>36.6a</b>	<b>39.8</b>	-	-
SD	2.9	3.9	4.4	-	4.1	-
n	20	20	20	-	-	60

*SD = standard deviation; mean values followed by the same letter are not significantly different at  $\alpha = 0.05$ ; tertiary roots including quaternary roots*

Biomass C of the system increased decisively with plantation age and was 16.6, 49.4, 65.3 and 84.6 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations, respectively (Table 5.6). These values are slightly lower than those reported by Noordwijk *et al.* (2000) and Hairiah and Sitompul (2000), which ranged from 62.4-91.0

Mg ha<sup>-1</sup>, given that they defined the belowground biomass C to depth of 30 cm only. Compared to the biomass C of the neighboring *I. cylindrica* grasslands of 3.0, 2.9 and 5.9 Mg ha<sup>-1</sup> for the aboveground, belowground and total biomass C, respectively, it is obvious that total biomass C of oil palm plantations has already surpassed that of *I. cylindrica* in a very early stage of the plantation. This suggests that conversion of *I. cylindrica* grasslands into oil palm plantations is beneficial if C sequestration and land rehabilitation are of interest. Of all compartments (crop, undergrowth and litter standing stock), the crop provided the major biomass C to the system, accounting for 87.8-94.5%. Undergrowth contributed 1.3-2.8% and litter standing stock 3.9-9.4%. Despite the minor contribution of these compartments, they could play an important role in the functioning of the system, such as in controlling soil erosion and surface run-off, and promoting soil C and nutrient cycles as well as soil biological activities.

Table 5.6: Above- and belowground biomass C distribution of four different ages of oil palm plantation systems in Sumatra, Indonesia

Plantation age (year)	Belowground biomass C	Aboveground biomass C			Total	Relative belowground to total (%)
		Litter	Undergrowth	Crop		
3	5.41	1.56	0.47	9.15	16.59	32.63
10	10.40	1.94	0.63	36.37	49.35	21.08
20	16.63	5.51	1.43	41.69	65.26	25.48
30	21.75	6.25	1.26	55.33	84.60	25.71

*Belowground biomass C was defined to depth of 5 m*

Carbon stored in the aboveground crop biomass increased from 9.2 Mg ha<sup>-1</sup> in the 3-year-old plantation to 36.4, 41.7 and 55.3 Mg ha<sup>-1</sup> for the 10-, 20- and 30-year-old plantations. Aboveground biomass C of previous studies varied considerably from 31.0-62.0 Mg ha<sup>-1</sup> for a 10-year-old oil palm to as high as 96.0-101.0 Mg ha<sup>-1</sup> for 14- and 19-year-old oil palm plantations (Sitompul and Hairiah 2000). It is clear that the aboveground biomass of the plantation systems is highly variable; this may be the result of inherited characteristics, pedoagroclicmatic conditions and management. However, to some extent, it also depends on the method of biomass quantification and conversion to the C pool.

There is only little information on the fractionation of biomass C of oil palm plantations in the literature. The following discussion is based on biomass fractionation data and an assumption of a biomass C content of 41.3%. Of the crop aboveground biomass C, the trunk contributed 57.3 to 75.7%. These figures are relatively higher than the 48% reported by Khalid *et al.* (1999a), but are in agreement with those reported by Rees and Tinker (1963) of 7- to 22-year-old oil palm plantations of 42.8-73.0%. Biomass C of the trunk in this study increased from 5.6 Mg ha<sup>-1</sup> for the 3-year-old plantation to 20.9, 31.5 and 40.2 Mg ha<sup>-1</sup> for the 10-, 20- and 30-year-old plantations, respectively (Table 5.7). Compared to the trunk biomass C of previous studies of 15.2-19.3 Mg ha<sup>-1</sup> (36.7-46.8 Mg ha<sup>-1</sup> biomass) for 22- to 27.5-year-old plantations (Khalid *et al.* 1999a; Corley *et al.* 1971; Tinker and Smilde 1963), these results are considerably higher. However, they are in agreement with the value for a 15-year-old plantation of 36.6 Mg ha<sup>-1</sup> (88.5 Mg ha<sup>-1</sup> biomass) reported by Ng *et al.* (1968).

Table 5.7: Above- and belowground biomass C distribution of four different ages of oil palm trees in Sumatra, Indonesia

Stand age (year)	Belowground		Aboveground				
	Root	Trunk base	Trunk	FronD base	Rachis	Leaflet	Others
3	4.8	0.6	5.6	0.5	1.9	0.6	0.6
10	6.5	3.9	20.9	8.5	4.1	2.1	0.9
20	11.1	5.5	31.5	1.0	6.5	1.9	0.7
30	14.4	7.4	40.2	1.4	10.0	2.8	1.0

*Trunk base, defined as part of trunk developed belowground including roots developed underneath the trunk base to depth of 1 m; rachis, including petiole; others, including spear, cabbage and inflorescences; root biomass was defined to depth of 5 m*

The C stored in the biomass of the frond base increased substantially from 0.5 Mg ha<sup>-1</sup> in the 3-year old plantation to 8.5 Mg ha<sup>-1</sup> in the 10-year-old plantation, then declined to only 1.0 and 1.4 Mg ha<sup>-1</sup> in the 20- and 30-year-old plantations, respectively. In line with the increase in the trunk dimension, there was an increase in the biomass C accumulated in the frond base in the early stage of the plantations (from 3- to 10-year-old). However, due to the abscission of the frond base in the older plantations (generally plantation age of 13 to 18 years), the biomass C accumulated in the frond base of the older plantations (20- and 30-year-old) was pronouncedly lower. Khalid *et al.* (1999a) reported a magnitude of frond base biomass of a 23-year-old oil

palm plantation of 129.1 kg palm<sup>-1</sup> equivalent to 7.3 Mg C ha<sup>-1</sup>. This is quite comparable to the 23.3% for the 10-year-old plantation in this study, which is in agreement with the 18-22% in previous studies (Khalid *et al.* 1999a; Henson 1993).

Carbon stored in rachis biomass, including petioles, increased from 1.9 to 4.1, 6.5 and 10.0 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations, respectively. These values are comparable to those reported by Khalid *et al.* (1999a) for a 23-year-old oil palm plantation (110.5-127.9 kg palm<sup>-1</sup> equivalent to 6.2-7.2 Mg C ha<sup>-1</sup>) and those reported by Rees and Tinker (1963) for 7- to 22-year-old oil palm plantations (42.7-101.8 kg palm<sup>-1</sup> equivalent to 2.4-5.7 Mg C ha<sup>-1</sup>). The relative contribution of the rachis biomass C to the crop aboveground C stock was considerably high in the early stage of the plantation. It was 20.7% in the 3-year-old plantation and dropped to only 11.2% in the 10-year-old plantation as the other compartments of the crop developed, especially trunk and frond base. Nevertheless, there was an increase in the contribution of rachis biomass C of the older plantations (15.7 and 18.1% for the 20- and 30-year-old plantations, respectively). A similar contribution through rachises (17.6-20.4%) of a 23-year-old oil palm plantation in Malaysia was reported by Khalid *et al.* (1999a) and 12.9-22.2% of 7- to 22-year-old plantations by Rees and Tinker (1963).

Leaflet biomass C increased from only 0.6 Mg ha<sup>-1</sup> (3-year-old plantation) to 2.1 Mg ha<sup>-1</sup> (10-year-old plantation), then fluctuating between 1.9 Mg ha<sup>-1</sup> (20-year-old plantation) and 2.8 Mg ha<sup>-1</sup> (30-year-old plantation). These figures are comparable to those of 7- to 22-year-old oil palm plantations of 24.7-48.5 kg palm<sup>-1</sup> equivalent to 1.4-2.7 Mg C ha<sup>-1</sup> (Rees and Tinker 1963) and of a 23-year-old plantation of 7.9 Mg ha<sup>-1</sup> equivalent to 3.3 Mg C ha<sup>-1</sup> (Khalid *et al.* 1999a). However, the relative contribution of leaflet biomass C was somewhat low, ranging from 4.6-6.8%. Compared to the 9.3% reported by Khalid *et al.* (1999a) and the 8.0-12.8% reported by Rees and Tinker (1963), these values are somewhat lower.

Biomass C of the other components (spear, cabbage and inflorescences) increased from only 0.6 to 0.9, 0.7 and 1.0 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantation systems, respectively. The relative contribution of these components was rather high in the early stage of the plantations. It was 6.0% for the 3-year-old plantation, decreasing to 2.4% for the 10-year-old plantation and only 1.8% for the 20-

and 30-year-old plantations. Khalid *et al.* (1999a) reported a slightly higher value for a 23-year-old oil palm plantation in Malaysia (3.2%).

Root biomass C was 4.8, 6.5, 11.1 and 14.4 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations, respectively. Compared to the root biomass of a 23-year-old oil palm of 16.0 Mg ha<sup>-1</sup> equivalent to 6.6 Mg C ha<sup>-1</sup> reported by Khalid *et al.* (1999b) and that of a 27.5-year-old oil palm of 17.8 Mg ha<sup>-1</sup> equivalent to 7.4 Mg C ha<sup>-1</sup> reported by Corley *et al.* (1971), the values for the mature oil palm were considerably high. However, instead of to a depth of 5 m as in this study, Khalid *et al.* (1999b) defined the root biomass to a depth of 60 cm and Corley *et al.* (1971) to a depth of 90 cm. The biomass C of the oil palm roots to a depth of 90 cm in this study was 3.2, 4.2, 7.5 and 10.0 Mg ha<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations, respectively. These figures are quite comparable to the findings of Khalid *et al.* (1999b) and Corley *et al.* (1971). Sommer *et al.* (2000) reported quite similar values for a 9-year-old oil palm plantation in Eastern Amazon (6.0 Mg ha<sup>-1</sup> 6m<sup>-1</sup>). Biomass C of roots contributed 13.8-33.1% and, together with that of the trunk base, produced 22.2-37.2% of the total crop biomass C. Individual values were 29.1, 13.1, 17.0 and 17.0% for the 3-, 10-, 20- and 30-year-old plantations, respectively, which, together with trunk base, gave 32.6, 21.1, 25.5 and 25.7% of the biomass C for the 3-, 10-, 20- and 30-year-old plantations, respectively. The low contribution of the belowground biomass C of the 10-year-old plantation was due to the accumulation of the frond base biomass; there was no abscission of the frond bases in the 10-year-old plantation in this study. Since belowground biomass C may contribute significantly to the total biomass C – in this study it was more than 20% of the total biomass C without abscission of the frond bases and more than 25% with regular abscission – incorporation of belowground biomass C in studies of C stock and budget is of utmost importance.

There was a persistent increase with age in the C accumulated in both below- and aboveground biomass of the oil palm plantations. However, aboveground biomass C was logarithmically correlated with age, while belowground biomass C was linearly correlated (Figure 5.8). A similar trend was observed in Malaysia by Nordin (2002).

As elaborated above, there was a strong dependency of C sequestration in the biomass of the oil palm plantations with plantation age. This suggests that, if biomass data are lacking, estimation of biomass C based on plantation age is quite credible.

Estimation of belowground biomass C with an allometric equation is strongly recommended, since data on belowground biomass are very limited, due mainly to the difficulty in its quantification, as quantifying belowground biomass is not only labor intensive and time consuming but also costly. If sufficient information on aboveground biomass C is available, estimating belowground biomass C with a factor of 0.2 of the total biomass C if there is no pronounced abscission of the frond bases or 0.25 if the frond bases are intensively detached is recommended.

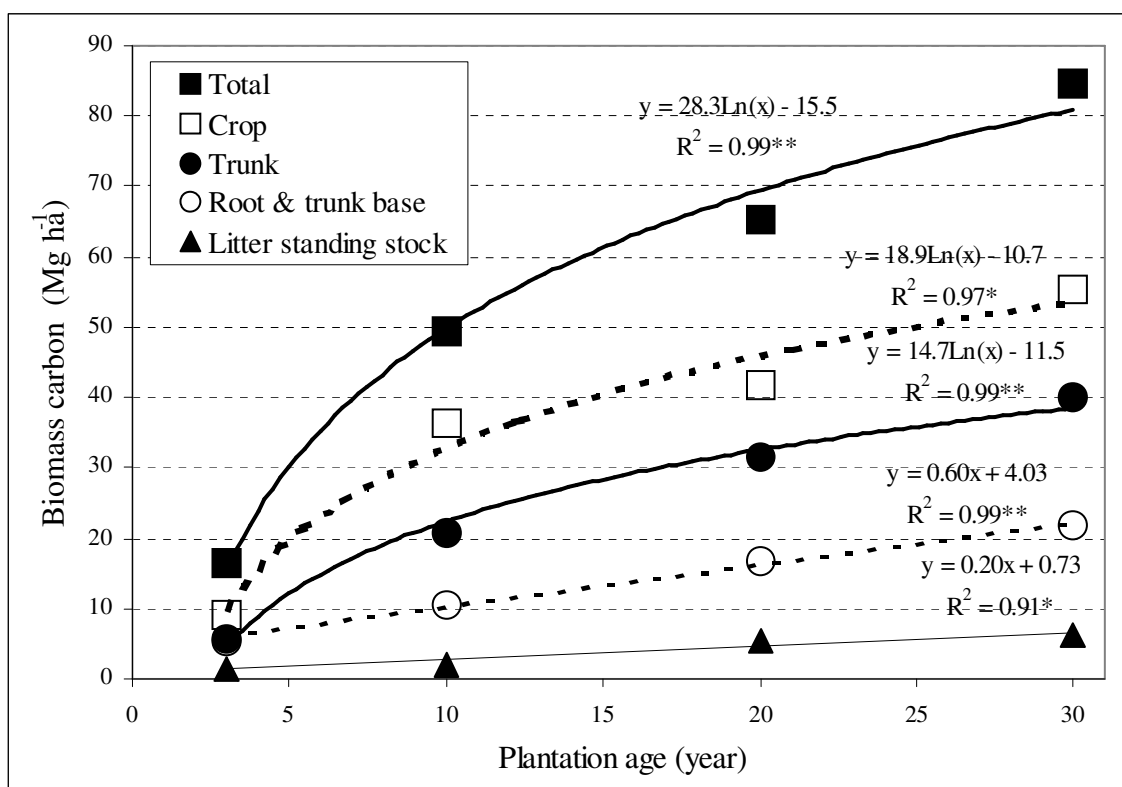


Figure 5.8: Trend of relation of biomass of oil palm compartments with the age of the plantations in Sumatra, Indonesia

The rate of biomass C accumulation of the system was 5.5, 4.9, 3.3 and 2.8 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the 3-, 10-, 20- and 30-year-old plantations and the overall weighed average 3.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>. In comparison with the value reported by ISME (2000) of 5.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>, the annual rate of biomass C accumulation in this study was somewhat lower. However, depending on how this rate is calculated, i.e., without weighing, the annual rate of biomass accumulation would come to 4.1 Mg ha<sup>-1</sup> yr<sup>-1</sup> and, employing the



assumption of a C content of 50%, increase the estimation of the biomass C accumulation to 5.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>.

#### 5.3.4 Soil carbon distribution

Soil C content of the systems varied highly depending on site, vegetation type, plantation age, spatial position and depth; all factors had a highly significant effect on soil C content ( $p < 0.001$ ). Although the values for the plantations in Sumatra and East Kalimantan differed, the vertical trend was similar (Figure 5.9). The effect of vegetation type, plantation age and spatial position (distance to closest trunk) on soil C content was primarily associated with the effect of the fine root biomass of the system. This is demonstrated by the high correlation between fine root (tertiary and quaternary roots) biomass of the system and soil C content ( $r^2 = 0.69-0.87$  and  $p < 0.001$ ). However, the correlation between fine root (tertiary and quaternary roots) biomass and soil C content of the younger plantations (3-year-old) was rather weak for the plantations in East Kalimantan ( $r^2 = 0.52$  and  $p < 0.001$ ), and there was no correlation for the 3-year-old plantation in Sumatra ( $r^2 = 0.04$  and  $p = 0.32$ ).

This suggests that the effect of roots in the younger plantations on soil C content was significantly held back by other factors, such as changes in soil temperature, moisture and disturbances in soil structure during the establishment of the plantation. A slight increase in root biomass from 8.9-12.2 Mg ha<sup>-1</sup> 1 m<sup>-1</sup> for the grassland system to 8.1-16.5 Mg ha<sup>-1</sup> 1m<sup>-1</sup> for the young oil palm plantation was not enough to maintain the level of the soil C content of the plantations.

One of the most important findings in this study is that the vertical distribution of soil C in the oil palm plantations was not the same as that in the *I. cylindrica* grassland system. The oil palm plantation system was apparently able to achieve higher soil C accumulation in the deep soils, either by enhancement of organic C deposition or by inhibition of decomposition of the soil organic matter in the respective soil depth. However, the former seems to be more important. As a consequence of the deep penetration of the roots of oil palm plantations (to a depth of 5 m) compared to the *I. cylindrica* grassland systems (to a depth of only 1.8 m) a substantial amount of organic

C could be deposited in the deep soils, thus increasing the soil organic C of the respective soil depth.

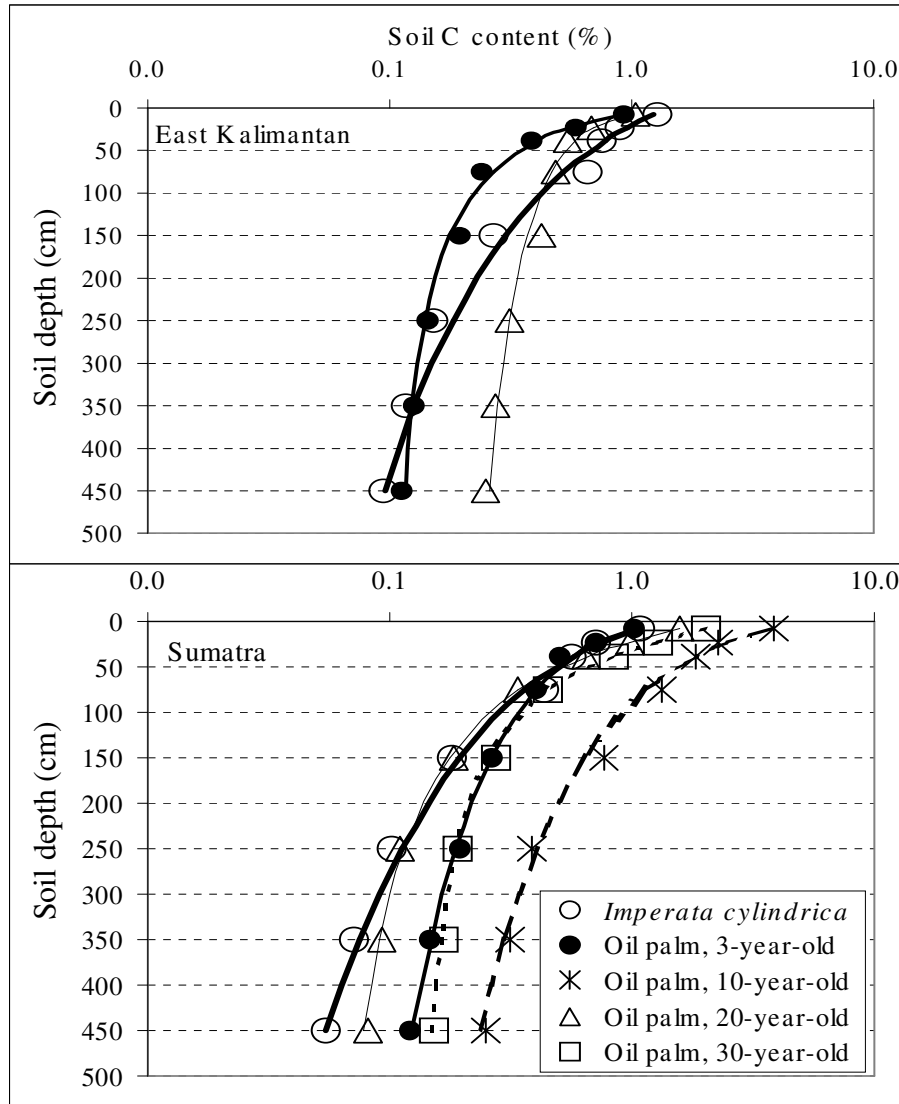


Figure 5.9: Vertical distribution of carbon content of soils in *Imperata cylindrica* grassland and oil palm plantation systems in East Kalimantan (above) and Sumatra (below), Indonesia

Although the C content in the soils in older oil palm plantations was higher than that in *I. cylindrica* grassland, it should, nevertheless, be noticed that there was a significant decrease in the upper soil layers in the younger plantations (3-year-old). This decrease indicates that there were losses in soil organic matter and thus nutrients, either by the more intensive decomposition of the soil organic matter due to changes in soil

moisture and temperature or through surface soil erosion; elimination of the *I. cylindrica* grassland with its dense root mat increases the soil erosion risk, especially on slopes.

The vertical distribution of soil C in both *I. cylindrica* grassland and oil palm plantation systems was quite similar to that reported by Syahrudin (1997) and Ruhayat (1989) in previous studies in the same region. Soil C content of the systems decreased in line with soil depth and was highly depth dependent ( $r^2 = 0.99$  and  $p < 0.001$ ). There was a very marked decrease in soil C content with depth in the upper 50 cm of the soil, which slowed down below this depth. Nevertheless, there was a distinct difference in the vertical soil C distribution between the *I. cylindrica* grassland and oil palm plantation systems. Compared to that in soils in the oil palm plantation system, the decrease in the *I. cylindrica* grassland was less abrupt in the upper 50 cm of the soil, whereas it was more distinct deeper down (see Figure 5.9). This demonstrates the strong influence of fine root biomass on soil C content. On the one hand, the high root biomass and dense root mat in the uppermost soils in the *I. cylindrica* grassland led to a higher C content in the upper soils (on average, root biomass density of the top 15 cm soil in the oil palm plantations of  $2.6 \text{ g cm}^{-3}$  was much lower than that of the *I. cylindrica* grassland of  $6.6 \text{ g cm}^{-3}$ ); on the other hand, the deeper root penetration of the oil palm plantations led to a higher C content in the deeper soils.

Soil C content is the result of litter (above- and belowground) production defined by the vegetation type and development stage of the system, and of the soil respiration, which is controlled by root respiration and decomposition of litter and soil organic matter. Soil physical properties such as texture and structure may also control soil respiration (De Jong and Schappert 1972). Soil temperature and moisture are, however, the most important factors regulating soil respiration (Kicklighter *et al.* 1994; Lloyd and Taylor 1994; Howard and Howard 1993). Conversion of *I. cylindrica* grasslands into oil palm plantations could affect soil C content several ways, such as through changes in the rate of litter production, increase in temperature of the uppermost soils, increase in surface run-off facilitating surface erosion, altered soil horizonization, and modified soil structure and bulk density. Carbon content of the upper soils in the younger plantations (3-year-old at both sites and 10-year-old in East Kalimantan) was significantly lower than that in the *I. cylindrica* grasslands ( $p < 0.001$ ). Biomass production of oil palm plantations is, indeed,

much higher than that of *I. cylindrica* grasslands; however, little of the produced biomass is returned to the soils, especially in the early stages of the establishment of the plantations. The impact of the plantations on the temperature of the uppermost soils could be significant for the younger plantations, as the canopy closure is not yet established and the development of undergrowth is suppressed. Elimination of *I. cylindrica* may reduce the rate of infiltration, causing an increase in surface run-off and surface erosion, which in turn may alter soil horizonisation, structurization and bulk density. The impacts on soil horizonisation and bulk density are summarized in tables 5.8 and 5.9.

It is clear that the establishment of oil palm plantations on *I. cylindrica* grasslands was, in most cases, detrimental to the pedogenesis processes, especially in the early stages of the plantations. This adverse impact was, nevertheless, reversed in later stages. In contrast to the impacts on soil horizonisation, the unfavorable impacts on the soil bulk density of the uppermost soils was retained till the end of the plantation cycle. Since soil fertility plays an important role in determining plant growth and productivity, proper attention should be focused on this subject, otherwise sustainability of the plantation will never be achieved.

Table 5.8: Horizonisation of soils developed under *Imperata cylindrica* grasslands and oil palm plantations in East Kalimantan and Sumatra, Indonesia

Soil depth	East Kalimantan			Sumatra				
	<i>Imperata cylindrica</i>	Oil palm		<i>Imperata cylindrica</i>	Oil palm			
		3-yr-old	10-yr-old		3-yr-old	10-yr-old	20-yr-old	30-yr-old
1	AE	E	EB	AE	E	E	AE	AE
2	E	BE	BE	E	Bt	EB	E	E
3	EB	Bt1	Bt1	EB	Bt2	Bt	Bt1	Bt1
4	Bt1	Bt2	Bt2	Bt1	BC	Bg/BC	Bt2	Bt2
5	Bt2	CB	BC	Bt2			BC	BC
6	BC			BC				

Table 5.9: Bulk density of soils developed under *Imperata cylindrica* grasslands and oil palm plantation systems in East Kalimantan and Sumatra, Indonesia

Soil depth (cm)	East Kalimantan			Sumatra				
	<i>Imperata cylindrica</i>	Oil palm		<i>Imperata cylindrica</i>	Oil palm			
		3-yr-old	10-yr-old		3-yr-old	10-yr-old	20-yr-old	30-yr-old
0-15	1.1	1.3	1.3	1.1	1.2	1.2	1.3	1.2
15-50	1.3	1.4	1.4	1.4	1.3	1.3	1.3	1.3
50-100	1.3	1.5	1.4	1.5	1.4	1.3	1.3	1.4
100-200	1.4	1.4	1.4	1.4	1.3	1.3	1.4	1.4
200-500	1.4	1.4	1.4	1.4	1.2	1.4	1.4	1.5

Soil C storage in this study is in the range of that reported in previous studies (Mackensen 1998; Syahrudin 1997; Bremen *et al.* 1990; Ruhyat 1989). Total C stored in the soils in oil palm plantation systems ranged from 139.2-260.6 Mg ha<sup>-1</sup> 5 m<sup>-1</sup>. These values are somewhat higher than those of primary and secondary forests of 156.0-176.0 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> and the value for a 9-year-old oil palm plantation of 131.0 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> reported by Sommer *et al.* (2000). However, there was an extremely high magnitude of soil C in the 10-year-old plantation in Sumatra (482.4 Mg ha<sup>-1</sup> 5 m<sup>-1</sup>). This reflects the high variation of C sequestration in tropical soils. Nevertheless, this figure does not represent the common magnitude of C stock in most Ultisols in the tropics; the soil C stock to a depth of 1 m of 250.2 Mg ha<sup>-1</sup> in this plantation was very much higher than that reported in previous studies (83.3-95.2 Mg ha<sup>-1</sup>) (Mackensen 1998; Syahrudin 1997; Bremen *et al.* 1990) and is, therefore, excluded in the estimate of the C sequestration rate of the oil palm plantation. The values for the C stored in the soils in *I. cylindrica* grassland varied strongly (from 137.6 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in Sumatra to 188.1 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in East Kalimantan).

Soil C storage is largely dependent on environmental, biogeochemical and land management factors. Different land use and management practices influence soil properties such as soil temperature, moisture, microbial biomass, organic matter and fine root biomass, which in turn affect the magnitude of soil respiration (Lee and Jose 2003; Raich and Tufekcioglu 2000; Kelting *et al.* 1998) and soil C dynamics. Trees could substantially increase the organic matter input into the system through the turnover of leaves and roots (Jose *et al.* 2000). The results in this study show that the conversion of *I. cylindrica* grassland into oil palm plantation considerably increased the amount of soil C stored in the system. However, the C stock in soils in the younger plantation (3-year-old) in East Kalimantan was considerably lower than that of the *I. cylindrica* grassland. However, the C stock to a depth of 3 m in the 3-year-old oil palm plantation in East Kalimantan was lower than that of the *I. cylindrica* grasslands; only at a depth of 0-1 m, it was significantly different (Figure 5.10). The C stock at a depth of 0-1 m in the 10-year-old plantation in East Kalimantan was also lower than that in the *I. cylindrica* grasslands but not significantly different. In contrast to the uppermost soils, the C stock in the deeper soils (1-5 m) in the 10-year-old oil palm plantation in East Kalimantan was significantly higher than that in both *I. cylindrica* grassland and 3-year-

old plantation. The overall C stock to a depth of 5 m of the soils in the oil palm plantations was higher than that of *I. cylindrica* grassland, and the rate of soil C sequestration to a depth of 5 m was 1.8 Mg ha<sup>-1</sup> yr<sup>-1</sup>.

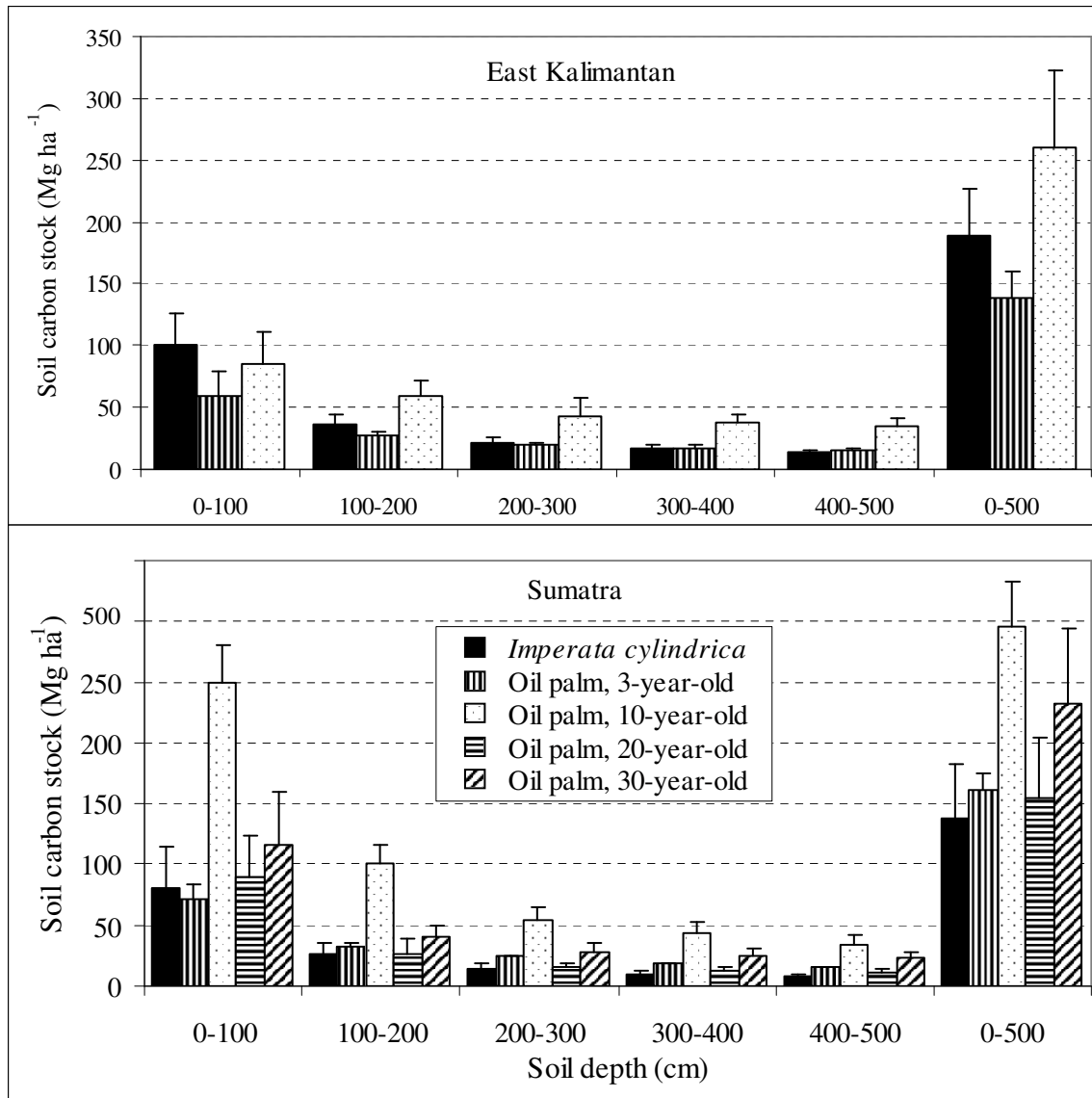


Figure 5.10: Carbon stock of soils in *Imperata cylindrica* grassland and oil palm plantation systems in East Kalimantan (above) and Sumatra (below), Indonesia

In Sumatra, the C stock only in 0-1 m depth in the 3-year-old plantation was lower than that in the *I. cylindrica* grasslands (Figure 5.10). The C stock to the depth 5 m in oil palm plantations of all ages was significantly higher ( $p < 0.001$ ) than that in the

*I. cylindrica* grasslands. On average, conversion of *I. cylindrica* grassland into oil palm plantations led to a soil-C sink of  $2.6 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ . Compared to East Kalimantan ( $1.8 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ ), the value in Sumatra was much higher; this is primarily due to the difference in the soil-C stock at the establishment of the plantation.

Oil palm plantations showed a higher C stock in the deeper soils (1-5 m), which was detected in the early stage of the plantations (3-year-old). In contrast to deeper soils, there was a decrease in the C stock in the upper 1-m soil in the oil palm plantations, especially in the early stage (3-year-old). However, the soil-C stock increased with age to a level that was higher than that of the *I. cylindrica* grasslands.

### 5.3.5 Carbon distribution in oil palm plantation systems

Biomass C of the system increased persistently with plantation age, and there was a strong correlation between biomass C and age of the plantations. Total and aboveground biomass C are highly logarithmically correlated with plantation age ( $r^2 = 0.99$  and  $0.97$ ,  $p = 0.006$  and  $0.015$ , respectively), whereas belowground biomass C is highly linearly correlated ( $r^2 = 0.99$  and  $p = 0.002$ ). These high correlation and probability levels suggest that the models might be applicable to other oil palm plantations elsewhere having similar pedoagroclicmatic conditions. However, in cases where there is sufficient information on aboveground biomass C of the system, estimates of belowground biomass C with a factor of 0.2 of the total biomass C (equivalent to 0.25 of the aboveground biomass C) if there is no pronounced abscission of the frond bases or 0.25 of the total biomass C (equivalent to 0.33 of the aboveground biomass C) if the frond bases are regularly detached from the trunk of the crops are recommended.

The rate of biomass C accumulation in the system was 5.5, 4.9, 3.3 and 2.8  $\text{Mg ha}^{-1} \text{ yr}^{-1}$  for the 3-, 10-, 20- and 30-year-old plantations, respectively, and the overall weighed average was  $3.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ . Total biomass C of the system was 16.6, 49.4, 65.3 and 84.6  $\text{Mg ha}^{-1}$  for the 3-, 10, 30-, 20- and 30-year-old plantations, respectively (Figure 5.11). Compared to the biomass C of the *I. cylindrica* grasslands in the neighborhood of the plantations of 3.0, 2.9 and 5.9  $\text{Mg ha}^{-1}$  for the aboveground, belowground and total biomass C, respectively, it is clear that total biomass C of oil palm plantations already surpasses that of *I. cylindrica* grasslands at a very early stage of the plantation. This suggests that conversion of *I. cylindrica* grassland into oil palm

plantations is beneficial if biomass C accumulation and land rehabilitation are the concerns.

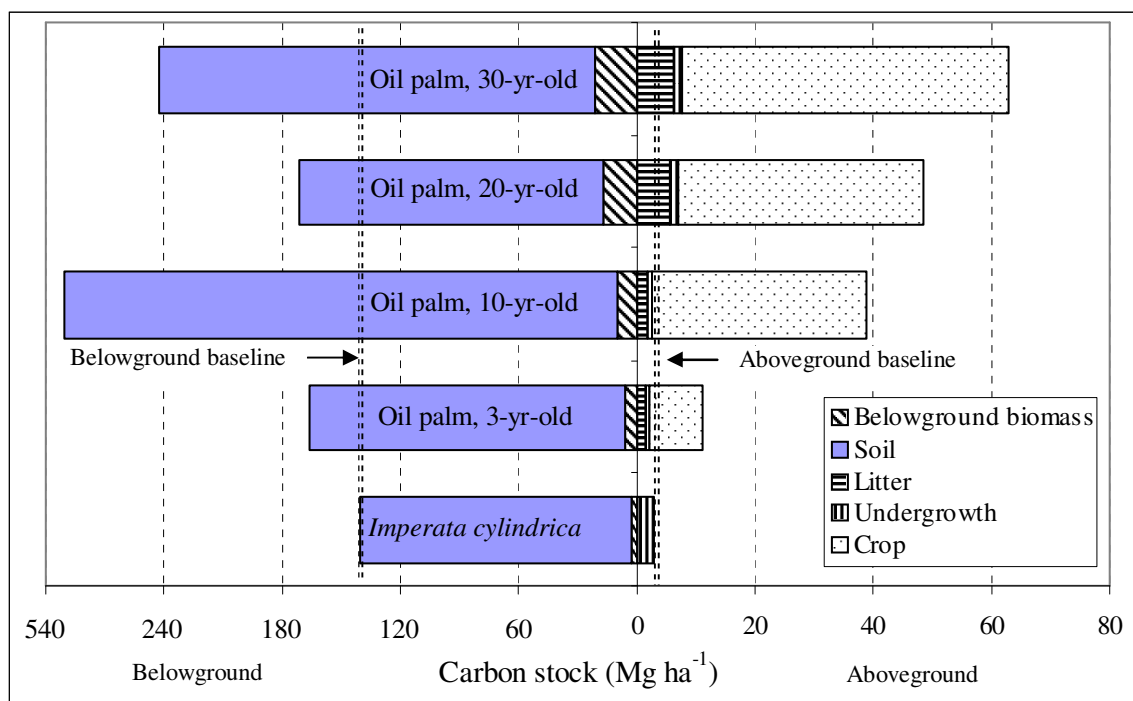


Figure 5.11: Carbon distribution of *Imperata cylindrica* grassland and oil palm plantation systems in Sumatra; belowground carbon stock was defined to depth of 5 m; values for above- and belowground carbon of *Imperata cylindrica* grassland were considered as baseline for the plantations

Of total biomass C, roots and trunk base produced 22.2-37.2%. The crop contributed the highest magnitude of aboveground biomass C (81.9-93.4%) followed by litter standing stock (5.0-13.9%) and undergrowth (1.6-4.2%). Of the crop aboveground biomass C, trunk contributed the highest portion (57.3 to 75.7%) followed by frond base (2.3-23.3%), rachis including petiole (11.2-20.7%) and leaflet (4.6-6.8%). Other compartments, including spear, cabbage and inflorescence, contributed 1.8-6.0% to the total crop aboveground biomass.

The soil-C content was strongly affected by vegetation type, plantation age, spatial position (distance to closest trunk) and depth ( $p < 0.001$ ). However, the effect of vegetation type, plantation age and spatial position on soil-C content was primarily associated with the effect of the fine root biomass; this is demonstrated by the high



correlation between fine root (tertiary and quaternary roots) biomass and soil-C content ( $r^2 = 0.69-0.87$  and  $p < 0.001$ ).

A sizeable amount of soil C could be gained by conversion of *I. cylindrica* grassland into oil palm plantations. The average rate of soil C sequestration was 0.7, 0.4, 0.5, 0.5 and 0.5 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the depths 0-1, 1-2, 2-3, 3-4 and 4-5 m, respectively. A potential soil C sink to depth 5 m of 76.8 Mg ha<sup>-1</sup> could be expected by this conversion. More than 70% of this amount was allocated to the deep soils (1-5 m depth). Together with that sequestered in the biomass of the plantations, a C sink of 178.8 Mg ha<sup>-1</sup> could be achieved. The average rate of soil-C sequestration to a depth of 5 m (2.6 Mg ha<sup>-1</sup> yr<sup>-1</sup>) was lower than the rate in the biomass (3.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>). This may reflect that oil palm assigns little biomass to the belowground compartment of the plantation system.

It is interesting that most of the C stored in the oil palm plantation was allocated to the belowground stock (soil and belowground biomass C); this has been ignored in most previous works due probably to the difficulty in the assessment of this component. The results show that belowground C contributed to more than 93% at the beginning of the plantation (3-year-old) and then declined with age to only 75% in the 30-year-old plantation (Table 5.10). However, the relative contribution of belowground C stock was lower than that of the *I. cylindrica* grassland system (98%).

Table 5.10: Below- and aboveground C-stock distribution in *Imperata cylindrica* grassland and oil palm plantations in Sumatra, Indonesia

System	Belowground		Aboveground biomass	Belowground / total (%)	
	Soil	Biomass (Mg ha <sup>-1</sup> )			
<i>Imperata cylindrica</i>	137.6	2.9	3.0	97.9	
Oil palm	3-year-old	161.2	5.4	11.2	93.3
	10-year-old	482.2	10.4	38.9	92.1
	20-year-old	155.0	16.6	48.6	71.7
	30-year-old	232.4	21.7	62.8	75.3

Belowground C stock was defined to depth of 5 m

#### 5.4 Conclusions

The persistent increase in biomass and biomass C of the oil palm plantation with age suggests that establishment of this plantation in degraded lands such as those infested by *I. cylindrica* weed is an effective tool to promote higher terrestrial C storage.

Although the rooting system of the oil palm plantation was deep, it could only moderately improve the soil C storage compared to *I. cylindrica* grassland. This implies that the plantation allocates only a small portion of the biomass to the belowground production, and thus oil palm plantations are less effective in soil C enrichment.

With a rate of C sequestration in biomass of  $3.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  and in soil of  $2.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ , conversion of *I. cylindrica* grassland into oil palm plantations could increase the terrestrial C storage of  $96.1 \text{ Mg ha}^{-1}$  in biomass alone; together with that sequestered in the soil (to depth of 5 m), a C sink of  $172.9 \text{ Mg ha}^{-1}$  in 30 years could be expected.

6 SUMMARY AND GENERAL DISCUSSION

6.1 Biomass distribution

Biomass production of both *A. mangium* and oil palm plantations increased with plantation age. Although the rate of biomass production of *A. mangium* plantations ( $21.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) was much higher than that of the oil palm plantations ( $8.3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ), due to the short rotation of *A. mangium* plantations (9 years for pulp production but 25-30 years for oil palm), the amount of biomass accumulated at the end of the rotation was quite similar (Figure 6.1).

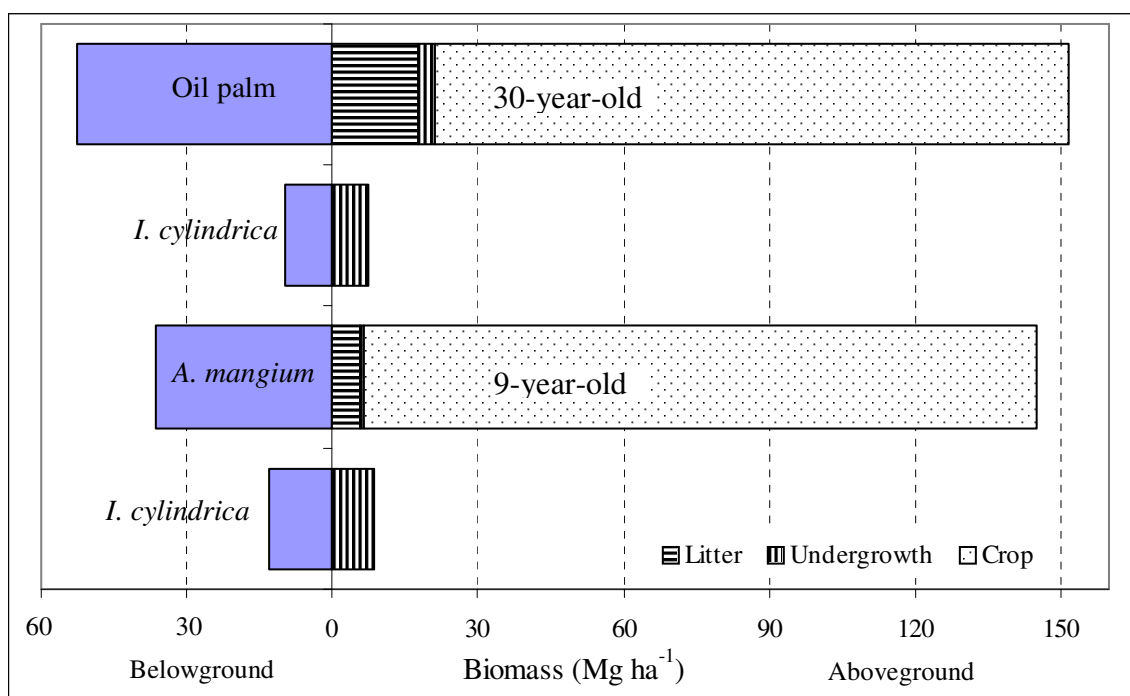


Figure 6.1: Biomass distribution of *Imperata cylindrica* grassland, *Acacia mangium* and oil palm plantations; belowground biomass defined to depth of 5 m for oil palm plantation, 3 m for *Imperata cylindrica* grassland and *Acacia mangium* plantation

In contrast to *I. cylindrica* grassland, the main part of the biomass of these plantations is allocated to the aboveground compartments. Furthermore, at the end of the rotation, the total biomass of the *A. mangium* and oil palm plantations ( $181.2$  and  $204.3 \text{ Mg ha}^{-1}$ , respectively) was much higher than that of the *I. cylindrica* grassland systems near these plantations ( $21.9$  and  $16.9 \text{ Mg ha}^{-1}$ ). This shows clearly that the

conversion of *I. cylindrica* grassland into *A. mangium* and oil palm plantations is highly beneficial if biomass enhancement is to be addressed.

The biomass of the undergrowth in the 9-year-old *A. mangium* plantation (0.8 Mg ha<sup>-1</sup>) was considerably lower than that of the oil palm plantation (3.2 Mg ha<sup>-1</sup>). This is probably related to the dense canopy closure of the *A. mangium* plantation. Although an allelopathic effect of leaf exudates of *A. mangium* has been reported, this low biomass accumulation was more likely the effect of light deficiency, as the undergrowth biomass was higher under the more open canopy of the 4-year-old plantation (12.2 Mg ha<sup>-1</sup>). A wide range of values of undergrowth biomass of fast growing tree plantations has been reported in previous studies with values ranging from 2.9 to 4.6 Mg ha<sup>-1</sup> for *A. mangium* plantations, 2.8 to 5.9 Mg ha<sup>-1</sup> for *Paraserienthes falcataria* plantations, and 2.6 to 18.5 Mg ha<sup>-1</sup> for *Eucalyptus deglupta* plantations (Syahrudin 1997; Ruhiyat 1989).

The litter standing stock accumulated under the *A. mangium* plantations (6.0 Mg ha<sup>-1</sup>) was significantly lower than that under the oil palm plantations (17.9 Mg ha<sup>-1</sup>). The values for fast growing tree plantations reported in previous studies ranged from 10.1 to 13.8 Mg ha<sup>-1</sup> for *A. mangium* plantations, 14.9 to 17.0 Mg ha<sup>-1</sup> for *Paraserienthes falcataria* plantations and 7.0 to 19.5 Mg ha<sup>-1</sup> for *Eucalyptus deglupta* plantations (Syahrudin 1997; Ruhiyat 1989).

The belowground biomass of the *A. mangium* plantations (36.3 Mg ha<sup>-1</sup>) was significantly lower than that of the oil palm plantations (52.4 Mg ha<sup>-1</sup>). However, the relative contribution of belowground biomass to total biomass for the *A. mangium* (20.1%) and oil palm plantations (25.6%) was not significantly different.

## 6.2 Root distribution

Tree root systems are involved in soil-C and nutrient enrichment through root turnover, acting as a safety net by interception of leached nutrients or the physical improvement of compact soil layers (Alongi *et al.* 2004; Suamy *et al.* 2003; Tufekcioglu *et al.* 1999). Root distribution in *I. cylindrica* grassland, *A. mangium* (fine root) and oil palm plantation systems is depicted in Figure 6.2. The fine root biomass of the *A. mangium* plantations ranged from 9.5 Mg ha<sup>-1</sup> 3 m<sup>-1</sup> (in the 1- and 4-year-old plantations) to 12.3 Mg ha<sup>-1</sup> 3 m<sup>-1</sup> (in the 9-year-old plantation). This is quite comparable to the root

biomass of *I. cylindrica* of  $12.4 \text{ Mg ha}^{-1} 3 \text{ m}^{-1}$ . However, the vertical distribution of the root biomass of *I. cylindrica* grassland was restricted to the top shallow soil layer, i.e., the roots were distributed to a depth of 1.8 m in the *I. cylindrica* grassland and up to 3 m in the *A. mangium* plantations. The root biomass of the oil palm plantations in East Kalimantan of  $20.0$  and  $30.3 \text{ Mg ha}^{-1} 3 \text{ m}^{-1}$  for the 3- and 10-year-old plantations, respectively, and that in Sumatra of  $11.4$ ,  $15.3$ ,  $26.3$  and  $34.3 \text{ Mg ha}^{-1} 3 \text{ m}^{-1}$  for the 3-, 10-, 20 and 30-year-old plantations, respectively, was considerably higher than that of the *A. mangium* plantations.

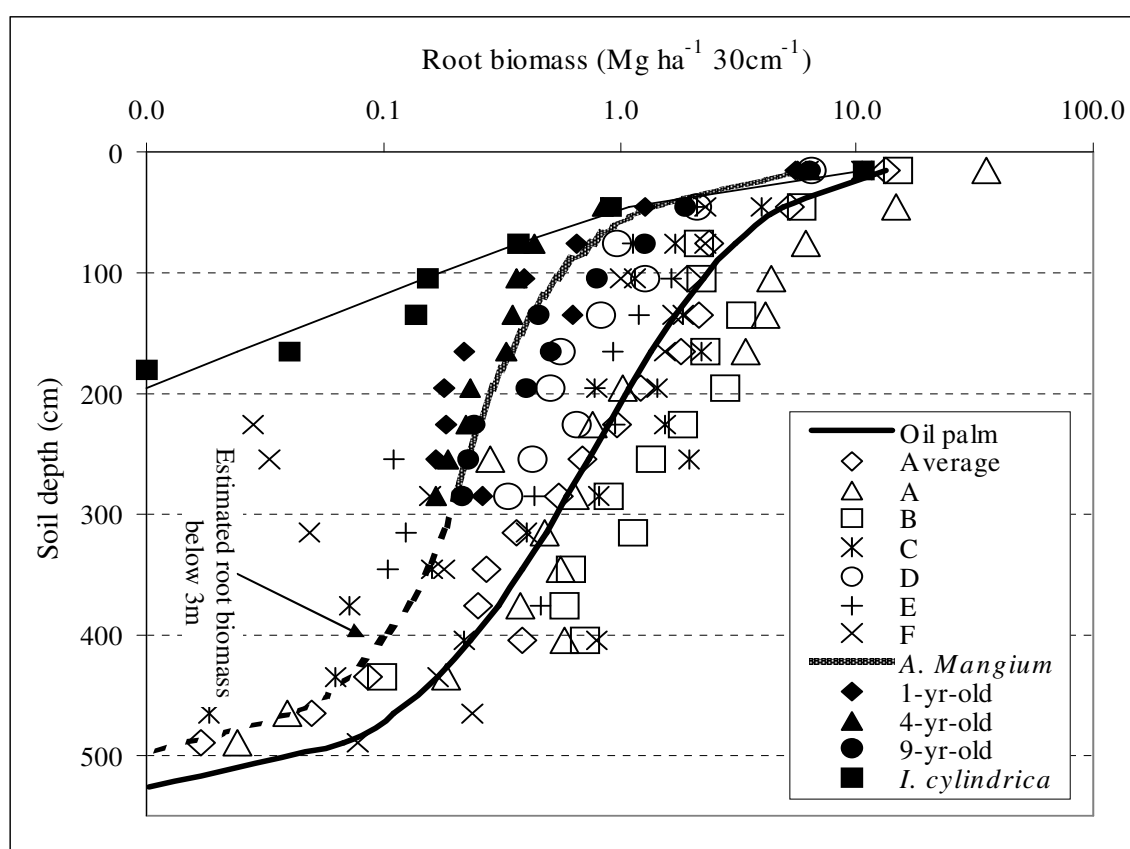


Figure 6.2: Vertical distribution of root biomass in 10-year-old oil palm plantation (to depth of 5 m; A, B, C, D, E and F = 10, 100, 200, 300, 450 and 520 cm from the trunk base), *Acacia mangium* plantation (fine root biomass; to depth of 3 m) and *Imperata cylindrica* grassland (to depth of 3 m)

The fine root biomass showed a continuous decrease with soil depth. In the 5-m deep soil profile, more than 50% of the fine root biomass of the *A. mangium* plantations was concentrated in the top 30 cm of the profile, which was considerably shallower than that of oil palm plantations of 50 cm. However, 50% of the root biomass

of both *A. mangium* and oil palm plantations was still deeper than that of *I. cylindrica* grassland, which was concentrated in the top 10 cm of the soil profile. Furthermore, 90% of the root biomass of *I. cylindrica* was confined to a depth of 41 cm; this was clearly much shallower than that in the *A. mangium* plantations with a depth of 237 cm and that in the oil palm plantations of 227 cm.

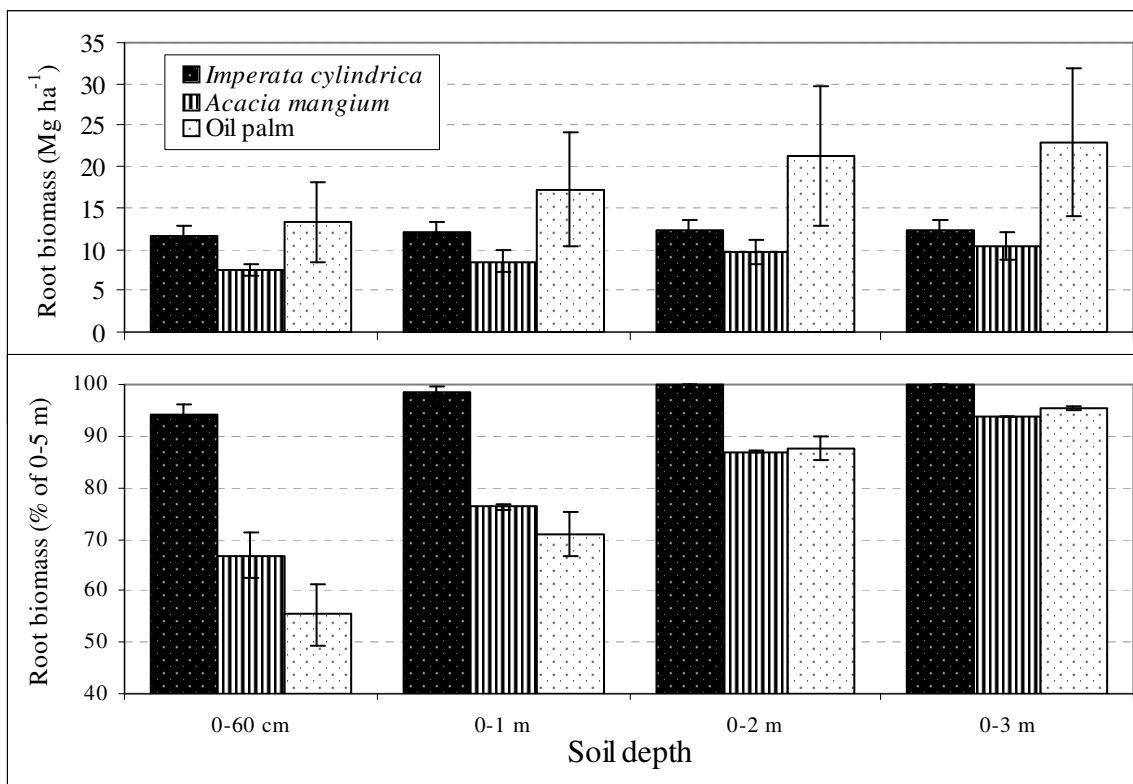


Figure 6.3: Vertical distribution of root biomass of *Imperata cylindrica* grassland, *Acacia mangium* (fine root biomass) and oil palm plantations; columns are means, stake bars are standard deviations

Figure 6.3 shows the distribution of the root biomass with depth. Both absolute (in Mg ha<sup>-1</sup>) and relative (in % of 0-5 m depth) root biomass cumulatively increased with cumulative soil depth. However, the variation of the relative root biomass decreased with the increase of the cumulative sampling depth, while the variation of the absolute root biomass increased or was maintained at a certain level.

The root biomass of *I. cylindrica* was distributed within a depth of less than 2 m (94, 98 and 100% for depths 0-0.6, 0-1 and 0-2 m, respectively). Root biomass of *A. mangium* was sampled to a depth of 3 m, but the established root distribution curve (Figure 6.2)

does not indicate that there are no roots immediately below this depth. The distribution of the roots below 3 m is, therefore, estimated based on the distribution curve of *A. mangium* at a depth of 0-3 m combined with the distribution curve of oil palm at a depth of 0-5 m. Root biomass of the *A. mangium* plantation was 67, 76, 87 and 94% for the depths 0-0.6, 0-1, 0-2, and 0-3 m, respectively. Root biomass of the 30-year-old oil palm plantation was 55, 71, 88 and 95% for the depths 0-0.6, 0-1, 0-2, and 0-3 m, respectively. The established curve for the oil palm plantations indicates that very little root biomass is to be found at a depth of more than 5 m.

Root sampling in the deep soils is time and labor consuming. It was found that when using a manual root sampler, sampling roots to a depth of 1 m took three times as long as sampling to a depth of 60 cm; sampling to a depth of 3 m required 16-20 times more time and labor than for the depth 1m. Sampling to a depth of 5 m took three times longer than for the depth 3 m. A flexible and reliable method for root studies should, therefore, be established.

The results of this study show that there is no great constraint in the estimation of roots of grassland systems, because these roots are mainly (> 98%) concentrated in the topsoil to a depth of less than 1m. However, this is not the case for the oil palm and *A. mangium* plantation systems, where 90% of the root biomass is distributed to a depth of more than 2 m. Given the constraints in root sampling and the coefficient variation of the relative root biomass to a depth of 1 m of less than 10%, root sampling to a depth of 1 m employing a factor of 1.3 and 1.4 to estimate the total root biomass of *A. mangium* and oil palm plantations, respectively, is recommended.

Although the lateral extent of woody roots may exhibit a high degree of plasticity and depend on environmental conditions (Millikin and Bledsoe 1999; Belsky 1994), the results show that the lateral distribution of the root biomass in the plantations (*A. mangium* and oil palm) was species specific and is probably genetically inherited. In contrast to that of the oil palm plantations, lateral distribution of root biomass in the *A. mangium* plantations was not significantly affected by the distance to the closest trunk base. However, in line with previous findings (Purbopuspito and Van Rees 2002; Jose *et al.* 2001; Peter and Lehmann 2000; Jones *et al.* 1998), there was a slight decrease in the horizontal distribution of the fine root biomass in the *A. mangium* plantations with distance to tree base (Figure 6.4), i.e., 9.3 and 7.4 Mg ha<sup>-1</sup> 1m<sup>-1</sup> at a distance of 10 cm

and 212 cm, respectively. Root biomass of the oil palm plantations, which was mostly concentrated at a distance of less than 1 m from the trunk base, is in agreement with former findings (Khalid *et al.* 1999b; Purvis 1956). Values were 30.2, 15.3, 10.0, 7.7, 7.7 and 8.1 Mg ha<sup>-1</sup> 1m<sup>-1</sup> at a distance of 10, 100, 200, 300, 450 and 500 cm from the trunk base, respectively.

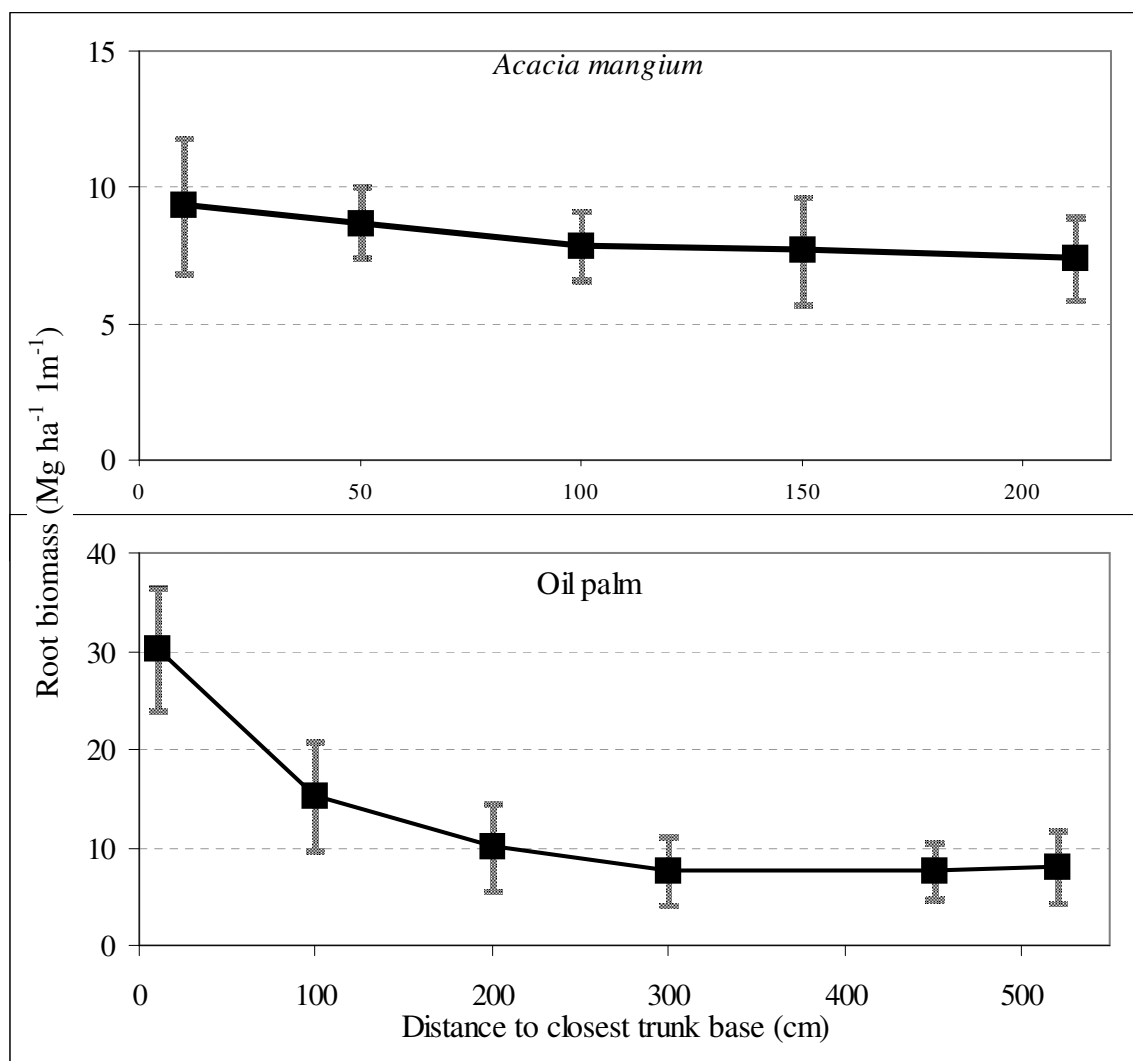


Figure 6.4: Lateral distribution of root biomass of *Acacia mangium* (fine root biomass) and oil palm plantations; rectangles are means, stake bars are standard deviations.



### 6.3 Carbon distribution

The C content of the biomass in the oil palm plantation systems ranged widely from 32.3 to 44.2% (Figure 6.5). However, while the C content of the leaf litter (32.3 %) and tertiary roots, including quaternary roots, (36.6%) was low, that of the other compartments ranged from 39.4 to 44.2%. The weighed average was 41.3%; this figure was used for converting biomass to C stock instead of the value of 50% (Hamburg 2000).

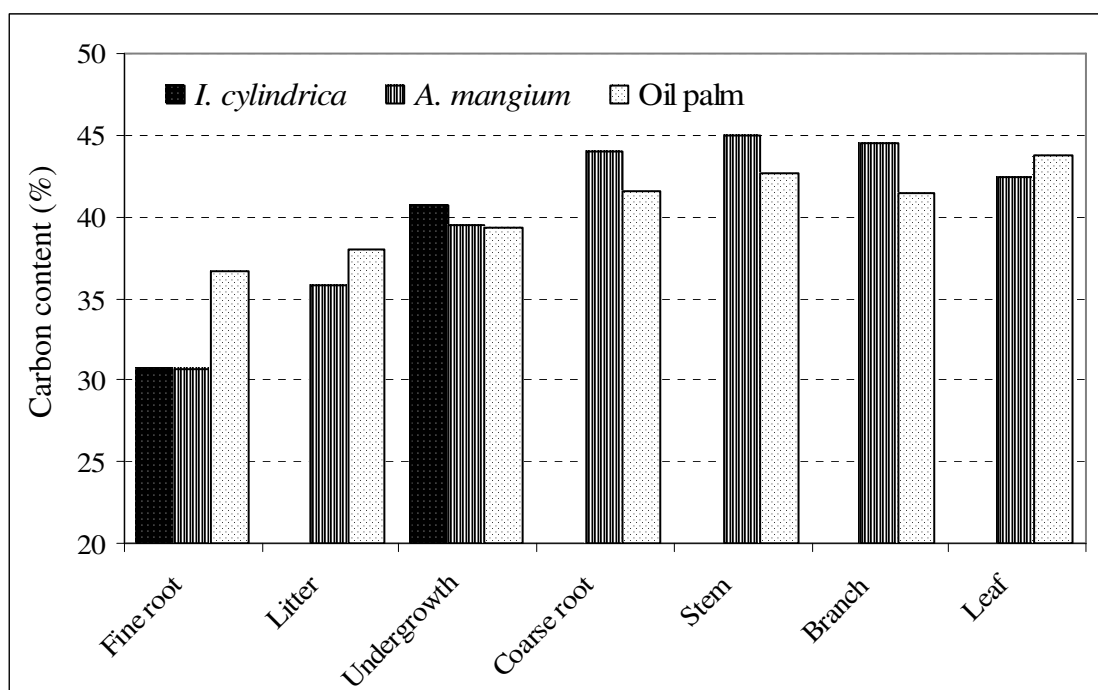


Figure 6.5: Carbon content of compartments of *Imperata cylindrica* grassland, *Acacia mangium* and oil palm plantations; branch = including twig for *Acacia mangium*, including frond base, petiole and rachis for oil palm plantations

The C content of the stand biomass of the *A. mangium* plantations varied from 27.9% to 45.6%, depending on the tree compartment. The C content of the fine root biomass was the lowest (mean of 30.6%) followed by litter standing stock (35.8%) and undergrowth (35.8%). The average C content of the other compartments (coarse root, stem, branch and leaf) ranged from 42.4 to 44.9%. The overall average of the C content of *A. mangium* (43.3%) was slightly higher than that of *I. cylindrica* (35.7%) and oil palm plantation (41.3%). These figures are slightly lower than the 50% proposed by Hamburg (2000). Compared to that of the root biomass of secondary and primary

forests (43.9-46.6%) (Sommer *et al.*, 2000), the C content of root biomass in this study (excluding that of fine root biomass) is quite comparable.

In the plantation systems, C content of fine roots, litter standing stock and leaf biomass of the oil palm plantations was higher than that of *A. mangium* plantations, while that of the remaining compartments (undergrowth, coarse roots, stem and branch) was lower. Excluding the C content of the leaf biomass, the order of magnitude of the *A. mangium* and oil palm plantations was identical, i.e., stem > branch and coarse root > leaf > undergrowth > litter > fine root.

The variability of the C content of litter standing stock and fine root biomass of both *A. mangium* and oil palm plantation systems was considerably higher than that of the other compartments; coefficient of variation was 13.6 and 10.9% for *A. mangium* plantations and 20.4 and 12.0% for the oil palm plantation systems, respectively, while the coefficients of the other compartments (undergrowth, coarse root, stem, branch and leaf) were less than 10%.

Below- and aboveground biomass C of both *A. mangium* and oil palm plantation systems increased persistently in line with age of the plantations. Carbon stored in below- and aboveground biomass of *A. mangium* plantations increased from 3.6 and 6.1 Mg ha<sup>-1</sup> in the early stage of the plantation (1-year-old) to 14.2 and 64.3 Mg ha<sup>-1</sup> at the end of the plantation cycle (9-year-old); this does not differ much from the values for the oil palm plantations, which increased from 5.4 and 11.2 Mg ha<sup>-1</sup> in the early stage of the plantation (3-year-old) to 21.8 and 62.8 Mg ha<sup>-1</sup> at end of the plantation cycle (30-year-old), respectively. At the end of the plantation cycle, the total C stored in the biomass of the *A. mangium* and oil palm plantation systems amounted to 78.5 and 84.6 Mg ha<sup>-1</sup>, respectively. Compared to that stored in the biomass of the *I. cylindrica* grasslands of 7.5, 4.0, 3.6 Mg ha<sup>-1</sup> for total, below- and aboveground biomass C, respectively, it is clear that the biomass C accumulated in both *A. mangium* and oil palm plantation systems already surpassed that of *I. cylindrica* grassland in the early stage of the plantation.

The rate of C sequestration in the biomass of the *A. mangium* plantations (9.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>) was remarkably higher than that of the oil palm plantation (3.4 Mg ha<sup>-1</sup> yr<sup>-1</sup>). However, due to the length of the plantation cycle, i.e., 9 years for *A. mangium* plantations for pulp production and 25-30 years for commercial oil palm plantations, at

the end of the plantation cycle, the magnitude of biomass C was similar (Figure 6.6). These rates are also higher than those of riparian poplars ( $2.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) (Tufekcioglu *et al.* 2003).

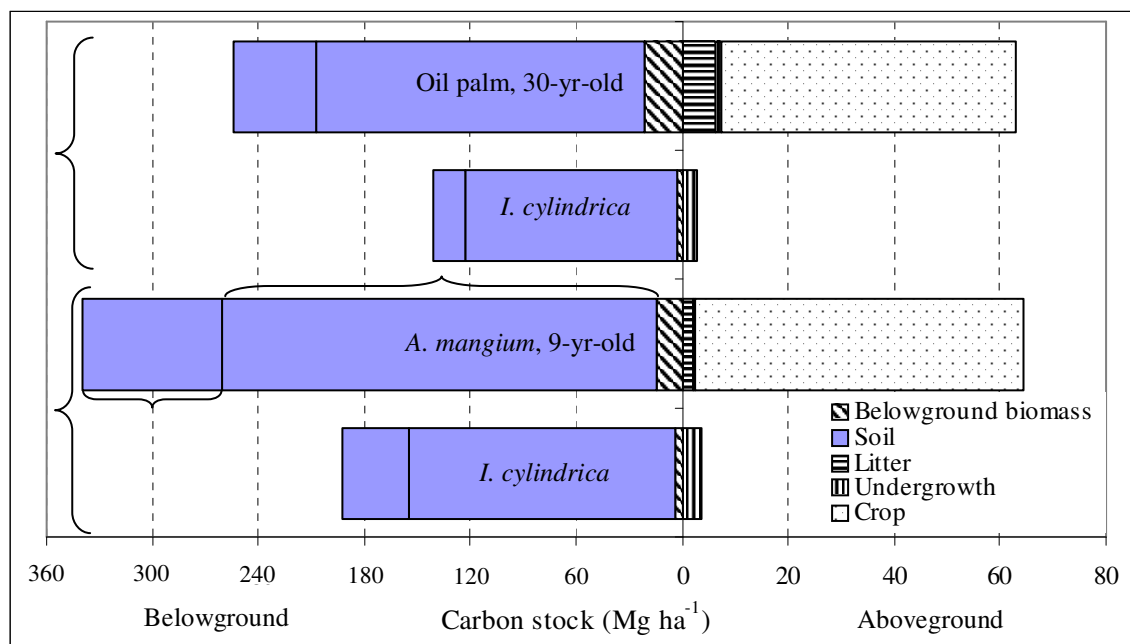


Figure 6.6: Carbon stock distribution of *Imperata cylindrica* grassland, *Acacia mangium* plantation and oil palm plantation systems

Of the total biomass C, belowground biomass C was 38.1, 20.1 and 20.0% for the 1-, 4-, and 9-year-old *A. mangium* plantations, respectively, equivalent to a root-shoot ratio (below-aboveground ratio) of 61.4, 25.2 and 25.0%, respectively. This high contribution of belowground biomass C in the early stage of the plantations was mainly due to the fast development of the fine roots in the beginning of the plantation cycle. It was maintained in a narrow dynamic range of magnitude until the end of the plantation cycle.

Belowground biomass C of the oil palm plantations gave 32.6, 21.1, 25.5 and 25.7% of the total biomass C equivalent to a root-shoot ratio (below-aboveground ratio) of 48.4, 26.7, 34.2 and 34.6% for the 3-, 10-, 20- and 30-year-old plantations, respectively. The low contribution of belowground biomass C of the 10-year-old plantation was due to the accumulation of frond base biomass; there was no abscission of the frond bases in the 10-year-old plantation in this study.

## Summary and general discussion

Since belowground biomass C may contribute significantly to the total biomass C of the plantation systems (in this study it was more than 20% in both systems), incorporation of belowground biomass C in studies of C stock and budget is of utmost importance. However, due to the difficulty in determining belowground biomass, it is proposed to estimate the magnitude of belowground biomass C from that of aboveground of the system. Estimation of belowground biomass C with a factor of 0.25 of the aboveground biomass for *A. mangium* plantations, of 0.25 for oil palm plantations if there is no pronounced abscission of the frond bases, or of 0.33 if the frond bases are regularly detached, is recommended.

Table 6.1: Aboveground biomass, C storage and C sequestration rate of plantation systems in different regions in the tropics

Plantation	Age (year)	Biomass (Mg ha <sup>-1</sup> )	Carbon (Mg ha <sup>-1</sup> )	C sink rate (Mg ha <sup>-1</sup> yr <sup>-1</sup> )	Site	Reference
<i>Paraserienthes falcata</i>	4	69.5	31.3	7.8	Philippines	Kawara <i>et al.</i> 1981
	5	87.4	37.8*	7.6	East Kalimantan	Ruhyat, 1989
	5	75.6	34.0	6.8	Philippines	Kawara <i>et al.</i> 1981
	7	96.4	43.4	6.2	Philippines	Kawara <i>et al.</i> 1981
	9	108.2	48.7	5.4	Philippines	Kawara <i>et al.</i> 1981
	10	111.5	48.3*	4.8	East Kalimantan	Ruhyat, 1989
	9	90.1	39.0*	4.3	East Kalimantan	Ruhyat, 1989
<i>Gmelina arborea</i>	9	120.7	54.3	6.0	Philippines	Kawara <i>et al.</i> 1981
	7	85.7	38.6	5.5	Philippines	Kawara <i>et al.</i> 1981
	9	87.4	39.3	4.4	Philippines	Kawara <i>et al.</i> 1981
<i>Tectona grandis</i>	5	49.6	21.5*	4.3		De Angelis <i>et al.</i> 1981
<i>Eucalyptus grandis</i>	4		63.7	15.9	North Sumatra, Indonesia	Retnowati 1998
<i>E. deglupta</i>	9	114.9	49.8*	5.5	East Kalimantan	Ruhyat, 1989
	7	89.0	38.6*	5.5	East Kalimantan	Ruhyat, 1989
	4	49.3	21.4*	5.3	East Kalimantan	Syahrudin, 1997
	6	65.3	28.3*	4.7	East Kalimantan	Syahrudin, 1997
	9	94.1	40.7*	4.5	East Kalimantan	Ruhyat, 1989
	5	47.4	20.5*	4.1	East Kalimantan	Ruhyat, 1989
<i>E. nitens</i>	5	72.6	31.4*	6.3	New Zealand	Oliver <i>et al.</i> , 1984
<i>E. saligna</i>	4	38.5	16.7*	4.2	New Zealand	Krapfenbauer and Andrea, 1989
<i>E. urograndis</i>	4.5	40.4	17.5*	3.9	North Amazon, Brazil	Spangenberg, 1994
<i>Acacia mangium</i>	4	64.8	28.5	7.1	East Kalimantan	This study
	9	139.2	62.1	6.9	East Kalimantan	This study
Oil palm	3	22.9	9.6	3.2	Sumatra	This study
	10	87.9	37.0	3.7	Sumatra	This study
	20	102.0	43.1	2.2	Sumatra	This study
	30	133.9	56.6	1.9	Sumatra	This study

\* Values were computed from aboveground biomass with a factor of 0.43.

Aboveground biomass C of plantations in the tropics ranges widely depending primarily on the plantation species (Table 6.1). *Acacia mangium* and *Paraserienthes falcataria* plantations are among the most productive plantations with regard to aboveground biomass and C accumulation. However, the rate of biomass and C accumulation of *Paraserienthes falcataria* declines sharply in the older plantations. There was a very high rate of aboveground biomass C sequestration of a 4-year-old *Eucalyptus grandis* plantation in North Sumatra, Indonesia, of 15.9 Mg ha<sup>-1</sup> yr<sup>-1</sup> (Retnowati 1998). This is twice as much as the values for *A. mangium* of 6.9 – 7.1 Mg ha<sup>-1</sup> yr<sup>-1</sup>. In contrast to the high annual net primary production of oil palm plantations, ranging from 11.9 Mg ha<sup>-1</sup> yr<sup>-1</sup> in Sumatra (Setyo *et al.* 1999; Lamade and Setyo 2002) to 20.1 Mg ha<sup>-1</sup> yr<sup>-1</sup> in Malaysia (Henson and Chai 1997; Henson 1998), the rate of the accumulation of the aboveground biomass C of oil palm, ranging from 1.9 to 3.7 Mg ha<sup>-1</sup> yr<sup>-1</sup> was the lowest among the plantations. This is primarily due to the removal of the harvested biomass, which can amount to 20-42% (Setyo *et al.* 1999; Lamade and Setyo 2002; Henson and Chai 1997; Henson 1998).

Compared to that of natural forests (Table 6.2), the aboveground biomass C density of plantations is much lower. This implies that if C sequestration is the concern, plantations should be established in non-forested areas or those with a low viability of natural succession.

Table 6.2: Aboveground biomass and C density of natural forests in different regions in the tropics

No	Biomass (Mg ha <sup>-1</sup> )	C Density	Site	Reference
1	406	175.8	Brazil	Klinge 1976
2	357	154.6	Caparo, Venezuela	Hase 1981
3	460	199.2	East Kalimantan, Indonesia	Ruhiyat 1989
4	390	168.9	Indonesia	Hairiah and Sitompul 2000
5	325	140.7	Indonesia	Sitompul and Hairiah 2000
6	254	110.0	Indonesia	Noordwijk <i>et al.</i> 2000
7	264	114.3	Khade, Ghana	Greenland and Kowal 1960
8	316	136.8	Panama	Golley <i>et al.</i> 1975
9	378	163.7	Rio Lara, Panama	Golley <i>et al.</i> 1975
10	276	119.5	Rio Sabana, Panama	Golley <i>et al.</i> 1975
11	265	114.9	Philippines	Kawara <i>et al.</i> 1981

Values for C density were computed from aboveground biomass with a factor of 0.43.

The patterns of soil C distribution vary highly with soil age, soil texture, rainfall, temperature patterns, and vegetation type. The vertical distribution of the soil C of both *I. cylindrica* grassland and *A. mangium* and oil palm plantation systems in this study was quite similar to that of previous studies by Syahrudin (1997) and Ruhayat (1989) for the soils in the same region. The soil C content decreased in line with soil depth and was highly depth dependent ( $r^2 = 0.97$  to  $0.99$  and  $p < 0.001$ ). However, spatial variation was driven by the distribution of the fine root biomass of the system:  $r^2 = 0.83$ - $0.99$  and  $p < 0.001$  for the *A. mangium* plantations and  $r^2 = 0.69$ - $0.87$  and  $p < 0.001$  for the oil palm plantations. Soil C content decreased sharply in the upper 50 cm of the soils and more gradually deeper down. Nevertheless, a distinct difference in vertical soil C distribution between *I. cylindrica* grassland and *A. mangium* and oil palm plantations was observed. Compared to *A. mangium* and oil palm plantations, the decrease in the soil C content under *I. cylindrica* grassland was less abrupt in the upper 50 cm of the soils and more distinct in the lower part of the soil profile. This difference seemed to be governed by the difference in fine root distribution. On one hand, a high root biomass and dense root mat in the top layer of the soils under *I. cylindrica* grassland led to a higher C content ( $6.6 \text{ g dm}^{-3}$ ) in the first 15-cm depth compared to the *A. mangium* plantations ( $2.6 \text{ dm}^{-3}$ ) and the oil palm plantations ( $3.4 \text{ dm}^{-3}$ ); on the other hand, deeper root penetration in the *A. mangium* and oil palm plantations led to a higher C content in the deeper soils.

Soil C storage in this study is in the range of that reported in previous studies (Mackensen 1998; Syahrudin 1997; Bremen *et al.* 1990; Ruhayat 1989). Total C stored in the soils in the *A. mangium* plantations ( $210.4 - 325.5 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ ) was considerably higher than that in the oil palm plantations ( $139.2 - 260.6 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ ). These values are somewhat higher than those of primary and secondary forests ( $156.0 - 176.0 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ ) and a 9-year-old oil palm plantation ( $131.0 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ ) reported by Sommer *et al.* (2000). However, there was an incredibly high magnitude of soil C in the 10-year-old plantation in Sumatra ( $482.4 \text{ Mg ha}^{-1} 5 \text{ m}^{-1}$ ). This reflects the high variation of C stock in tropical soils. This figure, however, does not represent the common magnitude of C stock in most Ultisols in the tropics; the soil C stock to a depth of 1 m in the 10-year-old oil palm plantation ( $250.2 \text{ Mg ha}^{-1}$ ) was very much higher than that reported in previous studies ( $83.3$ - $95.2 \text{ Mg ha}^{-1}$ ) (Mackensen 1998;

Syahrinudin 1997; Bremen *et al.* 1990) and is, therefore, excluded in the estimate of the C sequestration rate of the oil palm plantations. There was a wide range of C stored in the soils under the *I. cylindrica* grasslands (ranging from 137.6 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in Sumatra to 188.1 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> in East Kalimantan).

Soil C storage is largely dependent on environmental, biogeochemical and land management factors. Different land use and management practices influence soil properties such as soil temperature, moisture, microbial biomass, organic matter and fine root biomass, which in turn affect the magnitude of soil respiration (Lee and Jose 2003; Raich and Tufekcioglu 2000; Kelting *et al.* 1998) and soil C dynamics. Trees can substantially increase the organic matter input into the system through the turnover of leaves and roots (Jose *et al.* 2000). The results in this study show that the conversion of *I. cylindrica* grassland into *A. mangium* and oil palm plantations considerably increased the amount of soil C. On average, the rate of soil C accumulation in the *A. mangium* plantations (2.3, 4.0, 4.2 and 6.9 Mg ha<sup>-1</sup> yr<sup>-1</sup>) was much higher than that of the oil palm plantation (0.7, 0.4, 0.5 and 1.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>) for depths 0-100, 100-200, 200-300 and 300-500 cm, respectively. As oil palm plantations do not allocate a large part of the biomass production to the belowground compartment (Lamade and Setyo 2002), a lower soil C sequestration could be expected. An increase in soil-C accumulation (0-100 cm) from 0.7 to 1.2 Mg ha<sup>-1</sup> yr<sup>-1</sup> by incorporating legume trees into a grass pasture was reported by Tarré *et al.* (2001). Sataye *et al.* (2001) estimated an increase in soil C of 0.5 to 3.0 Mg ha<sup>-1</sup> yr<sup>-1</sup> in forest plantations in the tropics. A rate of soil organic matter sink of 1.1 Mg ha<sup>-1</sup> yr<sup>-1</sup> was reported by Lugo *et al.* (2004) for restored neotropical forest systems in Puerto Rico. The C sink in the first 1-m depth in this study is still in the range of the above-mentioned studies. To depth of 5 m, the rate of soil C sequestration in the *A. mangium* and oil palm plantations systems reached 17.5 and 2.6 Mg ha<sup>-1</sup> yr<sup>-1</sup> contributing to 157.7 and 76.8 Mg ha<sup>-1</sup> soil C for the entire plantation cycle, respectively (Figure 6.6).

It was, however, observed that there was a slight decrease in soil C storage at a depth of 0-100 cm during the early stages of both *A. mangium* and oil palm plantations. This may relate to the lower litter production in this stage. Nevertheless, the deeper soils experienced enrichment of C storage from the very beginning of the plantations.

It is interesting that the conversion of *I. cylindrica* grassland into *A. mangium* plantation led to a much higher amount of C sequestered in the deep soils than in the upper layers. In contrast, conversion of *I. cylindrica* grassland into oil palm plantation led to a higher amount of C sequestered in the upper soils (0-1 m). The results show that the soil C stock at a depth of 0-1 m represents only 36.1% and 46.7% of the total soil-C stock (0-5 m depth) of *A. mangium* and oil palm plantation systems, respectively. Compared to that of the *I. cylindrica* grassland system of 56.1%, there is no doubt that the conversion of *I. cylindrica* grassland into plantations improves the C sink in deep soils (1-5 m). This finding is in contrast to the proposed soil-C change measurement in forestry offset projects to a depth of only 1 m (Hamburg 2000). While most previous soil-C studies concentrate on the upper soil layers down to a maximum depth of 2 m (Tufekcioglu *et al.* 2003; Tarré *et al.* 2001; Brown and Lugo, 1990; Fisher *et al.*, 1994; Moraes *et al.*, 1995), the results confirm the findings of Sommer *et al.* (2000), Trumbore *et al.* (1995) and Nepstad *et al.* (1994), which show the importance of root penetration in deep soil layers for C sequestration. Moreover, the C sequestered in deep soils could be more beneficial than that sequestered in shallow soils, because soil organic matter in deep soils is more resistant to decomposition and thus has a longer resident time (Gaudinski *et al.* 2000; Van Dam *et al.* 1997).

Together with the C sequestered in the biomass of the plantations, a magnitude of soil-C sequestration during the whole plantation cycle of *A. mangium* (9 years) and oil palm (30 years) of 236.3 and 161.4 Mg ha<sup>-1</sup>, or an average rate of 26.8 and 6.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>, respectively, could be achieved. Of these amounts, 72.7 and 61.1% were assigned to the belowground C pool (soil and belowground biomass C). Thus, 81.2 and 76.9% of the total C of the *A. mangium* and oil palm plantations, respectively, were stored to depth 5 m. However, compared to the *I. cylindrica* grassland system (98.0%), the relative contribution of belowground C of *A. mangium* and oil palm plantations was much lower.



## 7 CONCLUSIONS AND RECOMMENDATIONS

### 7.1 Conclusions

*Imperata cylindrica* grassland stored only a small amount of biomass C (5.9 – 7.6 Mg ha<sup>-1</sup>) implying that conversion of this grassland into a biomass- and C-rich system is a promising tool for the building of the terrestrial C. Moreover, due to the root distribution pattern of this grassland, i.e., most of the roots were concentrated in the upper centimeters of the soil, only a small amount of C could be stored in the deep soils. Furthermore, although there was a dense mat of rhizomes in the top centimeters of the soil under the *I. cylindrica* grasslands, the magnitude of C stored in the uppermost soils was only moderate. Hence, if C sequestration is the concern, conversion of this grassland into a system promoting higher biomass accumulation and deep root penetration is of great interest.

Both oil palm and *A. mangium* plantations could sequester much more C than *I. cylindrica* grassland. However, although the magnitude of biomass C in these plantations was quite comparable (at the end of the plantation cycle it was 78.5 Mg ha<sup>-1</sup> in the *A. mangium* and 84.4 Mg ha<sup>-1</sup> in the oil palm plantations), due to the longer sequestration period (plantation cycle of 9 years for the *A. mangium* and 30 years for the oil palm plantations), the rate of C sequestration in the biomass of the oil palm plantation was much lower (9.3 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the *A. mangium* and 3.4 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the oil palm plantations).

The roots of both plantations penetrate to deep soils; however, due to the different nature of the roots and also probably the different allocation strategy of the produced organic constituents combined with the different management practices, significant differences in the soil-C sink of these plantations were determined. The C sink of the *A. mangium* plantation was much larger than that of the oil palm plantation: 157.7 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> or 17.5 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> yr<sup>-1</sup> for the *A. mangium* plantation and 76.8 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> or 2.6 Mg ha<sup>-1</sup> 5 m<sup>-1</sup> yr<sup>-1</sup> for the oil palm plantations.

These differences seemed to affect not only soil-C sink of the systems but also C accumulation pattern. Although the magnitude of biomass C stored in both systems was quite similar, the C accumulated in the biomass of the *A. mangium* plantations,

representing only 29% of the total C sequestered in the system, was much lower than that of the oil palm plantations of 45%.

On average, the total C sink (soil and biomass C) during the whole plantation cycle of *A. mangium* (9 years) and oil palm (30 years) reached a magnitude of 236.3 and 161.4 Mg ha<sup>-1</sup>, equivalent to the average rate of C sequestration of 26.8 and 6.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>, respectively. Of these amounts, 72.7 and 61.1% were assigned to the belowground C pool (soil and belowground biomass C) and, thus 81.2 and 76.9% of the C of the *A. mangium* and oil palm plantations, respectively, were stored to depth of 5 m. However, compared to the *I. cylindrica* grassland system (98.0%), the relative contribution of the belowground C stock of *A. mangium* and oil palm plantations was much lower. These figures demonstrate the importance of the aboveground biomass C in the plantations.

### 7.2 Recommendations

Neither the biomass of the plantations nor that of *I. cylindrica* grassland could reach the 50% C content suggested by former authors (Brown and Lugo 1984; Hamburg 2000). The calculations in this study on the C content of the biomass of *A. mangium* and oil palm plantations came to averages of 43 and 41%, respectively. However, there was a large difference in C content between above- and belowground biomass of *I. cylindrica* grassland (41 and 31%, respectively). Therefore, it is proposed to use these figures for the computation of the biomass C of these systems.

Measurements of the biomass of plantations with destructive sampling methods are lengthy and costly. Therefore, there is a need to develop methods for estimating the biomass of plantations with non-destructive methods. There was a high dependency of the biomass and biomass C of the oil palm plantations on age ( $r^2 > 0.9$ ,  $p < 0.05$ ) (figures 5.2 and 5.8). Biomass and biomass C of the *A. mangium* plantations were highly dependent on the tree diameter of the stand ( $r^2 > 0.9$ ,  $p < 0.001$ ) (Table 4.8). Allometric equations established in this study could be used to estimate both above- and belowground biomass and biomass C of the respective plantations, while belowground biomass could be estimated either with the allometric equation or with the belowground-aboveground ratio described in chapters 4 and 5.

Among the compartments of the biomass of the plantation systems, measurement of the fine root biomass is the most time consuming and labor intensive.

In the oil palm plantations, total belowground biomass and biomass C could be estimated with allometric equations, but this was not the case for the *A. mangium* plantations. Only those of coarse roots of *A. mangium* plantation can be estimated with allometric equations, but not for those of fine roots. The results show that there was a small variation of fine root biomass and biomass C among plantation ages, but the variation within sites was considerably high (see Figure 4.4). This implies that estimation of fine root biomass and biomass C with a small sampling size is subject to high errors. Applying a sample size of 153 auger points resulted in coefficients of variation of  $108.0 \pm 21.0\%$  for within and  $57.1 \pm 22.3\%$  among sites. However, fine root biomass C of *A. mangium* plantations ranging from 2.8 to 3.4 Mg ha<sup>-1</sup> produced less than 5% of the total biomass C of the mature plantation system. Therefore, estimation of fine root biomass C of *A. mangium* plantations with a factor of 0.04 of the total biomass C of the system for the mature plantations or adopting a magnitude of 3.0 Mg ha<sup>-1</sup> for the young plantations is recommended.

The biomass of undergrowth and litter standing stock of *A. mangium* plantations varied widely and there is no simple parameter which could be employed to estimate the magnitude of these compartments. They should, therefore, be measured directly in each specific stand. This also applies to soil C.

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