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THESIS

ABOVE- AND BELOWGROUND BIOMASS AND NET PRIMARY PRODUCTIVITY OF RUBBER PLANTATION (*Hevea brasiliensis* Muell. Arg.)

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A Thesis Submitted in Partial Fulfillment of
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The main objectives are to estimate above and belowgound biomass increments, to study the effects of environment on fine root growth dynamics, and to assess net primary productivity (NPP) of 14-year-old RRIM 600 rubber plantation at Chachoengsao Rubber Research Center from October 2007 to December 2009. Rainfall and its distribution during the two successive years showed strong differences with 1500 in 2008 and 950 mm in 2009. Aboveground and belowground standing biomass were 271.6 t ha^{-1} in 2008 and 35.9 t ha^{-1} in 2009. Approximately 95% of aboveground biomass was in trunk and coarse branches while 61% of belowground biomass was in tap roots. Moreover, 64% of fine, medium and coarse root biomass was in the top 30 cm of soil. Fine root production completely stopped during the dry season and resumed quickly after the first rains. During the rainy seasons, fine root production and the daily root elongation rate were highly variable and exhibited strong annual variations with an average root elongation rate of 0.16 cm day^{-1} in 2008 and 0.12 cm day^{-1} in 2009. The positive correlations found between fine root production, root elongation rate, the appearance of new roots, and rainfall indicated significant impact of rainfall seasonality on fine root dynamics. However, the rainfall patterns failed to explain the weekly variations of fine root dynamics observed during rainy seasons. Total NPP of rubber plantation were 13.68 t ha^{-1} y^{-1} in 2008 and 10.36 t ha^{-1} y^{-1} in 2009, respectively. Aboveground litter ranged from 44% to 51%, aboveground biomass increment varied from 35% to 22%, belowground biomass increment were from 3% to 14% and belowground litter were 9% to 12% of NPP in 2008 and 2009, respectively. Latex production was 9% of NPP in 2008 and 13% in 2009.

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Student’s signature Thesis Advisor’s signature

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LIST OF ABBREVIATIONS

AGB = Above-ground biomass

Ai = The one-side plan area of leaf (cm^2)

$a_{s,j}$ = The parameters to be estimated s represented the stands for a given component j

BGB = Below-ground biomass

$B_{n,j}$ = Fine root biomass after n month of re-growth during sampling period j

b_{sj} = The parameters to be estimated s represented the stands for a given component j

c_{sj} = The parameters to be estimated s represented the stands for a given component j

DBH = Diameter at breast height (cm)

DM = Dry mass

f_m = Function of a set

g = The amount grazed by herbivorous animal during that period

G = Tree circumference

GLA = Gap light analyzer

GPP = Gross primary productivity

h = Tree height (m)

L = Amount of dead material/litter

LAI = Leaf area index

ML = Maximum likelihood

N = The number of days throughout the study period between 1 and 6

NEE = Net ecosystem exchange

$N_{n,j}$ = Fine root necromass after n month of re-growth during sampling period j

NPP = Net primary productivity

P_a = Fine root production of each re-growth period

LIST OF ABBREVIATION **(Continued)**

P_{ij} = Fine root production after i months of regrowth (where i=2,3,6) months after mesh bag installation during season j

R = Respiration

SLA = Specific leaf area

W = Biomass

Wi = The dry weight of leaf (g)

Y = Year

Y_m = The biomass of component m

$Y_{s,i,j}$ = The dry matter of tree i for a given component j in stand s period

$\mu_{i,j}$ = The model expression

θ_m = Independent variables

β_m = A set of parameter

$\varepsilon_{s,i,j}$ = The residual variations not explained by the models

ABOVE-AND BELOWGROUND BIOMASS AND NET PRIMARY PRODUCTIVITY OF RUBBER PLANTATION
(*Hevea brasiliensis* Muell. Arg.)

INTRODUCTION

Tropical forests are disproportionately important in the world carbon budget, representing an estimated 59% of global carbon pool in forests (Dixon *et al.* 1994). Recent estimates based on standard field protocols suggest values larger than 10 MgC ha^{-1} y^{-1} (Clark *et al*., 2001b), and tropical forests may contribute to up to a third of the net primary productivity of terrestrial ecosystems (Field *et al*. 1998)

Large areas of the remaining tropical rainforests are being logged and converted to agricultural systems at high rates (Nepstad *et al*., 1999; Achard *et al*., 2002). Forest conversion together with selective logging in the remaining stands can have a profound effect on the forest carbon cycle (Raich, 1983; Lal, 2005; Jandl *et al*., 2006). Changes in terrestrial carbon stocks have significantly contributed to the increase of greenhouse gases (GHGs) in the atmosphere (Houghton and Hackler, 2001). Land use changes (deforestation-afforestation) are an important driver global C balance and land use systems differ in their ability to sequester carbon depending on the type of vegetation and management practices followed. Perennial tree crops have a greater carbon sequestration potential than annual crops since they function as carbon sinks for a longer period of time.

Tree plantations, like natural rubber (*Hevea brasiliensis)* are interesting, as they provide agricultural products (wood and latex), moreover, they are a forest-like ecosystem that can provide other ecosystem services like water regulation and stock large amount of carbon in their standing biomass and the wood and latex used for diverse long term products constitute an additional carbon sink for decades. To have these services recognized and possibly paid to the farmers, accurate data are requested.

Net primary productivity (NPP) and biomass are two widely used indices in evaluation of the patterns, processes and dynamics of C cycling in forest ecosystems at local, regional and global scales (Melillo *et al.*, 1993; Fang *et al.*, 2001; Luo *et al.*, 2002). Information about net and gross primary productivity (NPP and GPP) is available in forests but it is still scarce in tropical plantations. Our current ability to detect and predict changes in rubber tree productivity is controlled by several limitations. These include a poor understanding of belowground productivity. Some data are available for tree crop plantations such as coconut palm, oil palm, coffee, cocoa, rubber tree etc. (Navarro *et al*. 2007) that occupied over 47 Mha in humid tropics (FAO, 2003). Rubber tree plantations cover 23% (10 Mha) of that area.

Due to the increasing of world natural rubber demand, Thailand plan to increase rubber production by expanding rubber plantation to the North and Northeast with a dryer climate and poor soil fertility, and thus where their sustainability is questioned. Information on NPP and root dynamics would be important for understanding element fluxes in ecosystems and help management of plantations (timing of fertilization, control of understory etc.). Yet fine root dynamics has received little attention, mainly due to methodological difficulties.

Field measurement of rubber plantation was use to estimate above and belowground NPP based on a suite of diverse measurements and underlying assumptions. NPP comprises all materials that together represent: (i) the amount new organic matter that is retained by live plants at the end of the interval, and (ii) the amount of organic matter that was both produced and lost by plants during the same intervals (Clark *et al*. 2001a). Based on this concept, aboveground measurement such as trunk circumference, tree height, tree biomass and the relationship between diameters at breast height and tree components were used to establish the allometric relationship for estimated stand biomass increment. Litter collection used for estimated tree biomass loss during the studying period. Belowground biomass measurement will include fine and coarse root biomass, necromass, production, turnover and dynamics along the growing season.

OBJECTIVES

1. To estimate above and below ground biomass increments during the growing season and the effects of environment on above and belowground dynamics.

2. To assess net primary productivity of mature rubber plantation.

LITERATURE REVIEW

General review of rubber tree

The Para rubber tree (*Hevea brasiliensis Muell . Arg*), often simply called rubber tree, is a tree belonging to the family Euphorbiaceae and the most economically important member of the genus. It is of major economic importance because its sap-like extract (known as latex) can be collected and is the primary source of natural rubber (FAO, 2001).

Hevea brasiliensis is a tropical tree. It is native to the Amazon Basin in Brazil and adjoining countries. *Hevea* was taken from the Amazon to South Asia (Sri Lanka) and South East Asia (Singapore and Malaysia) by the British Colonial Office where it was grown experimentally and later on plantations. Subsequently, cultivation spread to what was then Indochina (Vietnam and Cambodia), the Dutch East Indies (Indonesia) and Thailand, and subsequently to Africa (Liberia, Nigeria, Cote d'Ivoire). Initially cultivation took place on plantations, but smallholders rapidly adopted it as a source of income.

Climatic factors

Hevea brasiliensis is a tropical tree. It grows best at temperatures of 20-28°C with a well-distributed annual rainfall of 1,800-2,000 mm. It grows satisfactorily up to 600 meters above sea level (but is capable of growing much higher - to at least 1000 meters near the Equator), and will perform on most soils provided drainage is adequate. *Hevea* tends to be damaged by high winds. Its required temperature and rainfall define its prime growing area as between the 10° latitudes on either side of the equator, but is cultivated much further north (Guatemala, Mexico and China) and south (Sao Paulo region of Brazil). Further discussion on environmental factors is available.

Maturity

Mature rubber trees on rubber plantations are 20-30 meters high, with graceful upwards-extending branches and a relatively slim trunk. Such trees flower once a year, and after insect cross-pollination produce large fruits containing several thimble-sized seeds with hard outer coats. If satisfactorily germinated and planted within 2-3 weeks, seeds grow to produce seedling plants. Depending on conditions, the latter then take 5-10 years to reach “maturity”, which is defined as the stage when tapping can be started. In practice, this is the time when the trunk has about 500 mm circumference at 1 meter above ground level. Rubber trees usually are tapped by cutting a spiral groove in the bark halfway or more around the stem at the angle of 25^o to 30^o from the horizontal. The latex flows down the groove from the opened latex vessels and is collected at the bottom and flow stops after a few hours because the latex coagulates when exposed to air. Latex yield varies greatly among *Hevea* clones and with tree vigor, season, stand density, age of trees, site and cultural practices (Kozlowski and Pallardy, 1997).

Biosynthesis

Rubber trees convert inorganic nutrients from the soil, and carbon dioxide from the atmosphere, into organic carbohydrates which are then turned into rubber latex and passes up the tree through millions of capillary vessels or tubes located in the soft outer bark.

Wintering

At least once a year the leaves of the tree, which are the sites of carbohydrate formation, die and fall off in wintering, and new leaves are formed. During wintering, which lasts for sixteen weeks, the metabolism of the tree and the constitution of its latex are substantially affected. The yield is also reduced, and this, together with other climatic factors, accounts for marked seasonal variations in natural rubber production in producing countries (FAO, 2001).

Uses and harvesting

The rubber tree is mainly used for its rubber latex. For obtaining the latex, one needs to cut the bark (about 1.5 mm deep), known as tapping (without damaging the cambium), and by doing so opening the latex vessels in the bark , which are arranged in concentric cylinders and run in counter-clock wise spirals up the trunk. One can start tapping at a tree age of 5-7 years, continuing from then on for 30 years. Only basal part (1.7m) of the trunk is tapped in Thailand. Daily or 2-3 days one has to renew the cut and by removing the bark opening the latex vessels in the bark until the base of the trunk

Carbon budget

The carbon cycle in forest ecosystems

Carbon is held in the terrestrial system in vegetation and soils. Oceans also hold large volumes of carbon, as does the atmosphere. Additionally, fossil fuels, coal, petroleum and natural gas, contain large amounts of carbon which are released upon burning. The problem being faced by human society is that large volumes of carbon previously held captive in fossil fuels are being released into the atmosphere due to intensive fossil fuel burning to meet energy demands. The global carbon cycle involves carbon flows among the various systems-terrestrial, atmospheric and oceanic. Biological growth captures carbon from the atmosphere and distributes it within the terrestrial system.

The process of photosynthesis combines atmospheric carbon dioxide with water, subsequently releasing oxygen into the atmosphere and incorporating the carbon atoms into the cells of plants. Additionally, forest soils capture carbon. Trees, unlike annual plants that die and decompose yearly, are long-lived plants that develop a large biomass, thereby capturing large amounts of carbon over a growth cycle of many decades. Thus, a forest ecosystem can capture and retain large volumes of carbon over long periods (Sedjo, 2001).

Forest ecosystems play major role in the global carbon cycle by exchanging carbon dioxide with the atmosphere. It stores about 80% of all aboveground and 40% of all belowground terrestrial organic carbon (IPCC, 2001). Plants of the forest absorb carbon dioxide by photosynthesis. A part is re-emitted by respiration of the different living organisms, while another part is sequestrated in wood and soil. Forests cover 65% of the total land surface, they contain 90% of the total vegetation C in terrestrial ecosystem, they contain 80% of total soil C in terrestrial ecosystems, and they assimilate 67% of the total CO_2 removed from the atmosphere by all terrestrial ecosystems (Stith, 2003). Ecosystem carbon is usually partitioned into four major pools such as carbon in above ground living biomass, carbon in woody and other debris, carbon in root system and soil carbon. It is important that boundaries between the different pools are clearly defined (Snowdon *et al*., 2002). Future forest carbon cycling trends attributable to losses and re-growth associated with global climate and land-use change are uncertain (Dixon *et al.*, 1994). Model projections and field experiments suggest that forests could be carbon sinks or sources in the future (Dixon *et al*., 1994).

Biomass is defined as "*organic material both aboveground and belowground, and both living and dead, e.g., trees, crops, grasses, tree-litter, root etc*." Aboveground biomass consists of all living biomass above the soil including stem, stump, branches, bark, seeds and foliage. Belowground biomass consists of all living roots excluding fine roots (less than 2 mm in diameter). Biomass of forests is very relevant for issues related to global change. For example, the role of tropical forests in global biogeochemical cycles, especially the carbon cycle and its relation to green house effect, has heightened interest in estimating the biomass density of tropical forests. The biomass of forests provides estimates of the carbon pools in forest vegetation because about 50% of it is carbon. Biomass density estimates also provide the means for calculating the amount of carbon dioxide that can be removed from the atmosphere by growing forests or by plantations because they establish the rates of biomass production and the upper bounds for carbon sequestering.

Carbon allocations in woody plant

The photosynthetic rate determines the total amount of fixed carbon available to the leaf. However, the amount of fixed carbon available for translocation depends on subsequent metabolic events. Carbon (C) allocation to roots is of widespread and increasing interest due to a growing appreciation of the importance of root processes to whole-plant physiology and plant productivity. Carbon allocation commonly refers to the distribution of C among plant organs (e.g., leaves, stems, roots); however, the term also applies to functional categories within organs such as defense, injury, repair and storage (Mooney, 1972). It also includes C consumed by roots in maintenance respiration and nutrient uptake (Lambers, 1987). In order to understand C allocation in rooted cuttings it is essential to have an appreciation of the general C allocation patterns that occur within intact woody plants. These patterns are highly integrated within the plant and are determined at the early embryonic stages of plant development. Moreover, they are regulated by a complex network of competing sources and “sinks” within plants (Dickson, 1991). Sources are defined as net exporters of photosynthates, and sinks as net importers of photosynthates (Ho, 1988). An interdependency between the shoot and root exists throughout the life of a plant (Kozlowski, 1971), with the feedback between the root and shoot playing an important role in the regulation of overall plant growth and development (Davies and Zhang, 1991).

C allocation patterns are a function of source-sink interactions. The sink-strength within woody plants varies markedly by species, genotype, shoot type, age of plant, location within the plant, season and environmental conditions (Kozlowski, 1992). There are three fundamental C allocation patterns in woody plants (Dickson, 1991; Kozlowski, 1992). The first pattern is associated with determinate (or fixed) shoot growth, which is characterized by a single, short burst of shoot growth in the late spring and early summer followed by a long lag period of budset. Distribution of assimilates is according to the flush-cycle with most of the assimilates (i.e., > 90%) directed upward to the flush during the flushing episode, and conversely most of the assimilates (i.e., > 95%) are directed downward to the lower stem and roots during the lag stage in between flushing episodes. The second pattern is associated with indeterminate (or free) shoot growth, characterized by continuous shoot growth over most of the growing season. Distribution of assimilate in these plants varies with the stage of development of each leaf. Young developing leaves are net importers of assimilate until they become fully expanded, at which time they export both acropetally to developing leaves and basipetally to the stem and roots. Mature leaves export almost exclusively to the lower stem and roots. The third pattern is associated with semi-determinate (or recurrent flushing) shoot growth, characterized by periodic flushes of shoot growth with intermediate lag stages. The distribution of assimilate in these plants is cyclic with transport upward to developing leaves during a flush and downward to the stem and toots during the lag; the cycle is repeated during each consecutive flushing episode.

Net ecosystem productivity

Net ecosystem productivity (NEP) is the difference of carbon dioxide absorption and emission of community. Alternatively, NEP is the difference between the amount of organic carbon (C) fixed by photosynthesis in an ecosystem (gross primary production or GPP) and total ecosystem respiration Re (the sum of autotrophic and heterotrophic respiration) (Woodwell and Whittaker, 1968). If NEP is positive, the ecosystem is carbon sink and if NEP is negative, the ecosystem is carbon source. NEP can be measured in 2 ways: first, by measure the changes in carbon stocks in the different components of the ecosystem (biomass, litter and soil). Second, by integrate the fluxes of carbon dioxide into and out of the vegetation (Net ecosystem exchange, NEE) (Barnes *et al*., 1997). For this latter approach, two methods can be distinguished depending on the fluxes that are measured: (i) the eddy-covariance method that measures net CO_2 exchanges between the ecosystem and the atmosphere and (ii) methods that determine the ecosystem carbon budget from measurements of NPP and R_h. Each of these methods has its own advantages and drawbacks and has the potential to complement the other. Methods based on carbon stock measurement require heavy sampling to deal with the spatial variability of carbon stocks in soil and biomass (Saint-Andre *et al*., 2007).

Gross and net primary productivity

Gross primary production (GPP) is the total amount of CO_2 assimilated by vegetation strata (i.e., overstory, shrub, herbs and bryophytes). Approximately 50% of CO_2 assimilated by vegetation is used to construct new tissue (growth respiration) and repair and maintain existing tissue (maintenance respiration). The sum of maintenance and growth respiration is referred to as autotrophic respiration (R_a) and results in a loss of CO_2 from vegetation to the atmosphere (Stith, 2003).

Net primary production (NPP) is the difference between total photosynthesis (Gross primary production) and total plant respiration in an ecosystem alternatively; NPP is defined as the total new organic matter produced during a specified interval. (Clark *et al*. 2001a) and it plays an important component of the carbon cycle and a useful indicator of ecosystem performance (Lobell *et al.*, 2002, Seaquist *et al.*, 2003) that can be used to quantify biogeochemical cycles and available energy and nutrient resources within the system. NPP covers the above and below ground build-up of biomass and non respiratory carbon losses (litter fall, herbivory, root death, root exudation etc.) (Roxburg *et al*. 2005) expressed by this equation

$$\mathrm{NPP}= \mathrm{GPP}-\mathrm{R} = \triangle W + L + G \tag{1}$$

$\triangle W$ shows the change (W2-W1) in biomass amount W between t_1 and t_2
L is amount of dead material/litter
G is the amount grazed by herbivorous animals during that period

The ratio between NPP and GPP, the so-called Carbon Use Efficiency ($CUE=NPP/GPP=1-R_a/GPP$) often ranges between 0.4 and 0.5 for plantations and natural forest ecosystems (e.g. Lansberg, 2004). Allocation of NPP to different plant components contributes to tree growth and litter production (L). NPP is usually expressed in t ha^{-1} $year^{-1}$, referring either to dry mass or carbon increase (Roy and Saugier, 2001). NPP is a key variable for comparing the productivity of ecosystems and biomass and being a driver for ecosystem carbon balance (Navarro *et al.*, 2008)**.**

The primary factors influencing NPP are the availability of light, CO_2, water, temperature, and nutrients. They affect productivity through the process of photosynthesis, itself a very complex process. Fundamentally, photosynthesis within cells is a function of the radiant energy absorbed (or limited by that), the rate at which CO_2 in ambient air is supplied, and several other factors. Thus photosynthesis depends on other processes. Those processes include energy, water, carbon, and elements (i.e., nutrients); for example, the hydrological cycle involving precipitation, interception, infiltration, storage, evaporation, and transpiration (Waring and Running 1998).

The largest uncertainty in deriving NPP may originate in estimates of belowground NPP (BNPP), including inputs from roots, exudates, and other root-derived organic material from root-turnover (root hairs and fine roots that are sloughed during the growing season). Though a large proportion of NPP is allocated to belowground plant parts (Stanton, 1988; Li *et al*., 2003), the amount of BNPP is one of the most poorly understood attributes of terrestrial ecosystems (Laurenroth, 2000). Quantifying these belowground C inputs, notably from exudates and other ephemeral root-derived materials, is difficult and remains a research priority (Balesdent and Balabane, 1996; Kurz *et al*., 1996; Kuzyakov and Domanski, 2000; Gill *et al*., 2002; Grogan and Matthews, 2002).

Assessment of carbon sequestration

NPP cannot be directly measured because of transformations such as consumption and decomposition during the measurement interval; it can be estimated based on a suite of diverse measurements and underlying assumptions. NPP (Fig. 1) is the sum of all materials that together are equivalent to:(1) the amount of new organic matter that is retained by live plants at the end of the interval, and (2) the amount of organic matter that was both produced and lost by the plants during the same interval (Clark *et al*., 2001b).

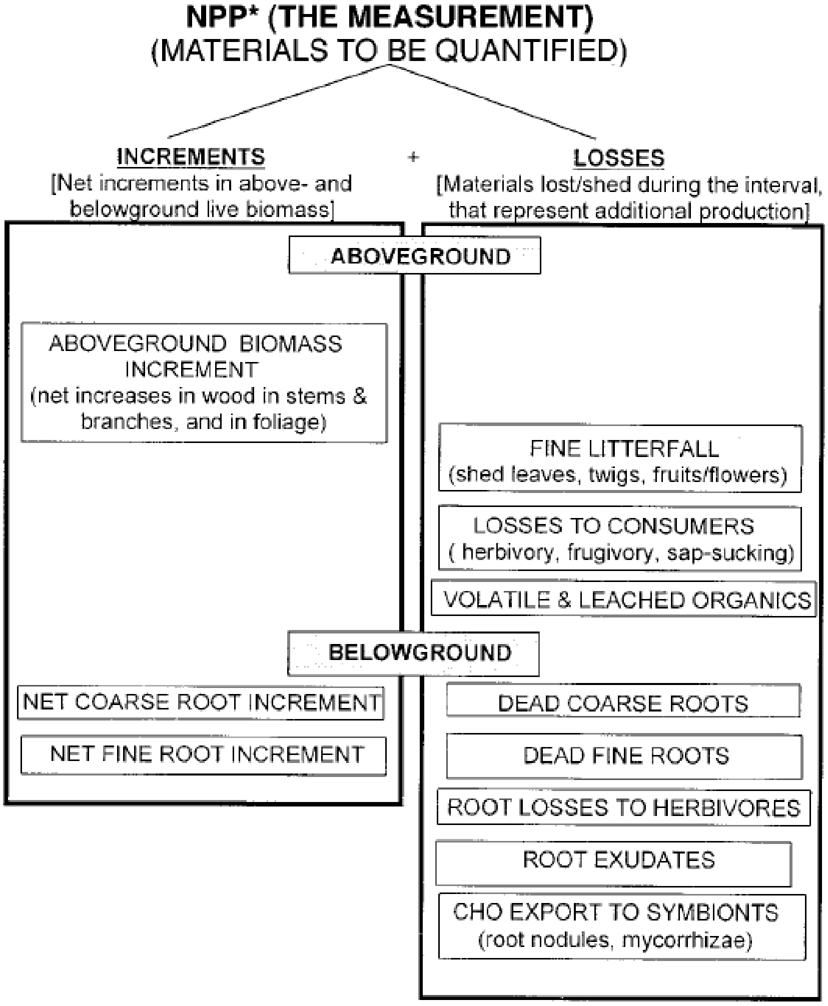

Figure 1 The components of forest NPP, the sum of all materials that together present: (i) the amount of new organic matter that is retained by live plants at the end of the interval, and (ii) the amount of organic matter that was both produced and lost by the plant during the same interval

Source: Clark *et al*.(2001b)

Carbon sequestration of the forest ecosystems could be assessed from two main approaches, according to (i) by measuring changes with plantation age of carbon stocks in the different components of the ecosystem (biomass, soil, litter), and (ii) by quantifying the forest carbon budget from measurements of the carbon input and output fluxes to and from the ecosystem (Net ecosystem exchange, NEE).The integrated NEE can be relatively easily and accurately measured by the eddy correlation technique and R_h can be measured by trenching or root exclusion, by isotope technique or indirectly as the difference between soil efflux and root respiration (Hanson *et al*. 2000). Each of these methods has its own advantages and drawbacks and has the potential to complement the other. Methods based on carbon stock measurements require heavy sampling to deal with the spatial variability of carbon stocks in soil and biomass. They are nevertheless more cost-effective than methods based on the carbon budget methodology, so that they can be used to estimate carbon sequestration at sites that differ in previous land-use, soil properties (e.g. soil texture), or management practice and they can integrate age-effects along chronosequences. Thus, they can be used to identify factors influencing carbon sequestration. On the other hand, results are subject to inter-annual variability of climatic conditions and may therefore not be easily extrapolated. Moreover, changes in some major ecosystem components such as soils are usually difficult to detect due to stand spatial variability and because they usually represent a small fraction of existing soil carbon stocks (Saint-Andre *et al*., 2007).

MATERIALS AND METHODS

Plant material and field conditions

The research was conducted on mature (13 to 15 years old) rubber plantation (*Hevea brasiliensis* Muell. Arg.). The study plant material was rubber tree clone RRIM 600 grown in Chachoengsao Rubber Research Center (CRRC-RRIT-DOA; 13^{o} 39.56$^{/}$N; 101^{o} 26.29$^{/}$E, 69 m from sea level) Sanamchaiket district, Chachoengsao province, Thailand. The annual mean air temperature was 26^{o}C and the mean air relative humidity was 71%. The average annual rain fall was 1,291 mm year^{-1}. The soil type was Kabin Buri soil series (sandy clay loam-clay loam) characterized by a compact lateritic layer with ferralitic concretions at around 1 m depth. Dry season continued from December to April, approximately 5 months. Rainy season is largely dominated by the monsoon starting from May to November. Tapping practice normally starts in May and stops at the end of January, allowing 9 months for latex production and 3 months of resting period. All trees in the experiments were planted in 1993 under 2 planting designs, 2.5m x7 m (571 trees ha^{-1}) and 2.5m x 9 m (444 trees ha^{-1}). The latex tapping started in 1998 when 50% of the trees reached 50 cm of trunk circumference, measured at 1.5 m height from ground.

Methods

The experiment consist of 3 parts

I. Standing biomass measurements

II. Growth dynamics, litter and latex production

III. Data processing for NPP assessment

I. Standing biomass measurements

A. Tree selection

Seventeen trees were sampled in order to cover the full range of basal area variation in the stand by two main criteria: (i) no missing trees to ensure homogeneous and representative growth, and (ii) clean plots to avoid unwanted roots (grass, shrubs).

B. Aboveground biomass measurements

Tree biomass measurement: The following components were considered: stem wood, leaves and branches. When felled, the total length of the tree was measured. The stem was cut into 1.5 m sections. Component biomass was sub-sampled to evaluate the moisture content: we took one 5 cm thick cross section for each log and leaf samples by level within the crown (bottom, middle, top). Each part of the tree was weighed in the field. The moisture content was calculated from weight after drying at 70^{o} C until a stable weight. The volume of stems and branches of subsample were measured by two procedures (i) the volume of water displacement (James and Hinckley, 1991) and (ii) calculate from formula ($22/7x\ r^2$ x h). Empirical relationships were established between biomass and various dimensions of tree and the volume of a stem approximated by the summation of volumes of cross sectional slices.

C. Belowground measurement

Trees were selected in different circumference classes (measured at 1.7 m height) which were representative of the tree diameter classes in the plantation. The selected trees were tapped for latex production with straight bole without missing neighbor trees and avoiding the unusual area (low land, cover with shrub or weed, nearby the construction or road etc.). Three types of root were examined by diameter: fine <2 mm), medium (2-10 mm) and coarse root (>10 mm) in the Voronoi polygons

(Honda, 1978; Saint-André *et al.*, 2005) defined as the elementary space around a sampled tree. The limits of this polygon were defined by the half distances between the sampled tree and its neighbors (Figure 2). The hypothesis is that all the roots of the sampled tree that grow outside the Voronoi polygon are balanced by those of neighboring trees growing inside the polygon. The Voronoi polygon can be subdivided into 4 equal parts around the tree, each of them were called Voronoi trench. One of these trenches per tree was randomly selected for root sampling.

1. Root biomass and distribution

Root biomass estimation and spatial distribution around the tree was compared by 2 methods: (i) soil auger (8.4 cm of inner diameter) was used for root sampling at 15 positions (ii) Voronoi trench excavation was used for root sampling in the Voronoi trench down to 100 cm depth (corresponding to the soil physical limit by the hard pan).

a) Soil cores

Soil cores were performed in Voronoi trench (1/4 of Voronoi polygons) in 15 positions (Figure 2) in 0-10, 10-30, 30-50, 50-70, and 70-100 cm soil depth layers for each 4 sampling tree. Roots were sorted into three diameter classes: less than 2 mm (fine roots), 2-10 mm (medium roots) and more than 10 mm (coarse roots). The sorting procedures were performed visually only for the live root with the help of reference test specimens for which diameters were measured using caliper. Rubber roots were separated from the other ones according to their texture, color and elasticity. The collected roots were dried at 65^{o}C to constant weight and weighed. Fresh weights of coarse roots were determined in the field and their dry weight was determined based on the corresponding dry/fresh weight ratios obtained from sub-samples.

b) Root excavation

A quarter of the Voronoi polygon of 4 sampled trees was selected in normal-inter-rows to get an average tree value of root biomass. Excavations were performed manually to a 1 m depth in 5 soil depth horizons (0-10, 10-30, 30-50, 50-70 and 70-100 cm). Roots were separated, sorted and processed with the same protocol as soil core method (Figure 3).

II. Growth dynamics, litter and latex production

A. Aboveground production and dynamics

1. Trunk diameter

Trunk diameter was measured above tapping panel (1.7 m) for all trees (~2,700 trees) of the plot with measuring tape every 3 months.

2. Height increment

Tree height was measured using a clinometer (Altimeter model BL6®) for 10% of all trees in the plot. This was done yearly in dry season when the rubber trees defoliated.

3. Litter trap

Twenty units of 1x1 m^2 traps were made from PVC pipe and nylon net installed in 3 locations (between tree in the row, between row and middle row and in middle row). Litter from each trap was collected and separated into parts of plant such as leaf, branch, petioles, flower and fruit for every week. The litter samples were dried at 65^o C for 72 hrs and weighed.

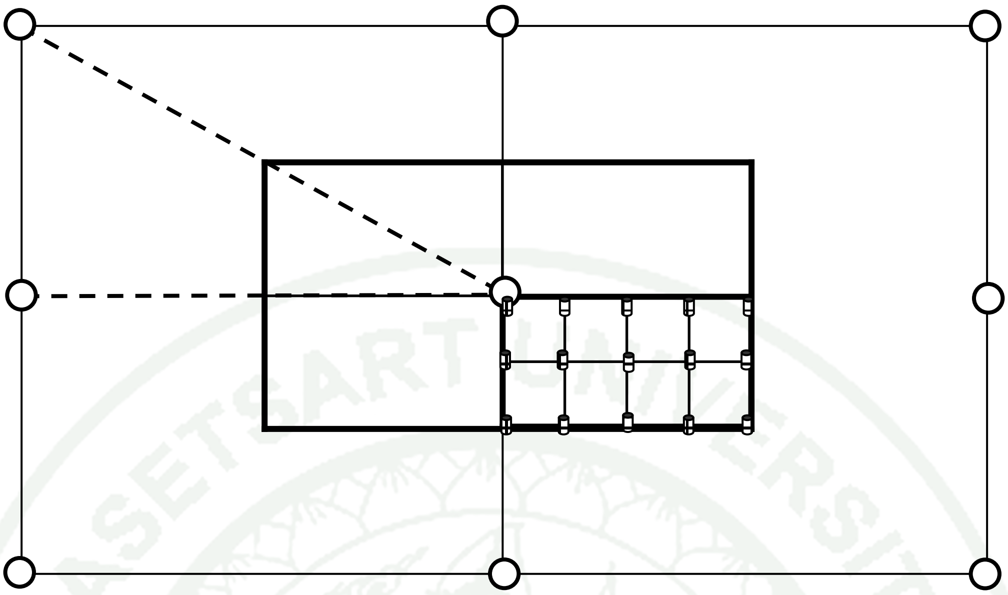

Figure 2 Voronoi trench and root sampling positions by soil core method at 1 m depth where ○ = Rubber tree ⛁ = Position for soil core sampling ⊞ = Position for soil core sampling and ▭ = ¼ Voronoi trench

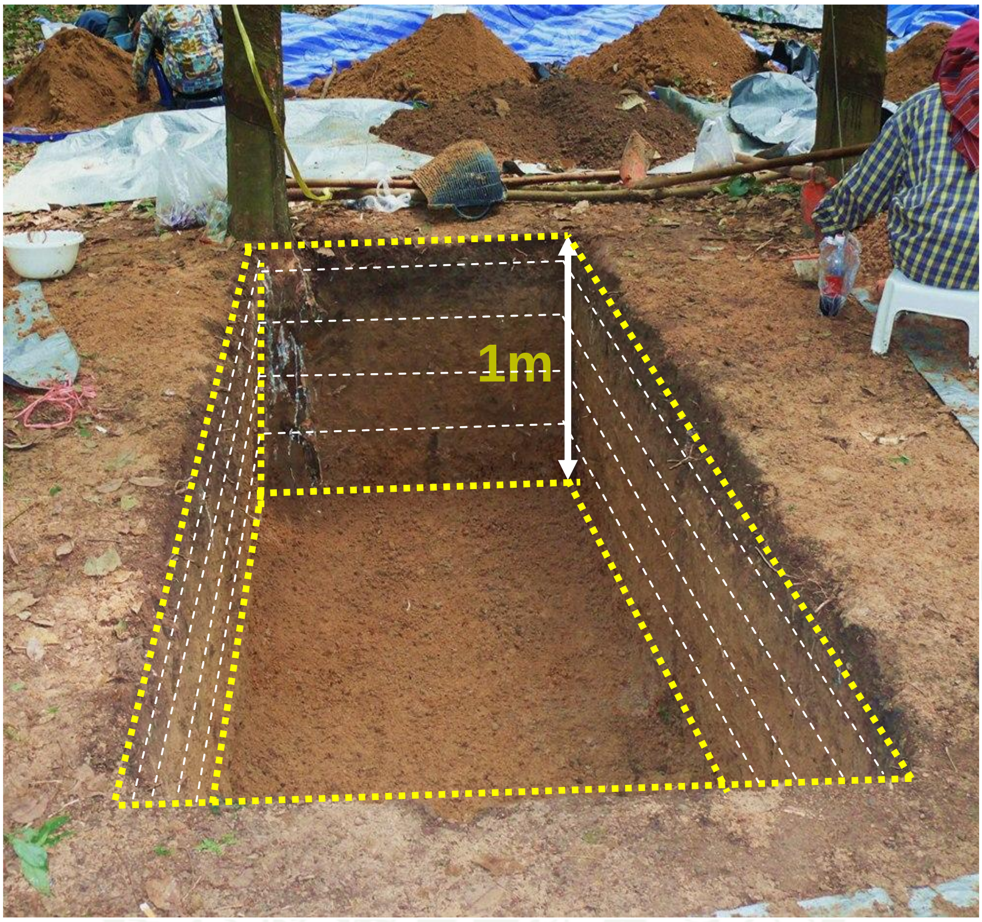

Figure 3 Root excavation method in Voronoi trench at 1 m depth

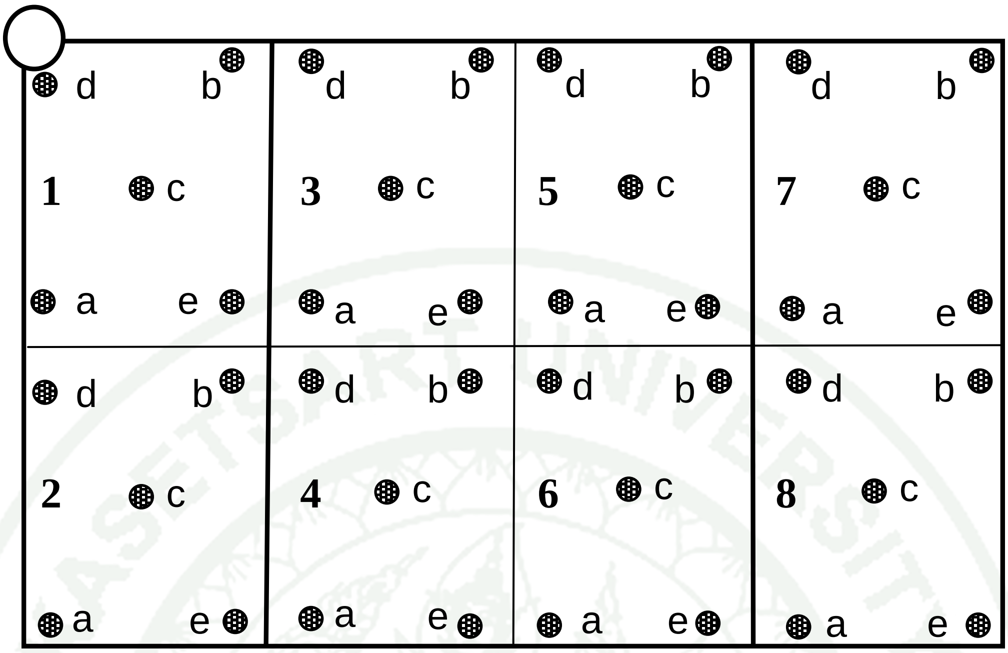

Figure 4 Sampling position for sequential and ingrowth cores method where number 1-8 = the number of cell, a = 1st, b = 2nd, c = 3rd, d =4th and e = 5th of sampling date, ○ = rubber tree and ● = the sampling position.

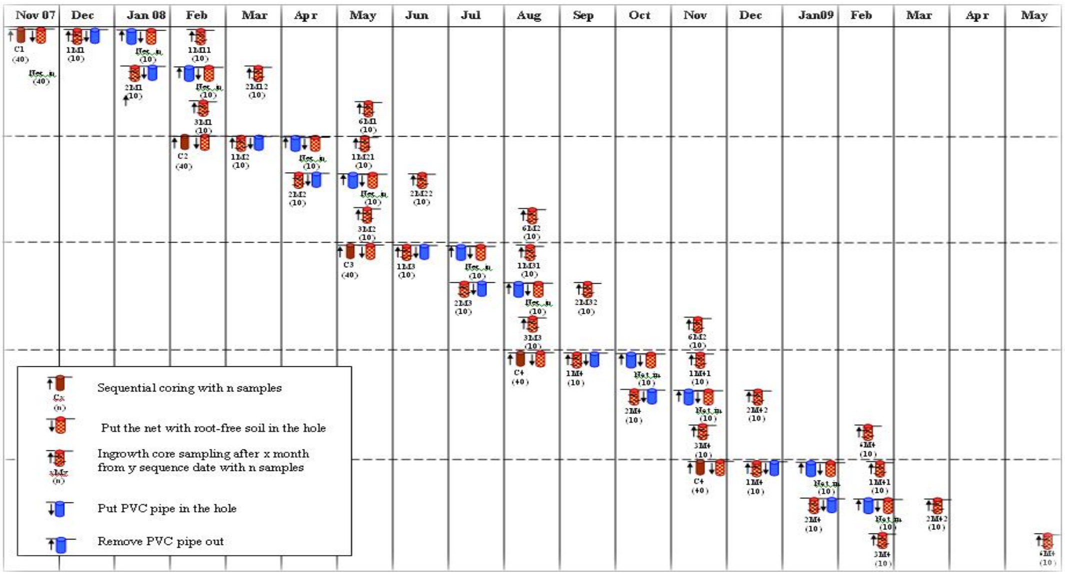

Figure 5 Protocol of fine root estimation by sequential soil coring and ingrowth core method during November 2007 to May 2009.

Figure 6 Horizontal and vertical rhizotron installation in the study plot

4. Leaf area index estimation

a) Estimating LAI through the litter trap

Specific Leaf Area (SLA) defined as leaf area per unit of dry mass, was estimated by collecting leaf litter from all 20 litter traps at the peak of leaf litter (December- January).

$$SLA = \frac{\sum Ai}{\sum Wi} \tag{2}$$

where SLA is the specific leaf area, A*i* the one-sided plan area of a leaf ‘‘*i*’’, and W*i* the dry mass of leaf ‘‘*i*’’. The leaf area was measured by LI-3100 leaf area meter (Li-COR Inc., 1987) and then dried at 65^{o} C to constant weight for the total. The relationship between leaf area and dry mass of leaves was established and LAI was then calculated through the SLA relationship. The obtained LAI values represent maximum seasonal LAI.

b) Estimating LAI through the optical method

Hemispherical photographs were taken beneath the rubber canopy 1 m from ground level at 20 positions along with the litter trap every week. The photos were taken by using digital cameras (COOL PIX 995®, 3.2 mega pixels, Nikon) with Fisheye converter (FC-E8®, Nikon).Gap fraction from the images were calculated by Gap Light Analyzer (GLA) (Frazer *et al*., 1999) software, a computer program designed to analyze hemispherical photographs.

5. Latex production

Latex production was collected by tapping sample trees in the plantation. For each studying period, tapping started in May and stopped in January. Average latex production in 2007, 2008 and 2009 collected from 519, 446 and 461 sample trees were 3.5, 3.3 and 3.8 kg tree^{-1}. Total dry mass of latex in our study area were 1.6 t ha^{-1} in 2007, decreased to 1.5 t ha^{-1} in 2008, and increased to 1.7 t ha^{-1} in 2009 (Table 1).

B. Belowground production and dynamics

1. Tap and coarse root biomass increments, estimated by allometric equation between tap and coarse root and trunk diameter/tree height (d or d^2h) which established from the same 17 sample trees as above ground biomass.

2. Medium and fine root growth, production and turnover, estimated by 3 independent approaches such as (1) Sequential soil coring (2) Ingrowth cores and (3) Rhizotrons.

a) Sequential soil coring

Sequential coring is the most common method for determining fine root production. The data produced from this method can be analyzed by the summation of biomass and necromass (dead root) of each sampling date in order to cover one year of studying period. In our study, 5 sampling dates separated by 3 months intervals were chosen from November 2007 to November 2008 according to seasonal variations. Eight soil samplings were taken in center of each cell of the Voronoi trench (Figure 4) of each tree with 5 replicates within the 0-30 cm soil horizon using a root auger (8.4 cm inner diameter).

b) Ingrowth cores

The ingrowth core technique was used in order to measure root growth activity over a certain period. This technique involves inserting a core of soil without roots into the ground, then removing it after a specified amount of time and measuring root biomass. Forty soil cores (8 cores x 5 sampling trees) were sampled by root auger (inner diameter of 8.4 cm) on 5 sampling dates (in November 2007, February, May, August and November 2008) for the installation of ingrowth bags. The first sampling position was made on position *a* followed by position *b*, *c*, *d* and *e* respectively (Figure 4). After root processing, the root-free soil was installed in nylon mesh bags (diameter 8 cm, length 30 cm and mesh size 5 mm) in same hole, with respect to the same soil layers and was compacted as similarly as possible to the bulk density. Every 3 months a new set of 40 mesh bags were installed. Ten mesh bags were removed randomly from all 5 trees in order to cover all 8 positions in the Voronoi trench after 1 month of root re-growth. After 2, 3 and 6 months of re-growth periods another set of 10 mesh bags were removed per re-growth periods (Figure 5). The additional method was PVC technique. After first sampling, a series of PVC drainage tube and a series of ingrowth cores were inserted into the soil profile. All tubes and core were 30 cm long, 8 cm diameter and inserted flush with the soil surface. PVC tubes were closed at both ends with expanding foam filter to minimize soil moisture and temperature changes in the vicinity of a tube (Lukac and Godblod, 2001).

c) Root dynamics estimation with rhizotron

Fine root dynamics were monitored using rhizotrons (Jourdan and Rey, 1997; Sword, 1998; Green *et al*., 2005; Metcalfe *et al*., 2007). Rhizotrons are clear glass/plastic chambers inserted into the soil which allow direct visual analysis of root growth dynamics at high temporal frequency. After the initial disturbance associated with insertion these chambers allow continuous *in situ* data collection. They can be used to determine rooting patterns and elongation rates, and provide qualitative information on root color, branching patterns, senescence and parasitism (Taylor 1987; Lussenhop *et al*., 1991; Hendrick and Pregitzer 1996). The rhizotrons were made of Plexiglas with 0.5 cm thick and square 0.8 x 0.8 m^2 (0.8 m^2 size, 5 mm thick) with metal frame for rigidity. Two types of rhizotron were installed in each sampled tree. The rhizotrons were inclined according two positions: (i) sub-horizontally with an angle of 30^o from the soil surface and (ii) sub-vertically with an angle of 20^o from the vertical (Figure 6). All rhizotrons were set up at 1.5 m far from the tree, in the inter row, and for each sampling tree, one horizontal rhizotron was opposite to one vertical one. Before Plexiglas installation, all roots were cut with the sharp scissors at the soil profile level and were covered with the sieved soil collected in the pit. The soil was mixed with insecticide powder to prevent small soil fauna to colonize the device. For the horizon rhizotron, the heavy soil bags were put on the Plexiglas after installation to make a good contact between soil and Plexiglas. For the vertical rhizotron, compaction of the sieved soil was helped by the special “T” tool and all rhizotrons were fixed to the soil with iron hooks. The rhizotrons were installed in late October 2007 which corresponded with the end of rainy season.

The transparent plastic sheets for root monitoring were put on the Plexiglas surface with the help of rubber glue and cover with the black plastic sheet to prevent the light from root growth area. The iron sheet roofs were installed for each rhizotron to protect light, high temperature, water and small animals.

The growth of the roots were recorded on transparent plastic sheets by using indelible felt pens with 8 different colors every 7 days (one color for each date) and with the same sequence order.

III. Data processing for NPP assessment

A. Standing biomass

1. Aboveground biomass

Biomass assessment method consists in (i) performing an inventory of the trees in the plot (diameter at breast height and/or tree height) (ii) applying appropriate allometric equations to the trees measured (iii) up-scaling to assess carbon stocks and their variation. Allometric equations to determine the dry weight of the stand were collected from 17 sample trees from the rubber plantation.

a) General model

The system of equations was written as follows:

$Y_1 = f_1(\theta_1,\beta_1)+\varepsilon_1$

$Y_1 = f_2(\theta_2,\beta_2)+\varepsilon_2$

.

.

$$Y_m = f_m(\theta_m,\beta_m)+\varepsilon_m \tag{3}$$

where Y_m, the biomass of component *m*, was a function *fm* of a set of independent variables θ_m and a set of parameters β_m. Functions f were first assessed individually. The system of equations was thereafter fitted using the SUR regression (Proc MODEL of SAS software, package ETS; SAS, 1990) which fits the component equations all together and takes the cross-equation correlations into account (see Parresol, 2001 for a detailed example of this procedure). Because the data set is unbalanced between the aboveground and the belowground part, we fitted three systems of equations: the first one with all aboveground components, the second one with all belowground components, and the last one with only the sum of biomasses (total above- and belowground components, total tree biomass).

b) Individual tree component model

Basic equations were of the following form:

Linear model :

$$\mathrm{Y_{s,i,j}} = \mathrm{a_{s,j}} + \mathrm{b_{s,j}X_{s,i}} + \varepsilon_{i,j} \tag{4}$$

Non-linear model :

$$\mathrm{Y_{s,i,j}} = \mathrm{a_{s,j}} + \mathrm{b_{s,j}X_{s,i}^{c_{s,j}}} + \varepsilon_{i,j}^{/} \tag{5}$$

where *s* represented the stands; $Y_{s,i,j}$ the dry matter of tree *i* for a given component *j*; $X_{s,i}$ the independent variable (either *d* or d^2h; d and h are, respectively, the diameter at breast height and the total tree height); $a_{s,j}$, $b_{s,j}$, and $c_{s,j}$ the parameters to be estimated; $\varepsilon_{s,i,j}$ and $\varepsilon^{/}_{i,j}$ *the* residual variations not explained by the models.

c) Fitting each tree component

The objective was to find the best model for each component. A curvilinear models were fitted using the power regression procedures for establishing the relation between d, d^2h or X and biomass The following steps were performed: (i) fitting the equations of individual components (component model), (ii) fitting the equations of all components together (tree model) (iii) comparing the ‘‘component model’’ to the ‘‘tree model’’. The regression procedure was used to find the optimal weight by using Non-linear procedure of SAS software.

Aboveground stand biomass (t ha^{-1} y^{-1}) was calculated as the sum of biomass production along the year.

2. Belowground standing biomass

Standing belowground biomass was calculated from 2 independent methods (i) Tap and coarse root were calculated from total excavation data of 17 sample trees(the same trees as aboveground estimation) (ii) medium and fine root, standing biomass data were obtained by the summation of each root types in each soil layer from Voronoi trench.

B. Growth dynamics and litter production

1. Aboveground dynamics

a) LAI estimated from litter traps

LAI estimated from litter traps was calculated from the summation of leaf mass in the litter traps along the growing season divided by specific leaf area (SLA)

2. Belowground dynamics

a) Sequential coring method

The fine root biomass and necromass were estimated by the summation of fine root biomass and necromass of each sampling date (n=1, 2, 3, 4 and 5 , see Equation 1), from the average of 8 soil cores coming from 8 positions in the Voronoi trench of 5 different trees.

$$P_a = \sum B_n + \sum N_n \tag{6}$$

where P_a is fine root production of each sampling date, B_n is fine root biomass at n sampling date and $N_{n,}$ is fine root necromass at n sampling period.

b) Ingrowth cores

Fine root production was calculated from 3 methods: additional approach estimated by (i) the summation of fine root biomass and necromass of each re-growth period (n=1, 2, 3 and 6 months, see Equation 1),

$$P_a = \sum_{j=1}^{5} B_{n,j} + \sum_{j=1}^{5} N_{n,j} \tag{7}$$

where P_a is fine root production of each re-growth period, $B_{n,j}$ is fine root biomass after n month of re-growth during sampling period j and $N_{n,j}$ is fine root necromass after n month of re-growth during sampling period *j*.

(ii) short-term approach calculated by the summation of mean biomass and necromass in all 3-months term cores (adapted from Neill, 1992 and Jourdan *et al*., 2008, see Equation 2) and

$$Pa = \sum_{j=1}^{5} Pn, j \qquad (8)$$

where P_a was fine root production during the whole sampling year (five seasonal sampling periods), *Pn* was fine root production after 3 months of re-growth during sampling period *j* and

(iii) positive increment approach calculated from the sum of positive increments of biomass and necromass between two successive sampling dates (adapted from Person, 1978 and Hendricks *et al*., 2006, see Equation 3).

Annual fine root production (*Pa*) could be then defined by three equations according the 3 different calculation methods used:

$$P_a = \frac{365}{N}\left(\sum_{i=2}^{3}\sum_{j=1}^{4}(P_{i,j} - P_{i-1,j})\right) \qquad (9)$$

where P_a was annual fine root production over the whole sampling year (4 seasonal sampling periods *j*), P_{ij} was fine root production after *i* months of re-growth (where *i*=2,3,6) during seasonal sampling period *j*, *N* was the number of days throughout the study period between 1 and 6 months after mesh bag installation (*N* = 446 days in this study).

c) Rhizotron

Fine root dynamics were collected from rhizotron with the observation sheets by manually digitized afterwards in the laboratory, on a 61 cm × 91 cm format digitizer (Summagrid V®, GTCO CalComp Inc., Columbia, MD, USA) which was operated by RhizoDigit software (CIRAD, Montpellier, France). The software enables semi-automatic acquisition of root data via the digitizer. RhizoDigit generates and manages a database that includes the appearance date of each root segment and its length at all observation dates. This information was then used to calculate the elongation rate of each root segment between 2 observation dates. The fine root elongation rate (cm d^{-1}) was calculated by dividing the increase in length of a root segment between two observations by the number of days between those two observation dates. To avoid the compensation of root growth from root cutting during rhizotron installation, root data in this study was sampled 3 months after installation to achieve equilibrium in new root growth.

C. Net primary productivity and carbon content

Net primary productivity of rubber plantation were calculated from the variations of dry mass (*DM*) of all plant components over time (t, yearly) and mortality of litter production (*L*,t) and exportation of latex (*E*, t), as follows (Equation 9)

$$NPP = \frac{\Delta DM}{dt} + L + E \qquad (10)$$

Carbon content of each component was obtained by multiplying dry weight by the carbon concentration from previous research on rubber tree in Thailand (Lunggee, 2007) (Table 2).

Table 1 Dry mass latex production during 2007 – 2009

Year	No. of sample tree	Total latex production (kg)	Latex production (kg tree^{-1})	No. of trees in study plot	Latex production (t ha^{-1})
2007	519	1,833	3.5	2,753	1.6
2008	446	1,456	3.3	2,693	1.5
2009	461	1,734	3.8	2,690	1.7

Table 2 Carbon content in rubber tree compartments (Lunggee, 2007)

Tree compartment	**Carbon content (%) w/w**
Latex	81.0
Seed	55.8
Leaf	48.0
Petiole	46.8
Stem	45.7
Branch	45.4
Root	
Tap root	45.3
Coarse root	45.4
Lateral root	44.8

RESULTS AND DISCUSSIONS

Results

I. Above and belowground standing biomass

A. Aboveground standing biomass

Table 3 presents the mean aboveground biomass partitioning of rubber trees collected from 17 sample trees of the 13-15 years old rubber stand.Stem and big branches represented about 95% of the whole tree biomass, follow by 2.4% for small green branches, 1.8% for leaves and 0.1% for fruit. The mean aboveground standing biomass during 2007-2009 was 271.56 t ha^{-1}.

Figure 7 presents the relationship between the dry matter of both above and belowground components with the independent variable *G* (circumference; cm). Due to the very low correlation between tree height and circumference, this experiment used *G* as the only independent variable to estimate tree biomass while relationships were good for aboveground biomass, the individual tree components were not very well related to tree size. That fitted curve of aboveground component and total biomass were found to have highly significant coefficients of determination (R^2) suggesting that biomass could be reasonably well estimated using a power function of circumference (Equation 10). The fitted equation can be adequately used for estimation of above ground biomass from circumference data. The belowground component and circumference relationship has also high R^2.The following general equations are derived by pooling data of 3 ages of rubber tree (13, 14 and 15 years old) in the plantation (Equation 10 - 11).

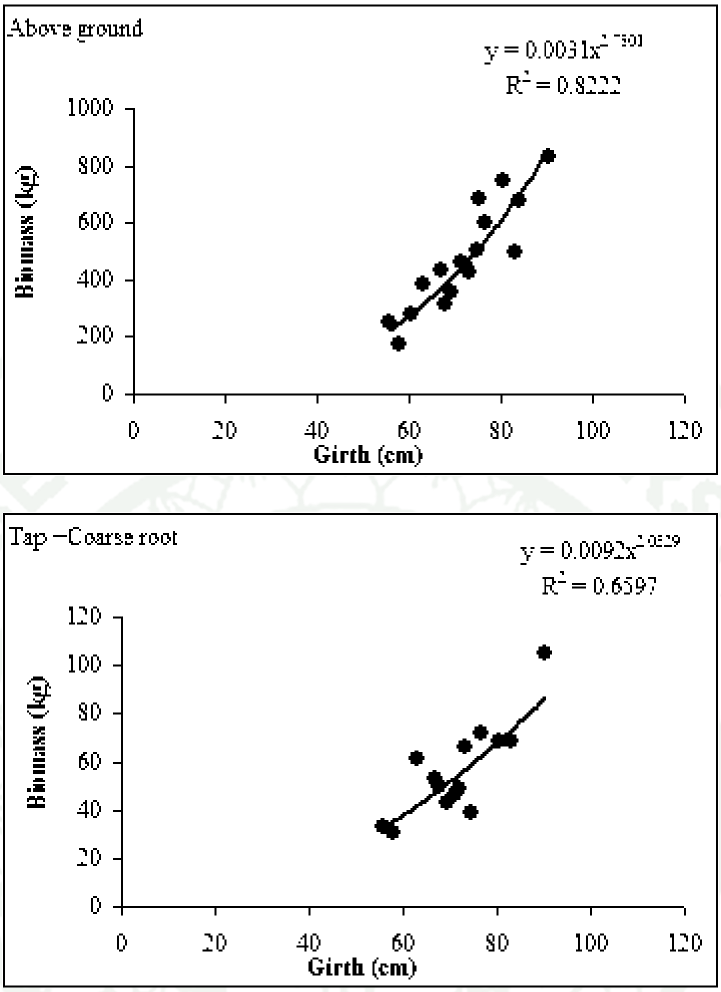

Figure 7 Above- and below ground standing biomass (kg tree^{-1}) related to girth (cm) from 17 sample trees of the study plot.

1. Aboveground biomass

The aboveground standing biomass measured from 17 sample trees during 2007- 2009 showed that about 95% (258.58 t ha^{-1}) found in trunk and coarse branches of rubber tree followed by small green branch, leaf and fruit (2.6%, 2.0% and 0.1%) respectively (Table 3).

$$W_{AG} = 0.0031X^{2.7801} \qquad R^2 = 0.82 \tag{10}$$

where W_{AG} was defined as biomass of all above ground components (*kg*), X was trunk circumference at 1.7 m (cm).

B. Belowground biomass production

Belowground standing biomass was about 11.7% (35.85 t ha^{-1}) of total standing biomass. The largest belowground biomass component was 21.74 t ha^{-1} in tap root follow by 7.9 t ha^{-1} for coarse root, 4.64 t ha^{-1} for medium and 1.57 t ha^{-1} for fine root (Table 4).

Tap and coarse root biomass could be reasonably well estimated by the following allometry equations, derived from data of 17 sample trees in the study plot:

$$W_{TC} = 0.0092X^{2.0329} \qquad R^2 = 0.66 \tag{11}$$

where W_{TC} was defined as biomass of tap and coarse root(*kg*), X was trunk circumference at 1.7 m(*cm*). Due to the very low correlation between fine and medium root with tree circumference, this experiment only calculated tap and coarse root biomass from this equation. Medium and fine root were estimated from excavation trench method.

Table 3 Aboveground standing biomass measured from 17 sample trees during 2007 – 2009 (planting design: 2.5x7 m^2, 571 trees ha^{-1})

Compartment	Mean aboveground standing biomass ($t\ ha^{-1}$) averaged 2007 - 2009
Trunk and coarse branches	258.58
Leaves	5.51
Small green branches	7.12
Fruits/seeds	0.35
Aboveground biomass	**271.56**

Table 4 Belowground standing biomass estimated from 17 sample trees and Voronoi trench during 2007 – 2009 (planting design: 2.5x7 m, 571 trees ha^{-1})

Compartment	Mean belowground standing biomass ($t\ ha^{-1}$) averaged 2007 - 2009
Tap roots	21.74
Coarse roots	7.90
Medium roots	4.64
Fine roots	1.57
Belowground biomass	**35.85***

* Tap and coarse root measured from 17 samples trees and medium and fine root estimated from Voronoi trench data.

C. Root biomass and distribution from excavation methods

1. Spatial distribution of fine root

From soil coring method, more than 55% (815 g m^{-3}) of rubber fine root mass (<2mm) occurred in 0-10 cm soil layer and decreased rapidly to 304 g m^{-3} in 10-30 cm soil layer thereafter decreased gradually to 84 g m^{-3} in 70-100 cm soil layer (Figure 8). Fine root biomass on the entire soil profile down to 1 m depth amounted to 2.41 t ha^{-1}. Fine root biomass estimated from Voronoi trench had the same pattern as soil coring method. More than 62% (685 gm^{-3}) of rubber fine root estimated in Voronoi trench occurred in 0-10 cm soil layer and decreased to 54.6 m^{-3} in 70-100 cm layer and total fine root from biomass within 0-100 cm soil profile was 1.57 t ha^{-1}. Therefore, fine root biomass measured from soil coring method was significantly greater than from Voronoi method (Table 5).

2. Spatial distribution of medium root

The distribution of medium root (2-10 mm) from soil cores had the same pattern as fine root. The highest density was found in 0-30 cm soil layer and more particularly in the 0-10 cm soil layer (1,347 g m^{-3}) then decreased to 983 g m^{-3} in 10-30 cm soil layer. In 30-50 cm soil layer, medium root density decreased sharply to 456 g m^{-3} and to 432 gm^{-3} in 50-70 cm soil layer. The lowest density was 199 g m^{-3} which occurred in 70-100 cm soil layer. Medium root estimated from Voronoi trench had similar pattern as soil core method which highest density (1,404 g m^{-3}) found in 0-10 cm followed by 828 g m^{-3} then decreased to 258 and 256 g m^{-3} in 30-50 cm and 50-70 cm soil layer respectively. The lowest density was 182 g m^{-3} occurred in 70-100 cm soil layer (Figure 9).The total medium root density estimated from soil cores was higher than Voronoi trench method about 35% (Table 5).

3. Spatial distribution of coarse root

The pattern of coarse root distribution was different from fine and medium root distribution and significant different was found between 2 sampling methods. For soil coring method the highest density occurred in 30-50 cm soil layer (46%) and the lower density occurred in 0-10 and 10-30 cm soil layers which were 384 and 430 g m^{-3}, respectively. In 50-70 and 70-100 cm soil layers, coarse root density decreased markedly to 120 and 87 g m^{-3}, respectively. The spatial coarse root distribution estimated in Voronoi trench was different from soil coring method. The highest density was 1,260 g m^{-3} in 10-30 cm soil layer followed by 600 gm^{-3} in 0-10 cm soil layer. Root density droped to 305 g m^{-3} in 30-50 cm soil layer then increased to 454 g m^{-3} and finally decreased to 200 g m^{-3} in 50-70 and 70-100 cm soil layers respectively (Figure 10). Total fine and medium root biomass from soil coring method was tended to over-estimated compared to Voronoi trench and no relationship was found between two methods for coarse root (Figure 11).

Root mass distribution of each root type estimated by excavation in the Voronoi trench varied with root size with the highest biomass found in coarse root (5.24 t ha^{-1}) and most of coarse root was located at 10-30 cm soil layer. Medium root mass was 4.64 t ha^{-1} and 66% of medium root located at 0-30 cm soil layer. Fine root biomass was 1.57 t $ha^{-1}$with 95 % located at 0-30 cm and decreased gradually with soil depth (Table 6).

II. Growth dynamics and litter production

A. Aboveground growth dynamics

1. Tree circumference

The average circumference of rubber stand increased significantly over three observation years.The lowest averaged value was 613.9 mm in 2007 and increased to 627.84 mm in 2008 and 642.34 mm in 2009. Six percent of all tree

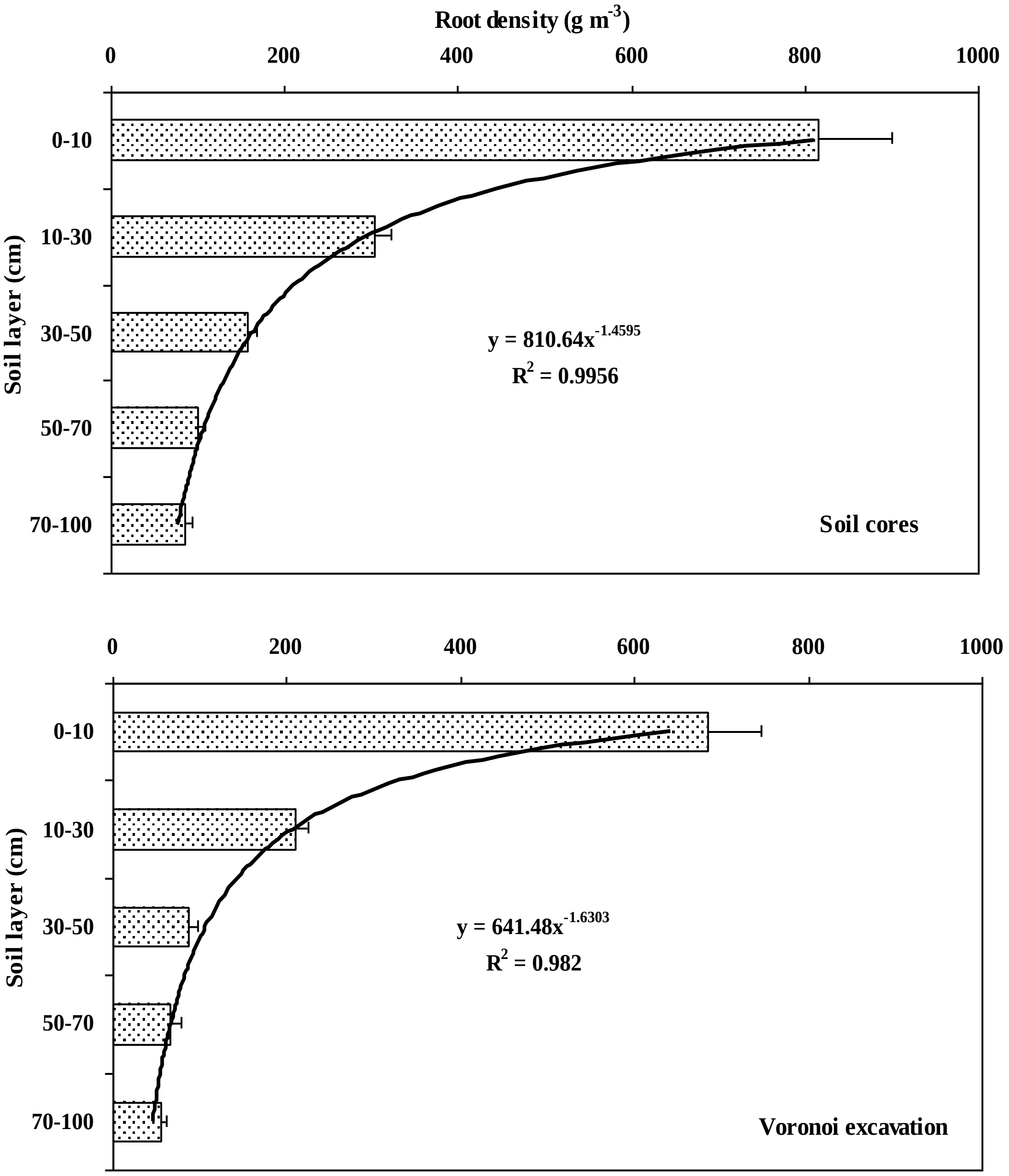

Figure 8 Fine root (<2mm in diameter) dry mass density (g m^{-3}) along 1 m depth from soil surface by 2 sampling methods (soil cores and Voronoi)

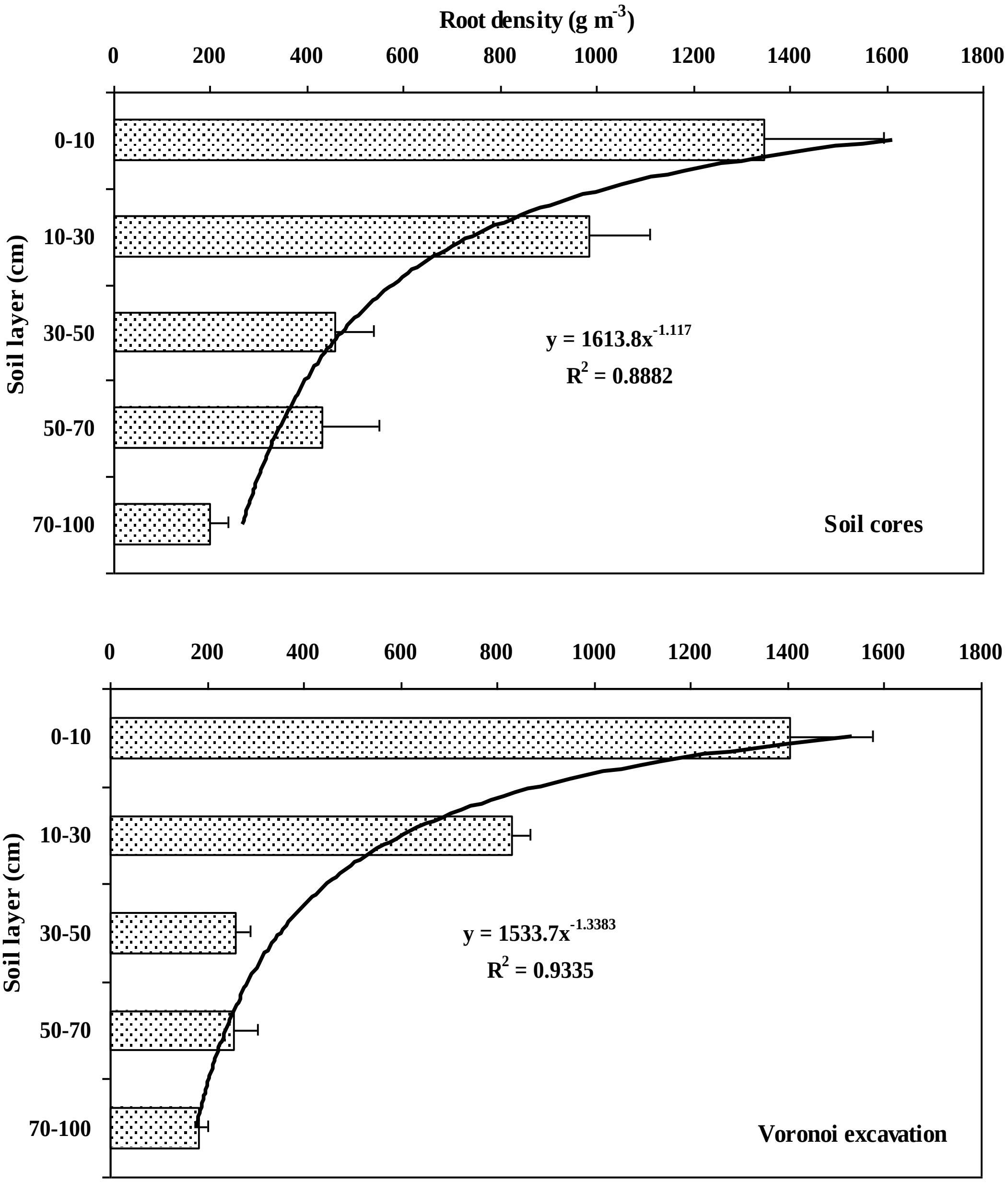

Figure 9 Medium root (2-10 mm in diameter) dry mass density (g m^{-3}) along 1 m depth from soil surface by 2 sampling methods (soil cores and Voronoi trench)

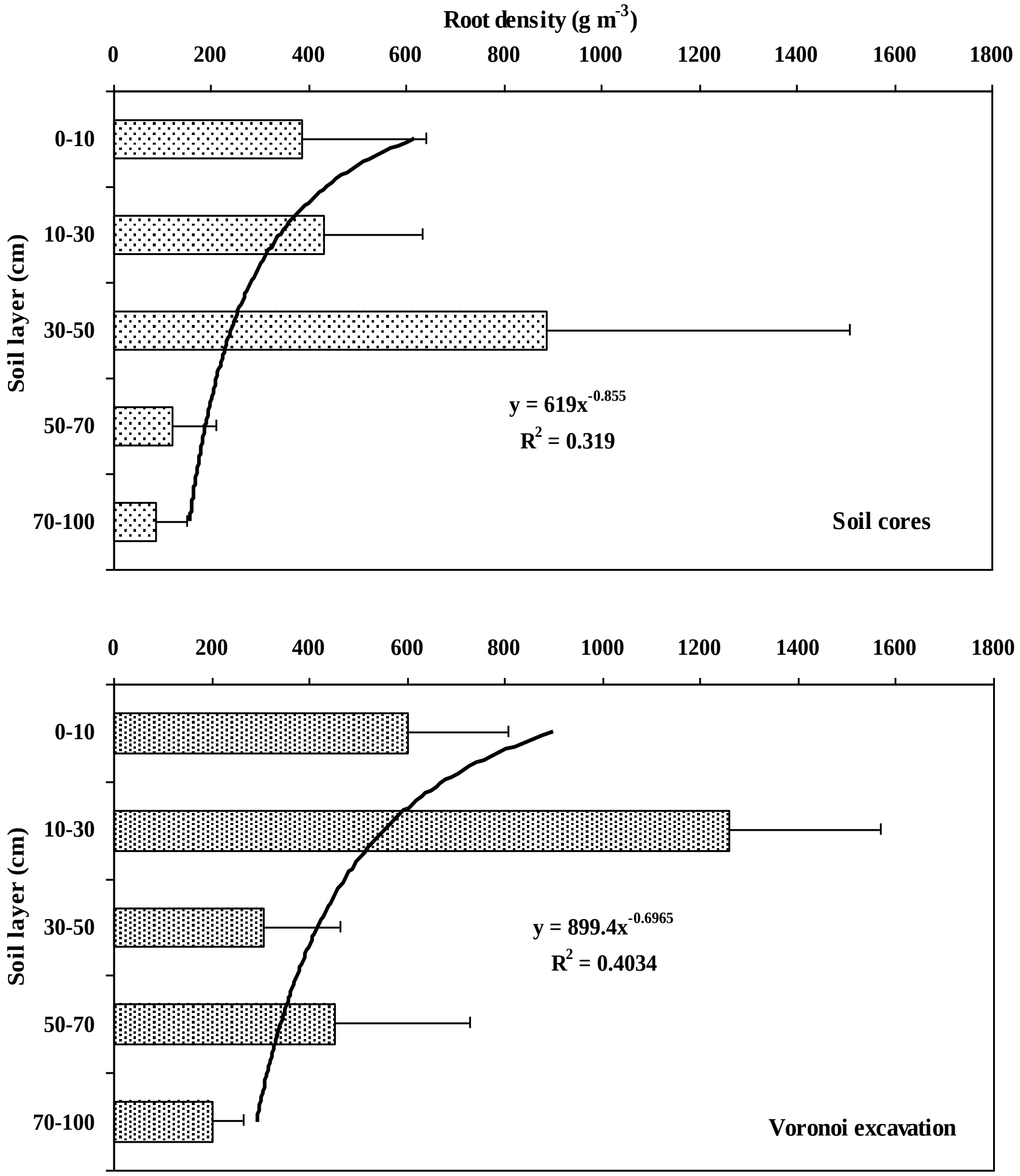

Figure 10 Coarse root (>10 mm in diameter) dry mass density (g m^{-3}) along 1 m depth from soil surface by 2 sampling methods (soil cores and Voronoi trench)

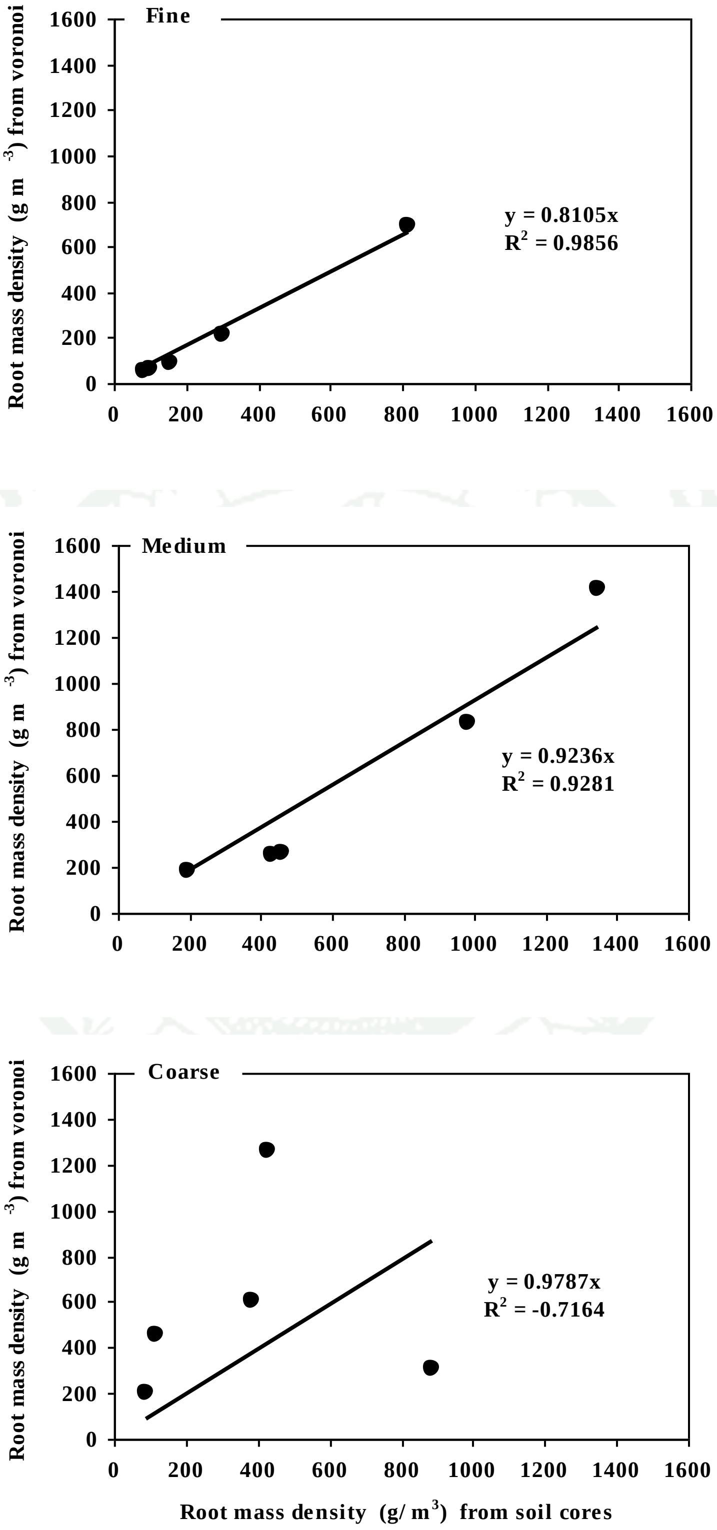

Figure 11 Relationship between mean root mass density of 3 different root types along 1 m depth from soil surface by 2 sampling methods (Voronoi and

soil cores)

Table 5 Root mass density estimation from 2 sampling methods (Soil cores and Voronoi trench) along 1 m depth from soil suface.

Method	**Root mass density (t ha^{-1})**			**Total mass (t ha^{-1})**
	Fine root	**Medium root**	**Coarse root**	
Soil cores	2.42	6.27	3.87	**12.56**
Voronoi trench	1.57	4.64	5.24	**11.45**

Table 6 Root mass (t ha^{-1}) distribution estimated from excavation in Voronoi trench at 5 depths along the soil layer.

Soil depth (cm)	**Root type**			**Total**
	Fine	**Medium**	**Coarse**	
0-10	0.69	1.40	0.60	**2.69**
10-30	0.42	1.66	2.52	**4.59**
30-50	0.17	0.52	0.61	**1.30**
50-70	0.13	0.51	0.91	**1.55**
70-100	0.16	0.55	0.60	**1.31**
Total	**1.57**	**4.64**	**5.24**	**11.45**

circumferences in the plantation during 2007 to 2009 was between 600-700 mm (Figure 12). Statistical analysis shows that rubber tree circumference was significantly different for each year (Figure 13).

2. Tree height

In 2007, the highest frequency of tree height was found at 20 m (26 % of 180 sample trees), 92% of tree height was found between 17-22 meters and the average tree height of the plantation in 2007 was 19 m. In 2008, averaged tree height

increased to 19.6 meters. The highest frequency height in 2008 was 21 m (21% of 310 sample trees). In 2009, the averaged tree height was 19.4 m and the highest frequency was found at 20 m height (19% of 321 sample trees) (Figure 14). Averaged tree height of 2007 was significantly different from 2008 and 2009, but 2008 was not different from 2009 (Figure 15).

The relationship between tree height and circumference at 1.7 m height was low in all observation years with low R^2 (Figure 16), due to (a) rubber clone RRIM 600 was breeded for high latex yield not for high growth rate (b) the effect of tapping

3. Litter fall dynamics and production

a) Leaf

Leaf litter during 3 studied years show similar pattern that the maximum leaf litter peaked during dry season (December-January). In 2007, leaf litter decreased gradually from early February 2007 to the minimum in late April after that increased slowly with a small peak occurred in mid-July 2007 corresponded to rainy season thereafter decreased until September. During November – December 2007, leaf litter increased slowly then rapidly rising to the peak in late December 2007.

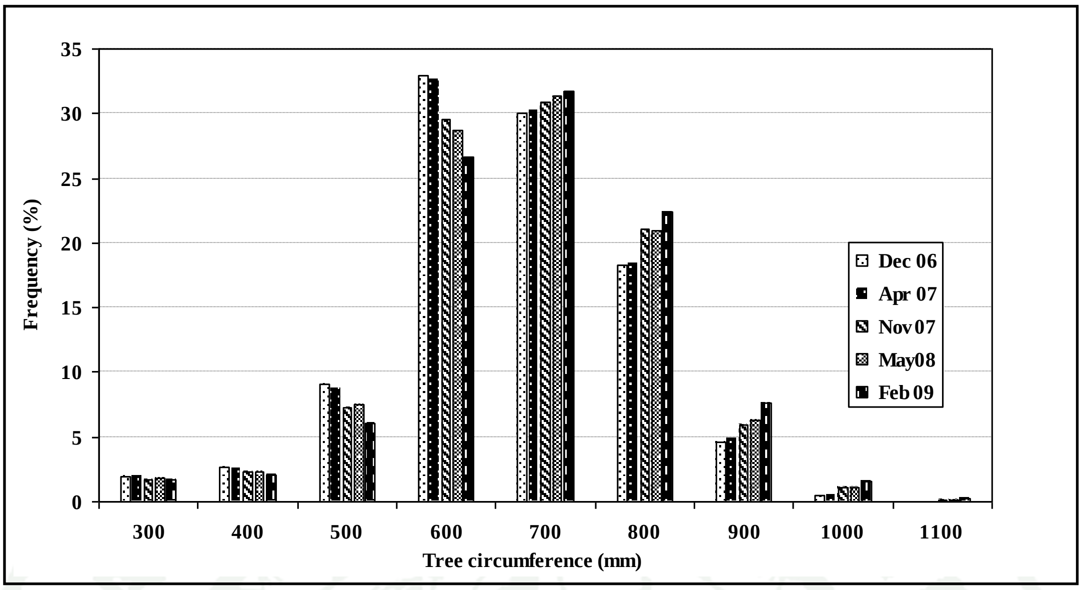

Figure 12 Tree circumference frequencies (%) in rubber plantation during December 2006 to February 2009

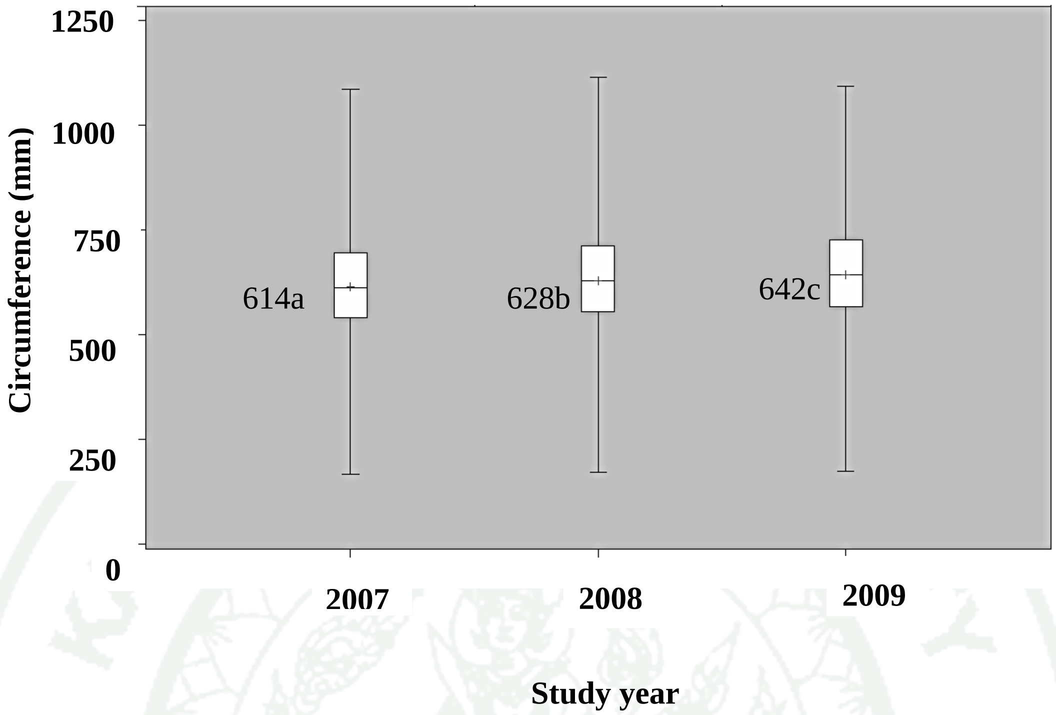

Figure 13 Mean tree circumference (mm) with error bar of rubber tree observed during 2007-2009

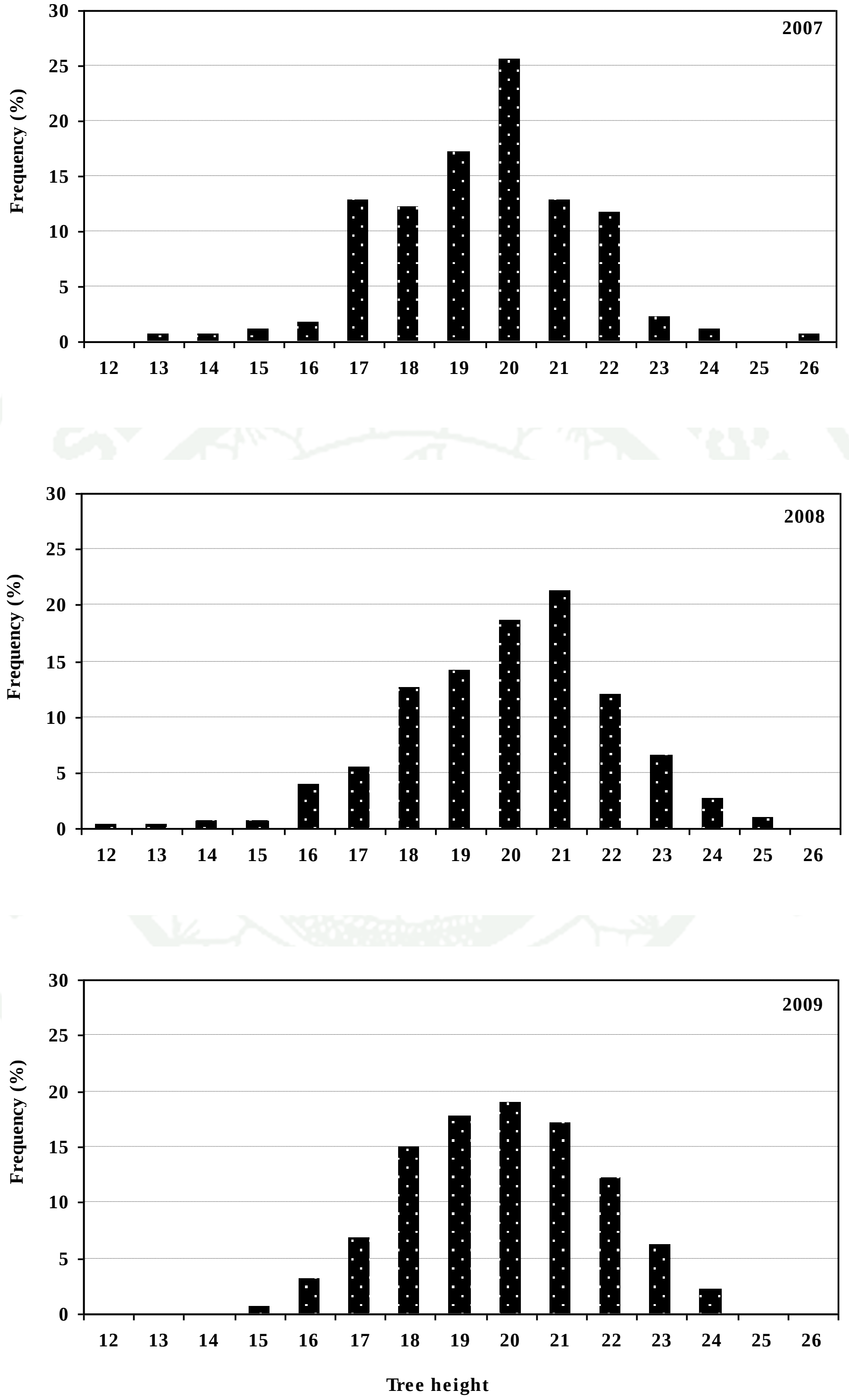

Figure 14 Tree height frequency of rubber plantation measured at defoliation period in 2007, 2008 and 2009.

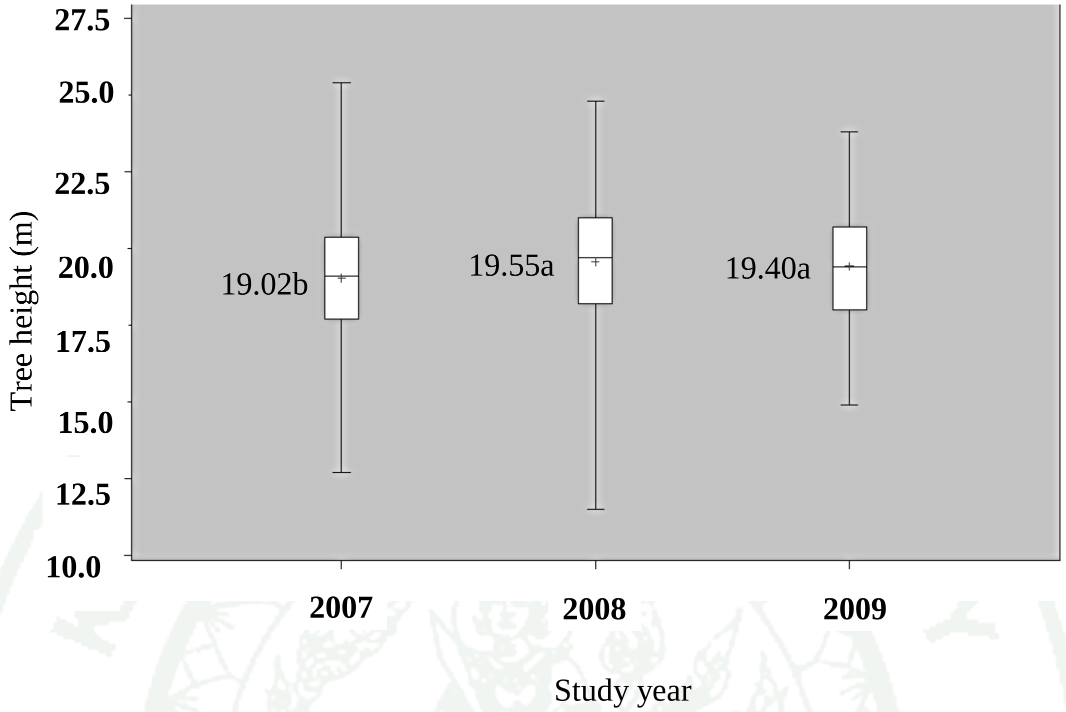

Figure 15 Mean rubber tree height with error bar observed during defoliation period in 2007 to 2009

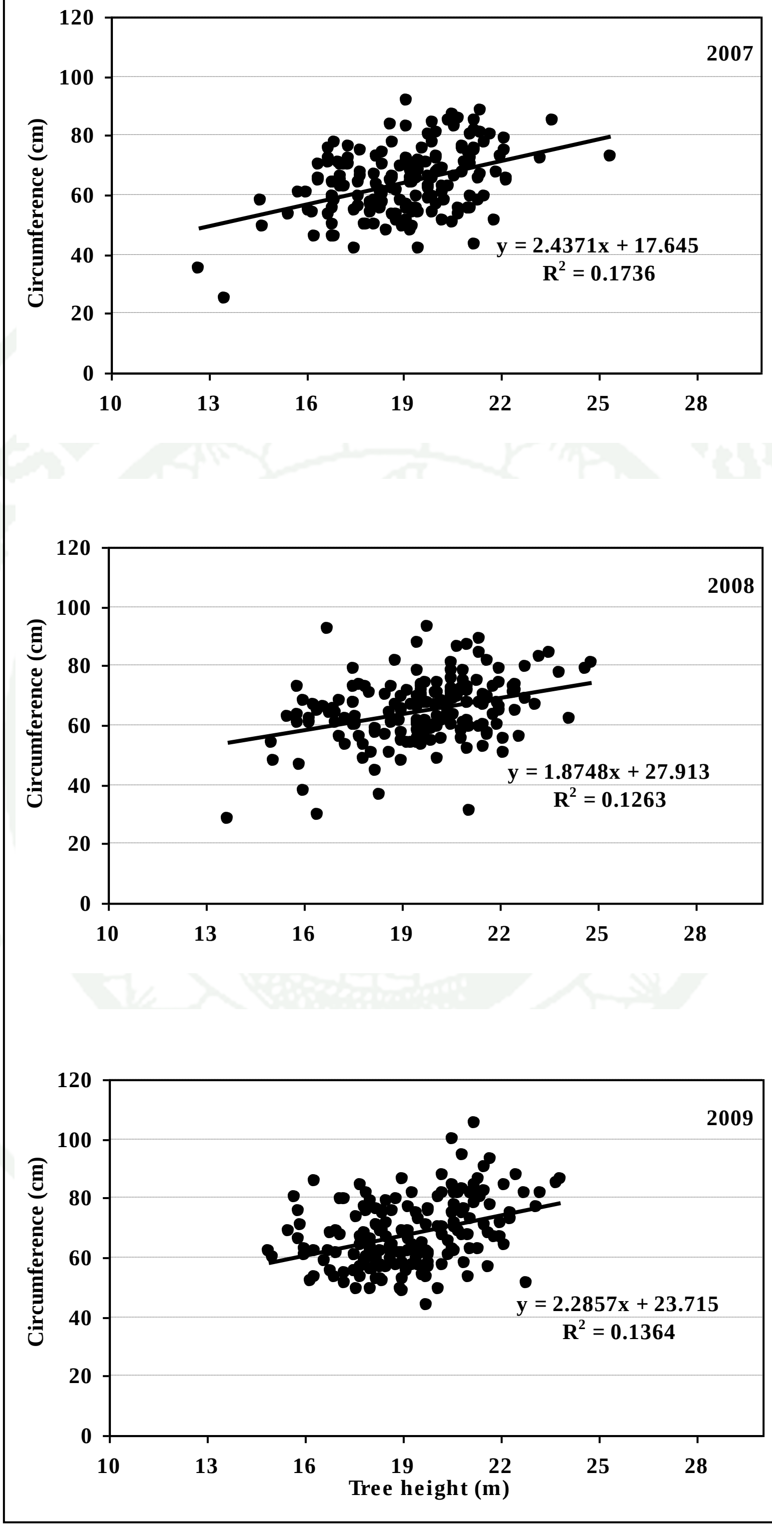

Figure 16 Relationship between tree height and circumference at 1.7 m height from soil level in rubber plantation during 2007 – 2009

at about 151.5 g m^{-2} then decreased to 86 g m^{-2} one week after. In 2008, a small peak of leaf litter was found in October then decreased slowly in November. In late December 2008, leaf litter increased rapidly and reached the maximum (83.2 g m^{-2}) in late January 2009 thereafter decreased rapidly to 5.3 g m^{-2} in early February. There was very low leaf litter during February-April then leaf litter increased gradually and fluctuated from May to October 2009, leaf litter peaked again in mid December 2009 to early January 2010 (Figure 17).

The annual leaf litter production was calculated from the late defoliation period of each studied year (February 2007 – January 2010). The annual dry mass leaf production was 626.4 g m^{-2} from February 2007 to January 2008, 547.7 g m^{-2} from February 2008 to January 2009 and 486.1 g m^{-2} from February 2009 to January 2010 (Table 7).

(1) Leaf area index (LAI) and Plant area index (PAI) dynamics

(a) LAI estimation from leaf litter

Leaf litter at the beginning of study period in November 2006 increased slowly causing a reduction in LAI. At the peak of leaf litter fall, during defoliation period, LAI decreased sharply. One week after defoliation period LAI began to increase with initiation of new leaves. The high correlation (R^2 = 0.95) between dry leaf area and leaf weight were found from leaf sample collected from litter traps. The specific leaf area (SLA) calculated from dry leaf litter was 101.63 g m^{-2}. The variation of leaf litter weight during the year reflected high variation in LAI. The highest estimated LAI during one year reached 6.14 in 2007, 5.39 in 2008 and 4.78 in 2009.

(b) PAI estimation from fisheye photographs

The pattern of PAI estimated from from fisheye photographs using software GLA along the growing period of each year showed the similar pattern as PAI estimated from leaf litter. The lowest PAI was found in dry season during defoliation period and increased rapidly during refoliation. In December 2006, PAI was stable at 2.1 before defoliation period which PAI decreased sharply from 2.1 to 1.1 in a few days. This decrease in PAI corresponded with the highest leaf litter fall period.During refoliation period that lasted 4 weeks PAI increased rapidly from 1.1back to 2.1. During March to October 2007, LAI increased gradually and reach the maximum in October (PAI~3)(Figure 19). Similar patterns were observed in 2008 and 2009

b) Petiole

The pattern of petiole litter synchronized with leaf litter along the year. The lower number was found in April - May for each studied year and the peak occurred in December – January. The pattern of petiole litter during February 2008-January 2009 showed small peak during October – November (Figure 18).

The annual petiole litter production was 116.7 g m^{-2} from February 2007 to January 2008, 110.1 g m^{-2} from February 2008 to January 2009, and 114.2 g m^{-2} from February 2009 to January 2010 (Table 7).

c) Branch

There was no distinct pattern of fluctuation of branch litter occurred along the studied year (Figure 20).

The annual branch litter was 250.5 g m^{-2} from February 2007 to January 2008, 213.9 g m^{-2} from February 2008 to January 2009 and 185.4 g m^{-2} from February 2009 to January 2010 (Table 7).

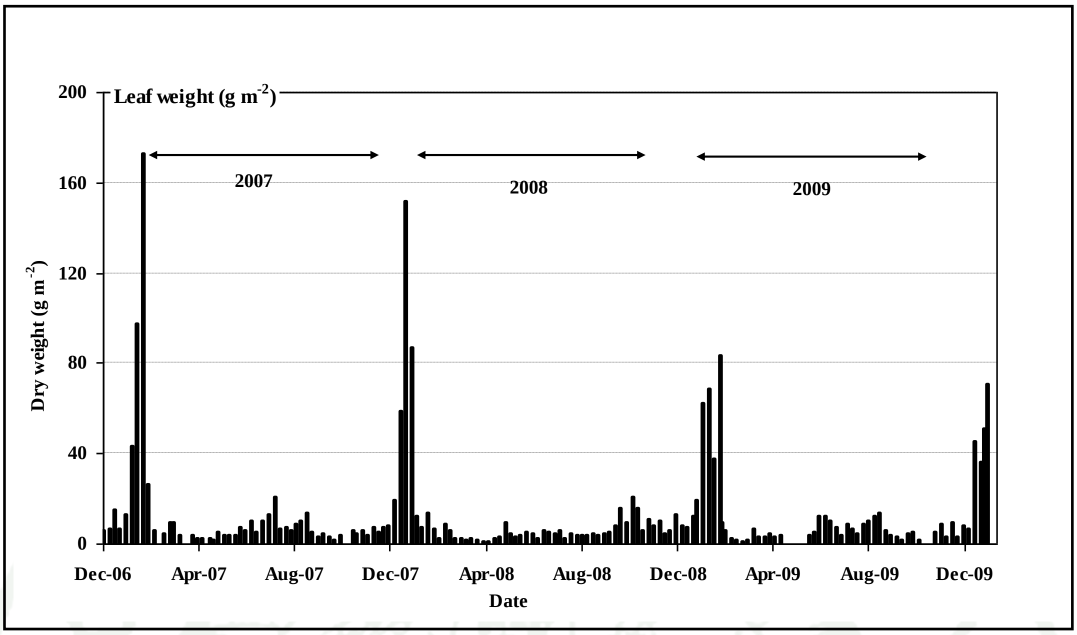

Figure 17 Leaf litter fall dynamics during December 2006 – December 2009

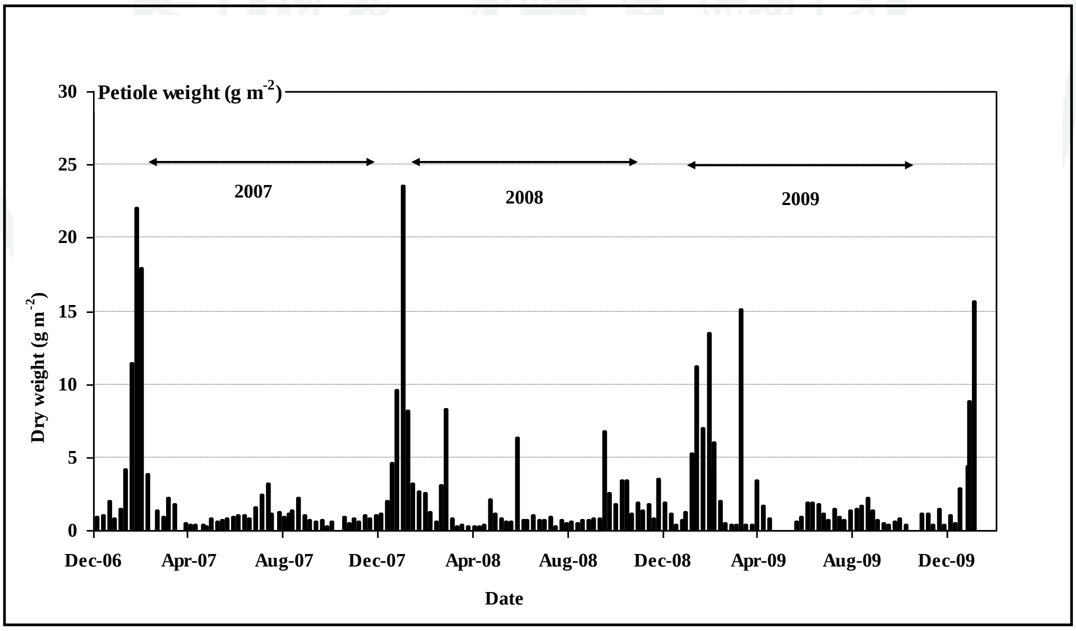

Figure 18 Petiole litter fall dynamics during December 2006 – December 2009

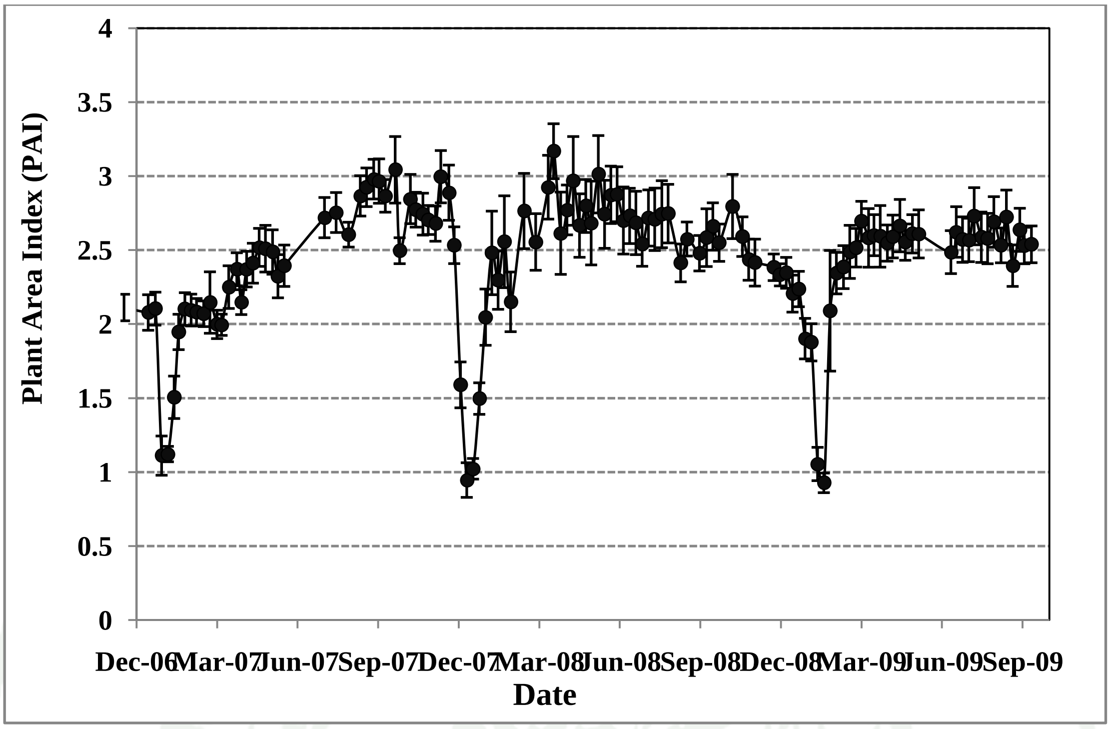

Figure 19 Plant area index dynamics during December 2006 – September 2009, estimated by fisheye photographs and analyzed with Gap Light Analyzer, (GLA) software. (I = standard error of mean, n=20)

d) Seed

The seed litter peaked during the rainy season and small amount of litter was found during late dry season to early of rainy season (Figure 21).

The annual seed litter production of each studied year showed small differences varied from79.6 g m^{-2} from February 2007 to January 2008, 83.7 g m^{-2} from February 2008 to January 2009, and 98.4 g m^{-2} from February 2009 to January 2010 (Table 7).

e) Husk

The pattern of husk litter synchronized with seed litter.Most of husk litter was found in rainy season and some husk litter was found in February for all studied year (Figure 22).

The annual husk production was 167.2 g m^{-2} from February 2007 to January 2008, 189.9 g m^{-2} from February 2008 to January 2009, and 167.8 g m^{-2} from February 2009 to January 2010 (Table 7).

f) Flower

Flower litter showed the same pattern in all 3 studied years. The peak of flower litter occurred during February-March (late dry season) and some flower litter was found in April to June. In 2009, some flower litter was found in July - September. (Figure 23).

The annual flower litter production was 102.1 g m^{-2} from February 2008 to January 2009, 57.4 g m^{-2} from February 2007 - January 2008 and 57.2 g m^{-2} from February 2009 - January 2010 (Table 7).

Rubber litter fall from 3 observation years had the same pattern which leaf produced the highest litterfall (45%) followed by branch (18%), husk (14%), petiole (9%), seed (7%) and flower (6%). The total litter fall produced was 13.43 t ha^{-1} from February 2007 – January 2008, 12.78 t ha^{-1} from February 2008 –January 2009, and 11.22 t ha^{-1} from February 2009 – January 2010 (Table 8).

B. Belowground dynamics

Tap and coarse root increment for each studied year were calculated from allometry equation.

1. Fine root dynamics observed by observation chamber (Rhizotron)

a) Root elongation rate

The pattern of root elongation rate during 2 growing seasons (Jan 08-Oct 09) was rather similar: it decreased in dry season and increased in wet season (Figure 24). The variations during the wet season in 2009 were greater than in 2008 with a rapid decreased from 0.1 cm d^{-1} to near zero in August 2009. The highest mean root elongation rate in 2008 occurred in June (0.28 cm d^{-1}) and in 2009 it was 0.31 cm d^{-1} in October. The lowest mean elongation rate in both years were very close to zero (0.004 cm d^{-1} in 2008 and 0.0005 cm d^{-1} in 2009) during January to February which corresponded to the driest period (no rainfall and low soil water content).

b) Number of growing root

One month after rhizotron installation in October 2007, the number of growing root increased rapidly until December 2007 and decreased sharply from December to very low number of growing root in February 2008. Number of growing root varied during February to May and increase to the maximum in June 2008 thereafter decreased sharply from about 120 roots to less than 20 roots in September and increase to 61 roots in the mid of October 2008. In late October 2008 the number

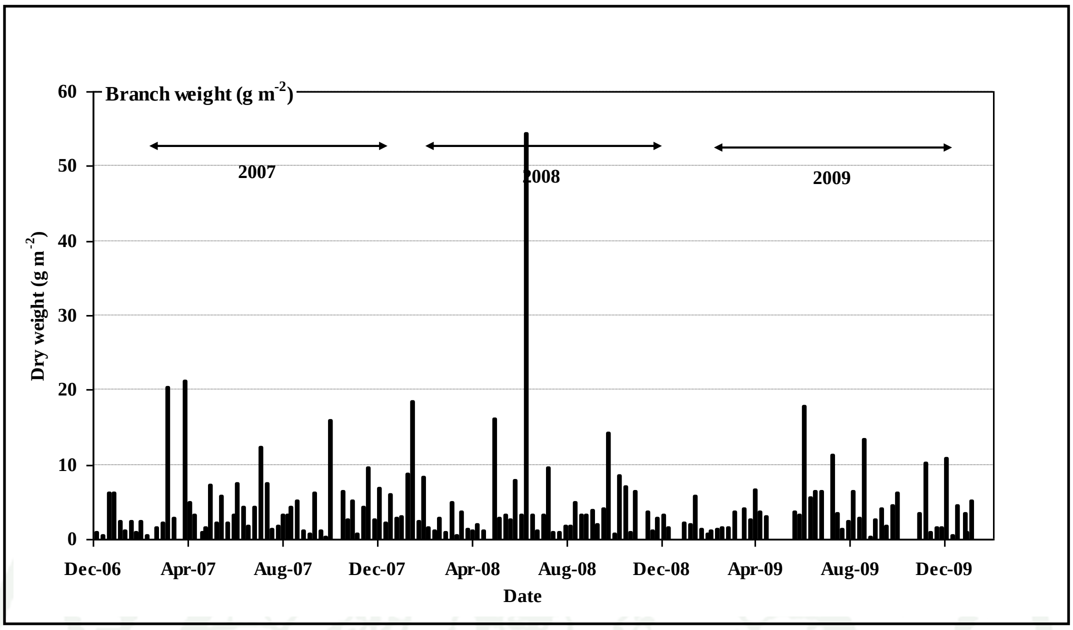

Figure 20 Branch litter fall dynamics during December 2006 – December 2009

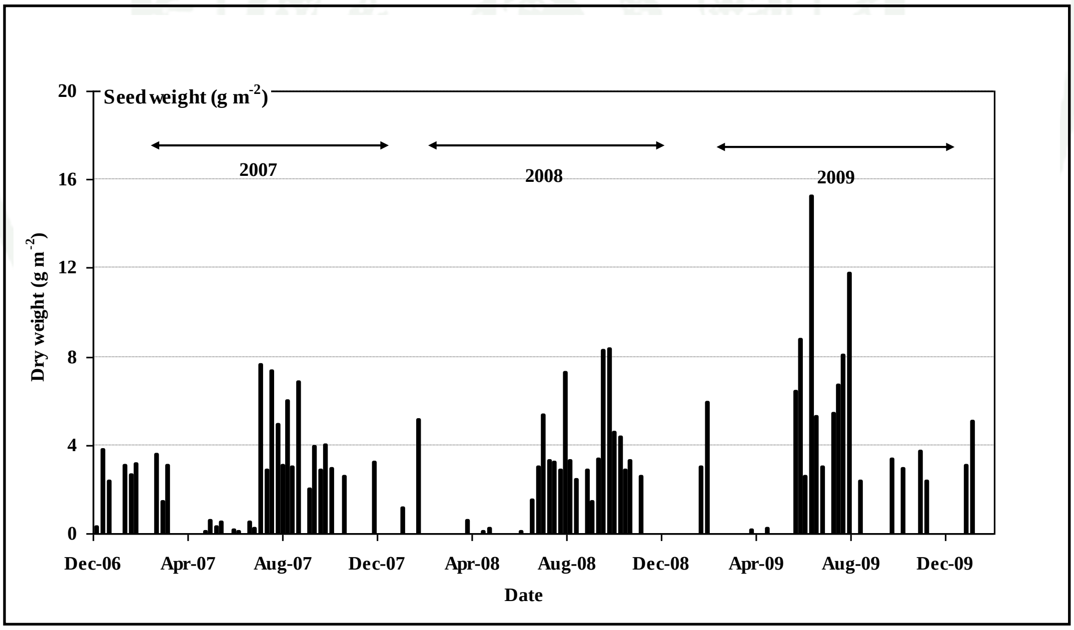

Figure 21 Seed litter fall dynamics during December 2006 – December 2009

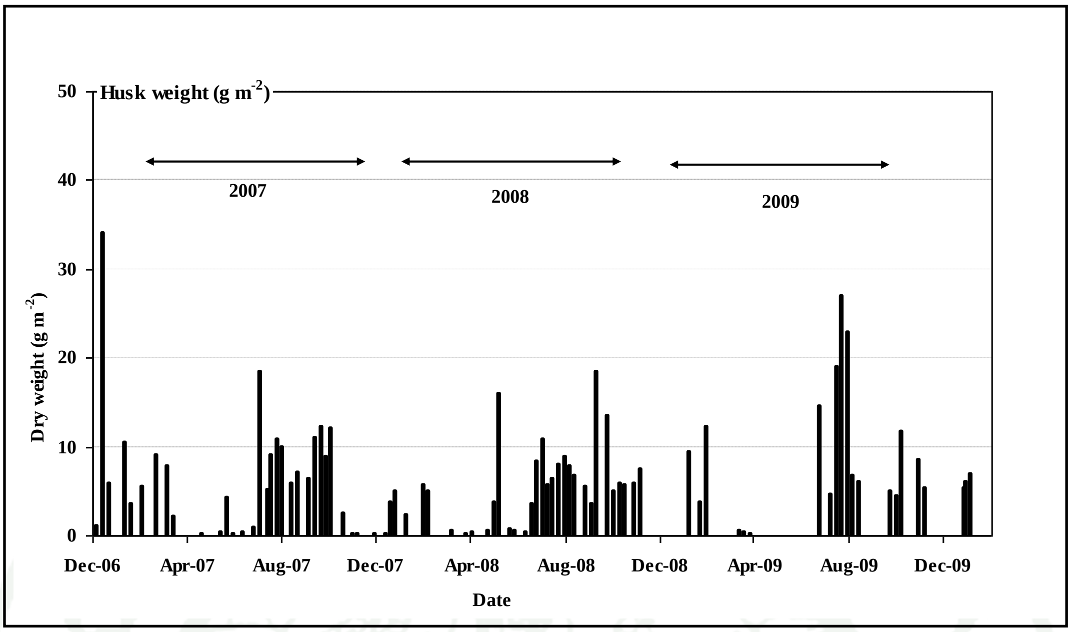

Figure 22 Husk litter fall dynamics during December 2006 – December 2009

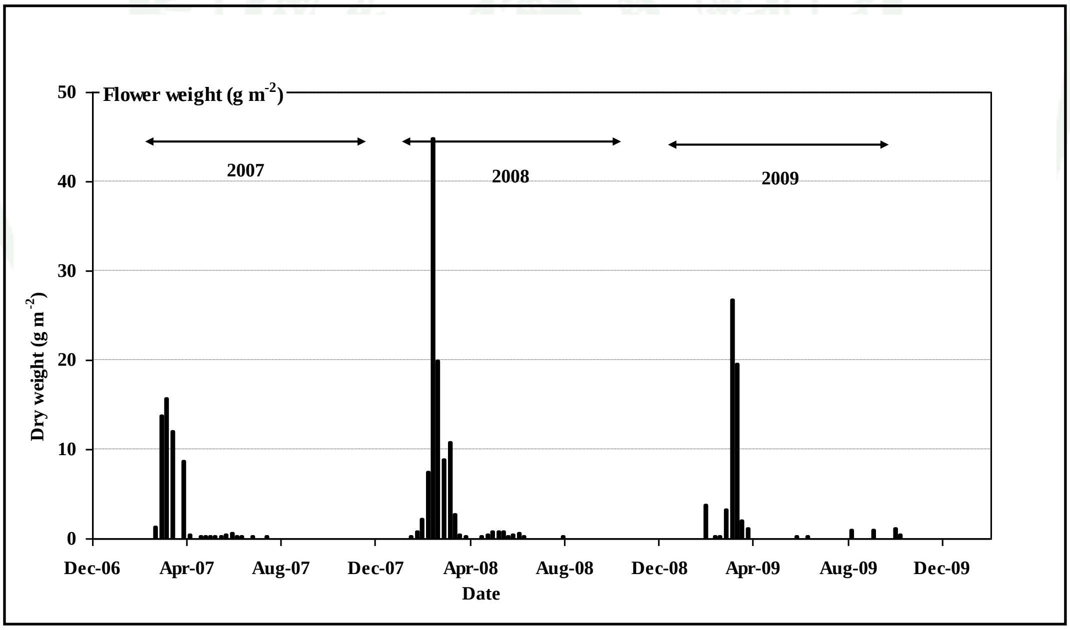

Figure 23 Flower litter fall dynamics during December 2006 – December 2009

Table 7 Annual rubber stand litter production during December 2006 – January 2010

Year	Plant Litter (g/m^2)						Total
	Leaf	Petiole	Branch	Seed	Husk	Flower	(g/m^2)
2007	626.4	116.7	250.5	79.6	167.2	57.4	1,343.1
2008	547.7	110.1	213.9	83.7	189.9	102.1	1,278.2
2009	486.1	114.2	185.4	98.4	167.8	57.2	1,122.3

Table 8 Percentage of litterfall production during 2007-2009

Plant litter	Total litter weight (%)
Leaf	45
Petiole	9
Branch	18
Seed	7
Husk	14
Flower	6

of growing root decreased slowly to near zero during February to March 2009 then increased slowly to 34 roots in April 2009 and varied from 7 roots in June to 49 roots in September 2009 (Figure 25).

c) Number of new root

The pattern of new root occurrence in 2008 varied along the year with a lower number of new roots in February and August and a higher number in May and September. In 2009 the pattern was the same as in 2008 but the total number of new roots in 2009 was less than in 2008 (Figure 26).

d) Number of stop growing root

The number of stop growing roots (root with no elongation) of all root types increased sharply during December 2007 (Dry season) to the peak in April 2008 then decreased gradually. The number of stop growing root increased again in May 2009 until a maximum value in August 2009 (wet season) after that it decreased sharply until October (late wet season) (Figure 27).

e) Number of dead root

The number of dead root synchronized with the number of new root. The fluctuation started with the lowest number during the dry season in 2008, increased rapidly in May and decreased again in August (mid wet season). The number of dead roots increased again during late August to the highest number in October then it decreased In 2009, only few dead roots were found in the rhizotrons (Figure 28).

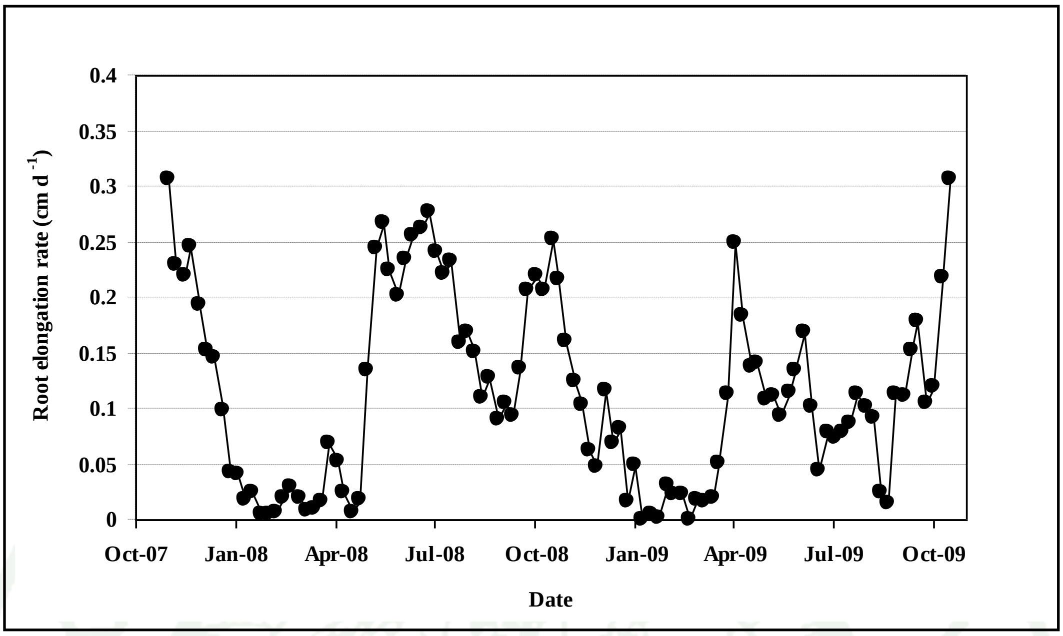

Figure 24 Dynamics of fine root elongation rate(cm d^{-1}) from October 2007 to October 2009

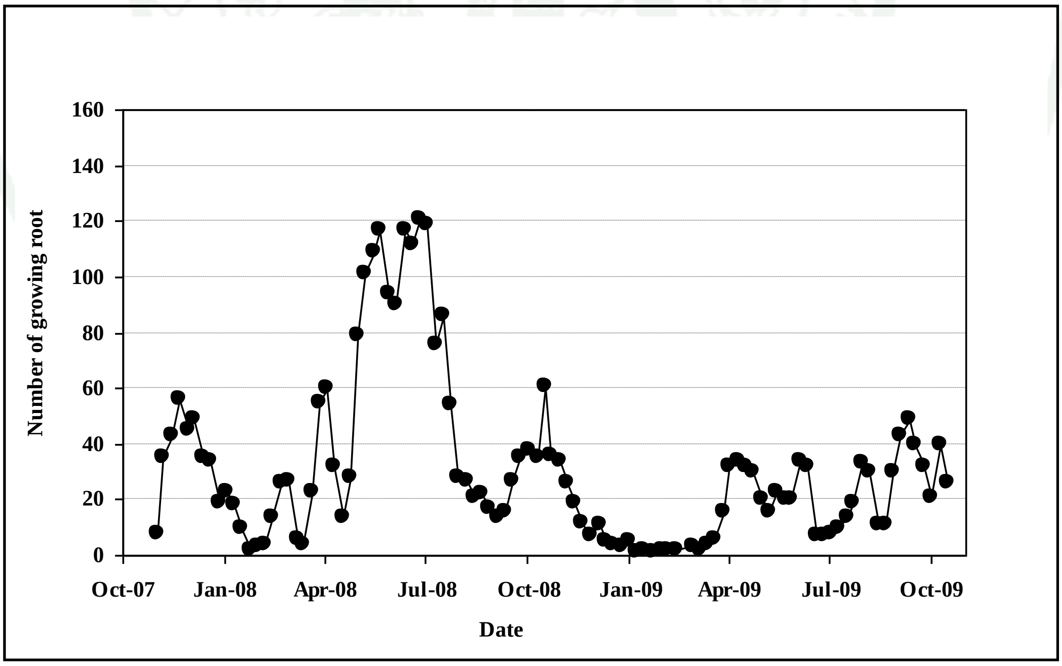

Figure 25 Dynamics of number of growing fine root from October 2007 to October 2009

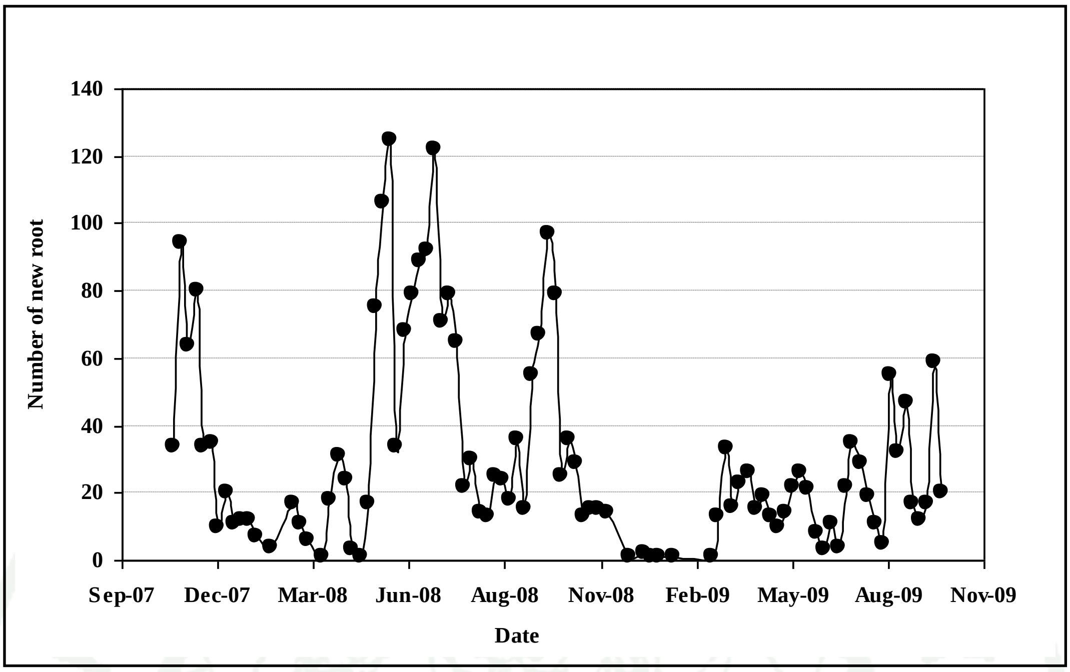

Figure 26 Dynamics of number of new root from October 2007 to October 2009

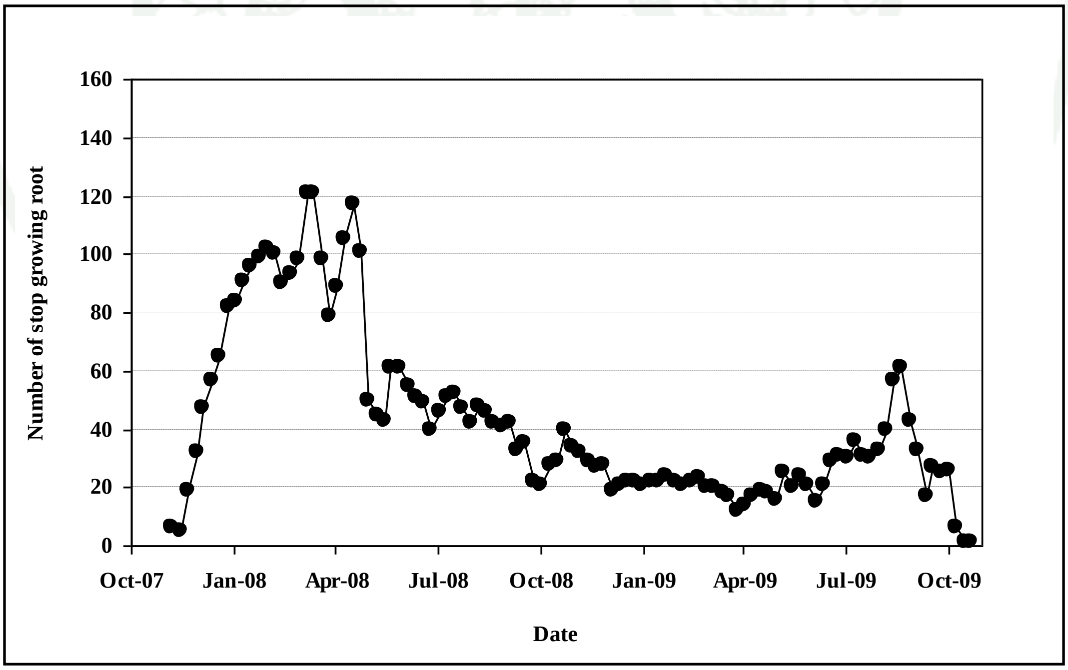

Figure 27 Dynamics of number of stop growing root from October 2007 to October 2009

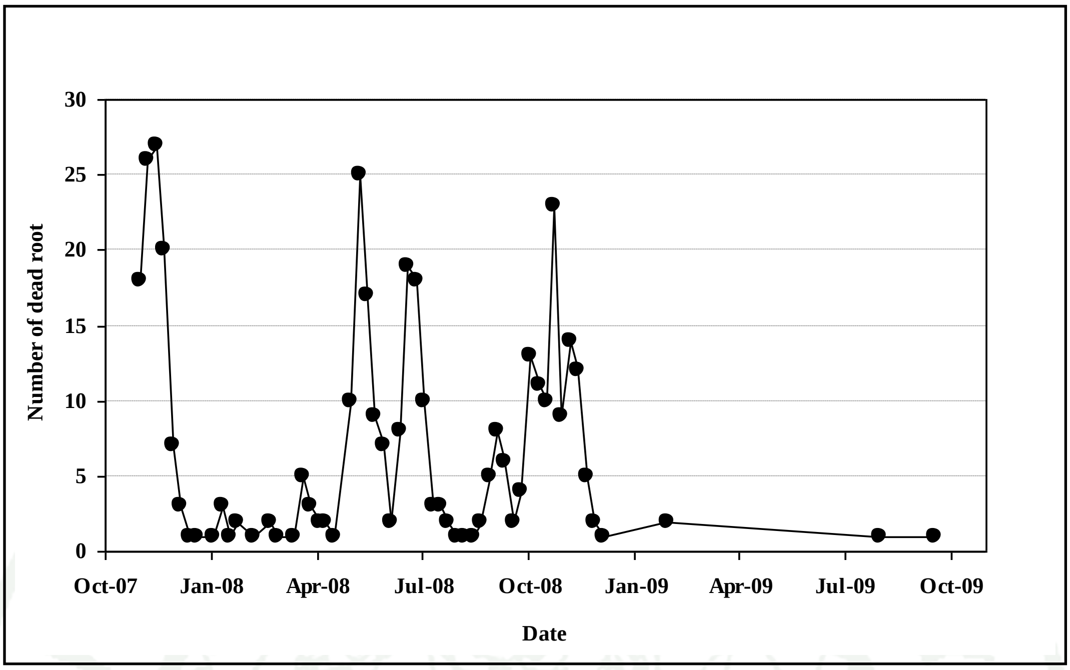

Figure 28 Dynamics of number of dead root from October 2007 to October 2009

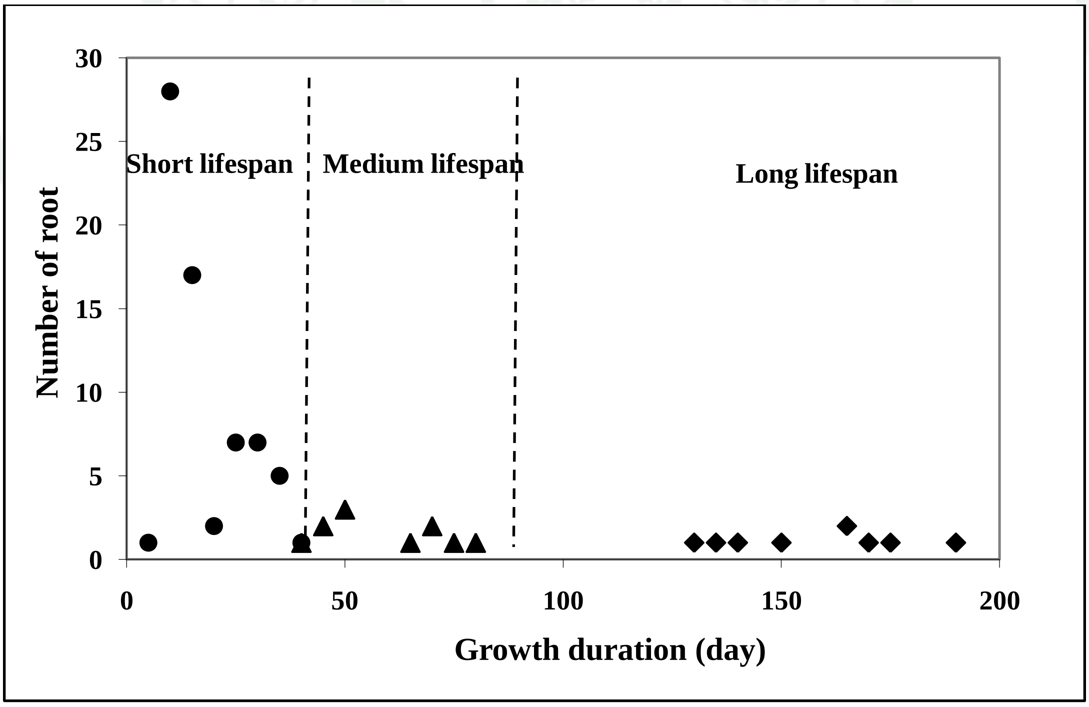

Figure 29 Growth duration (day) of fine root from October 2007 to October 2009

f) Growth duration (root lifespan)

The growth duration of fine root was anlysed using only fine root with known the birth date. Although all roots were categorized as “fine root” but their lifespan was different which ranged from 5 - 190 days. After classified according to their age, they could be further classified in 3 groups: roots with a short lifespan which lived between 5 – 40 days, those with a medium lifespan (40 – 80 days) and those with a long lifespan (130 – 190 days) (Figure 29).

g) Relationship between root dynamics and other factors

(1) Soil water content

Soil water content in each soil layer showed similar pattern of change during the year. The lowest value was found in dry season (January – February) in 2008 (Figure 31). In dry season 2008, soil water content at 20 cm soil depth was rather lower than other layers. After mild rain in March, soil water content increased gradually until it reached the maximum in June and decreased gradually since middle of July. The pattern in 2009 was different from 2008. The highest soil water content was found in April 2009 and decreased gradually until it reached minimum in August 2009.

The response on root elongation rate with soil water content showed the same pattern along the studied period (Figure 32). In dry season 2008, when the soil water content decreased to the lowest value, the root elongation rate decreased to the minimum. After soil water content increased in May, root elongation rate increased rapidly and reached the maximum in June. After September 2008, the elongation rate decreased along with the decreasing of soil water content. The pattern of root elongation rate in dry season of 2009 was the same as in 2008 except the rapid decrease in elongation rate in April. In wet season 2009 the pattern was similar to 2008. Root elongation rate was very low and close to zero in August then increased rapidly until 0.3 cm day^{-1} in October (Figure 32).

The number of growing roots during November 2007 to July 2008 were synchronous with soil water content but the pattern changed in August 2008. The number of growing roots decrease while the soil water content reached the maximum (20.1%). The pattern in 2009 was almost the same as 2008 but the number of growing root and soil water content were lower (Figure 33).

The number of new root increased rapidly along with soil water content within one month after rhizotron installation in October 2007. Thereafter the number of new root decreased sharply from 85 roots to 0 during November 2007 to February 2008 with the decreased of soil water content. The number of new root increased again after soil water content increase in March 2008 then decreased to near zero in April. In wet season, number of new root increased to the maximum when the soil water content increased to near 20% level. In the middle of wet season (August 2008) when the soil water content reached to the maximum the number of new root decreased sharply and increased again in the end of wet season. The pattern in 2009 was similar to 2008 but the number of new root and soil water content was lower (Figure 34).

The number of stop growing root increased rapidly from November 2007 to March 2008 when the soil water content decreased to the minimum, then the number of stop growing root decreased gradually along with the decrease of soil water content until February 2009. In 2009, the number of stop growing root increased slowly during varied of soil water content (Figure 35).

The relationship between number of dead root and soil water content was clear in the end of in 2007. The decrease in number of dead root corresponded to the decrease in soil water content. The contrary was founded in September 2008 which the number of dead root increased when the soil water content decreased. The pattern in 2009 was not clear due to few number of dead root (Figure 36).

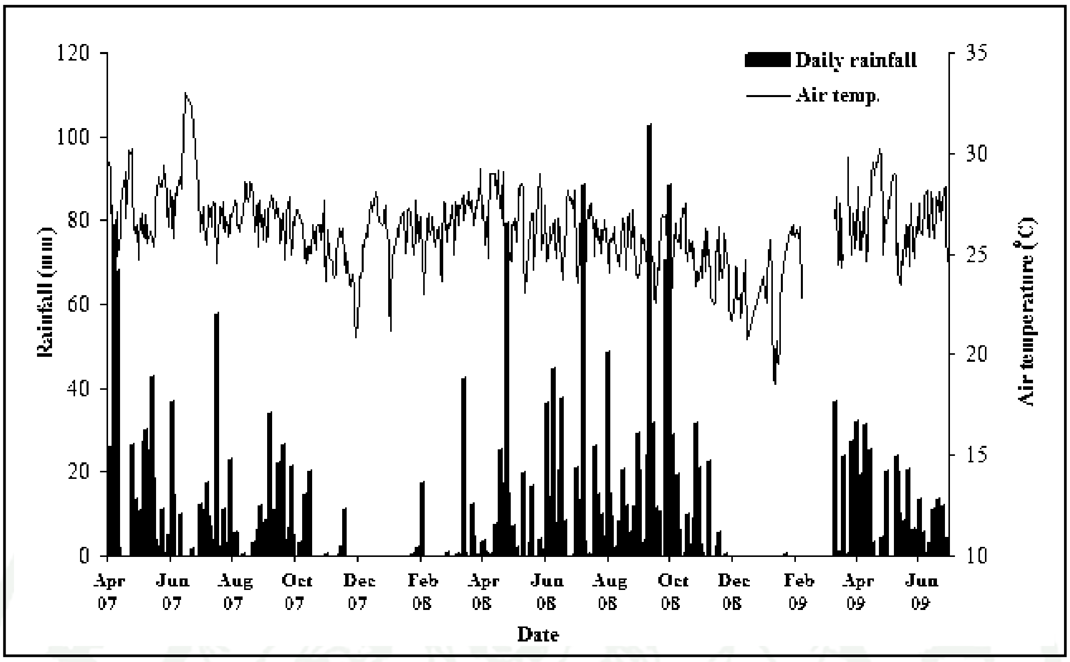

Figure 30 Daily rainfall (mm) and air temperature (^{o}C) during 2007 – 2009 at Chachoeng Sao Rubber Research Center, Sanamchaiket District, Chachoeng Sao Province

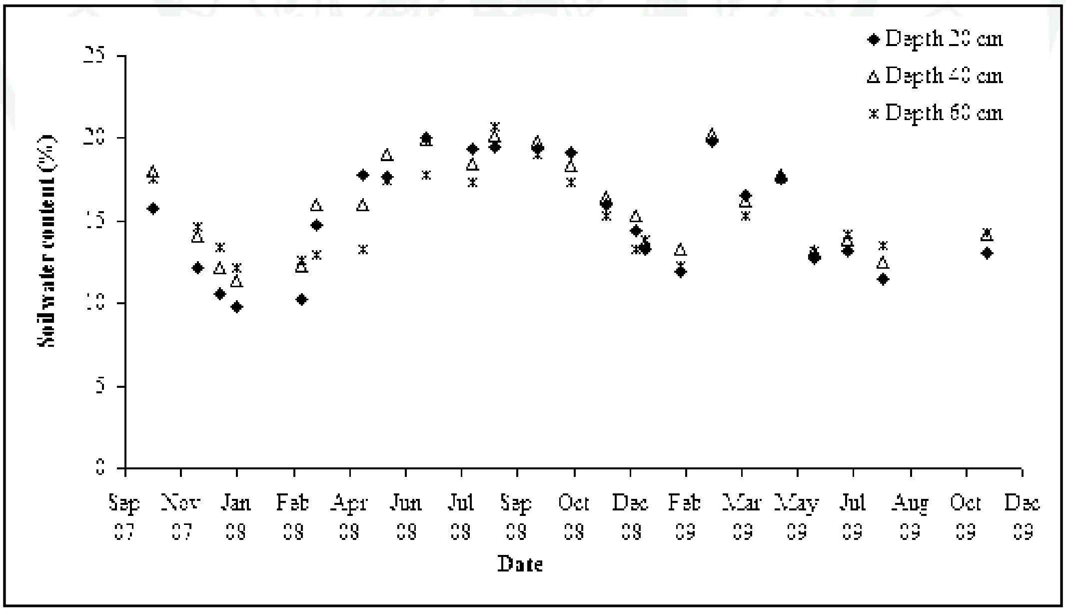

Figure 31 Soil water content (%) in 3 depths along the soil layer during September 2007 to December 2009.

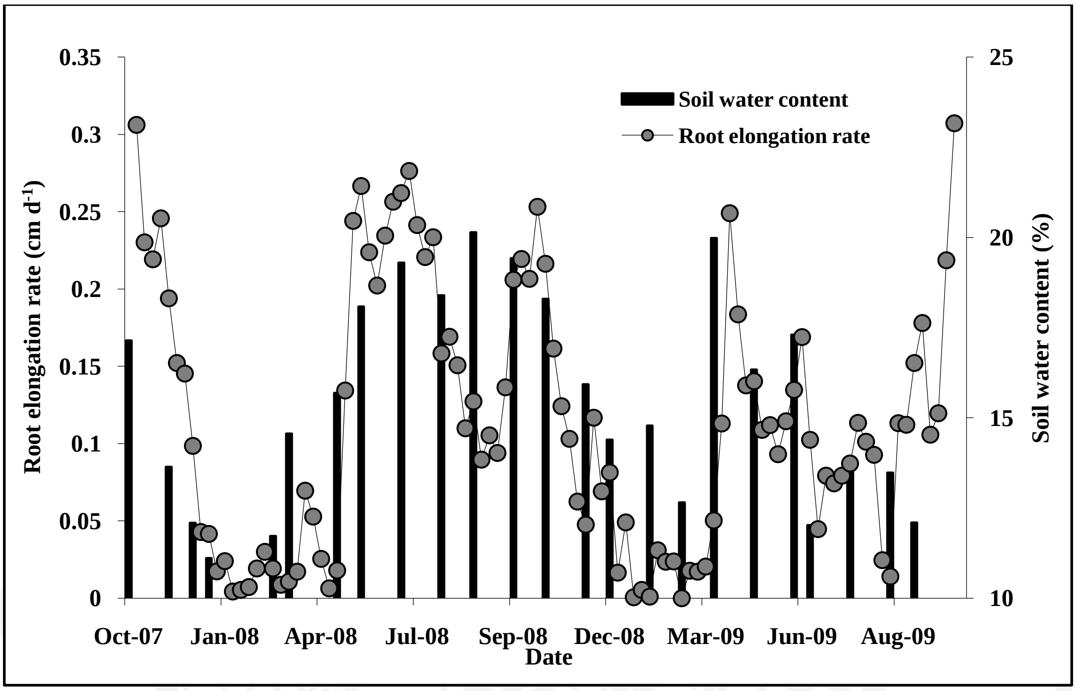

Figure 32 Relationship between root elongation rate (cm d^{-1}) and soil water content (%) from October 2007 to October 2009

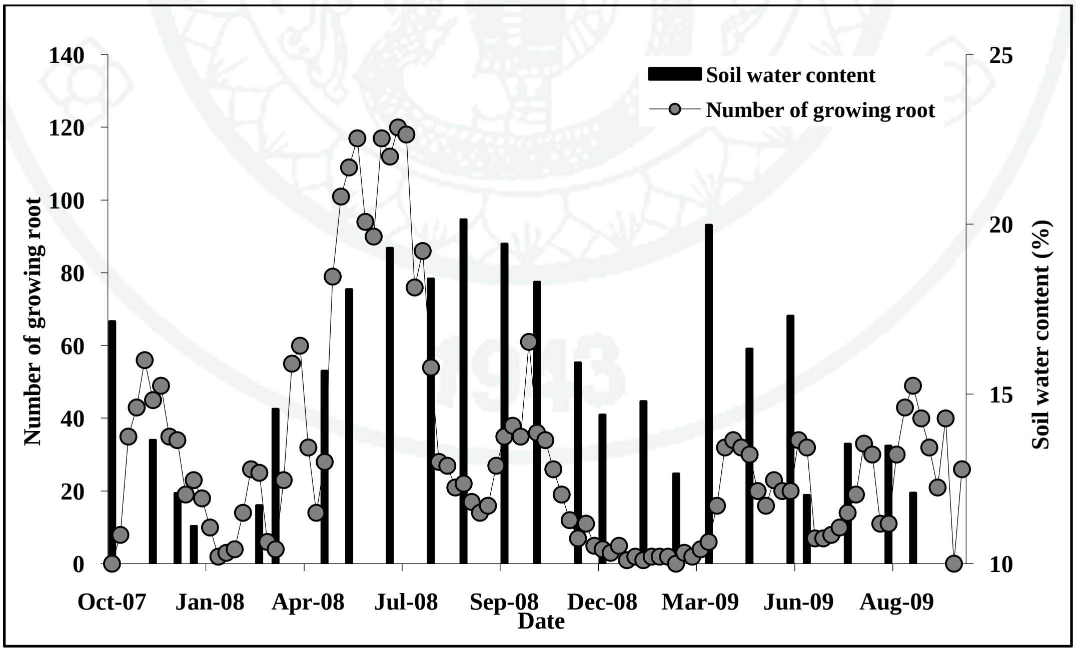

Figure 33 Relationship between number of growing root and soil water content (%) from October 2007 to October 2009

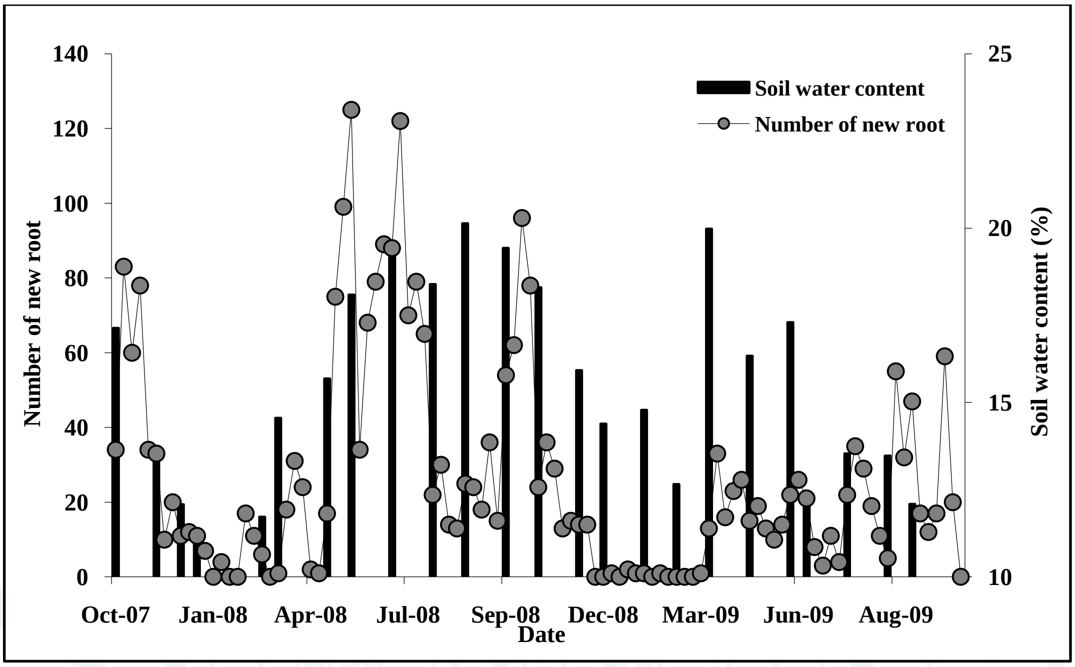

Figure 34 Relationship between number of new root and soil water content (%) from October 2007 to October 2009

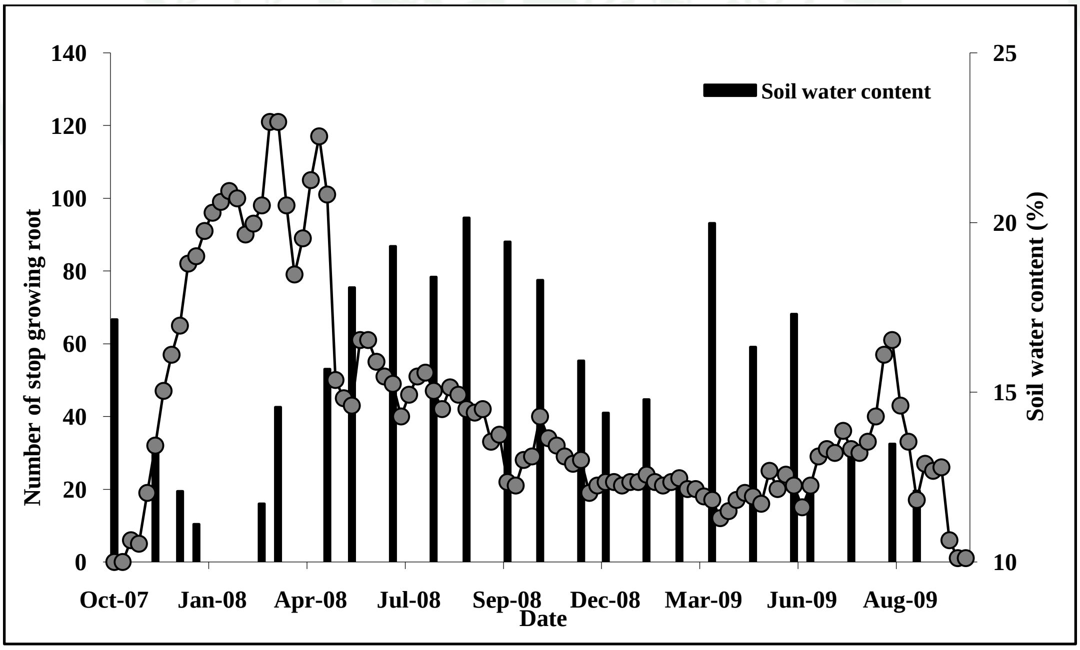

Figure 35 Relationship between number of stop growingroot and soil water content (%) from October 2007 to October 2009

(2) Rainfall

The pattern of rainfall in both 2008 and 2009 were similar. The rain started in March and stopped in December but the sum of rainfall in 2008 was significantly higher than 2009 (Figure 30). Root elongation rate was highly related to rainfall throughout the observing period. In dry season 2008, root elongation rate was very low until small number of rainfall events occurred in March, during which time, root elongation rate increased rapidly. During wet season, root elongation rate increased significantly and varied with rainfalls (Figure 37).

The pattern of rainfall synchronized with the number of growing root in both 2008 and 2009. Higher number of growing root was found in rainy season and the lower number of growing root was found during dry season. That number of growing root in 2009 was lower than in 2008 might be due to the smaller amount of rainfall (Figure 38).

The number of new roots had the same pattern as root elongation rate, it increased along with the increasing of rainfall. The maximum number of new roots was found in May 2008. The lowest number of new roots found was in early 2009 due to no rainfall. In 2008, the wet season was longer and had the higher amount of rainfalls than the average of wet seasons (1,294 mm). However, in 2009 the annual rainfall was lower than normal (Figure 39).

The number of stop growing root was highest during the dry season with little rainfall. After rain resumed in May 2008, the number of stop growingroot decreased sharply and showed small fluctuations during the wet season. Number of stop growing roots decreased significantly in August when rainfall peaked. On the other hand, the number of stop growing roots increased when rainfall decreased in November. In 2009, the number of stop growing roots had the similar pattern as in 2008 but the total number of stop growing roots was lower than in 2008 (Figure 40).

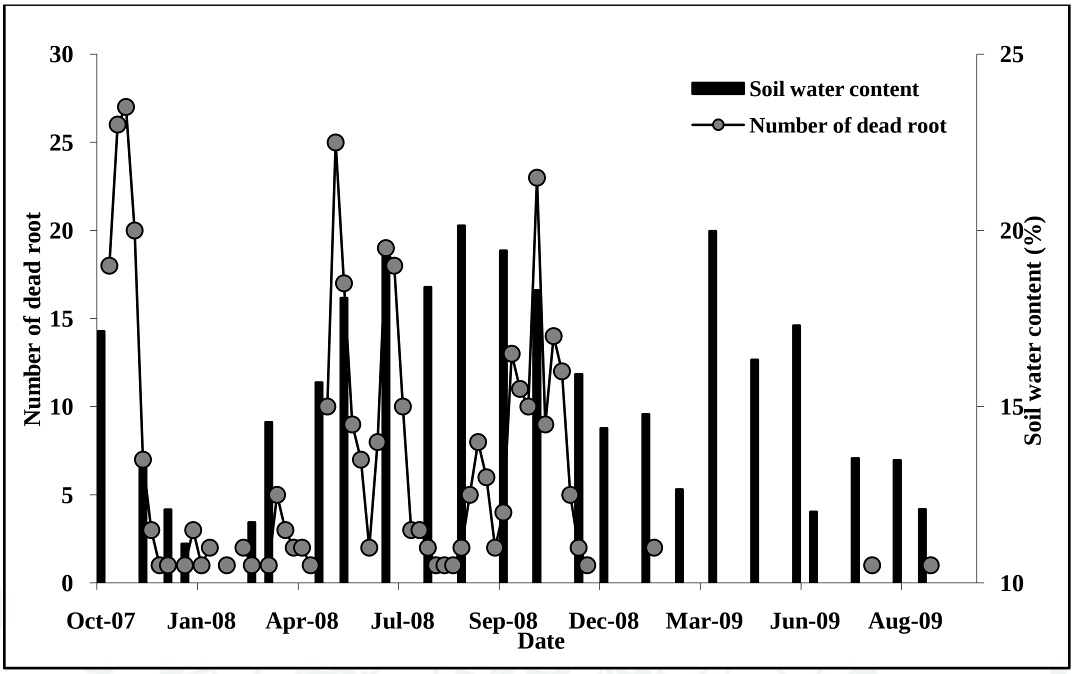

Figure 36 Relationship between number of dead root and soil water content (%) from October 2007 to October 2009

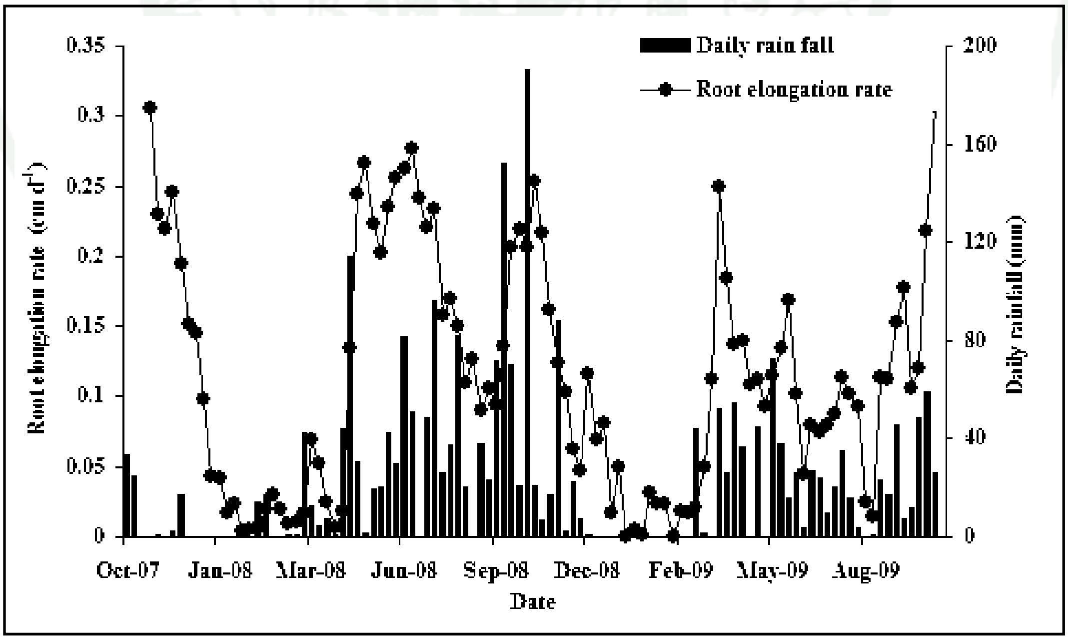

Figure 37 Relationship between root elongation rate (cm d^{-1}) and daily rainfall (mm) from October 2007 to October 2009

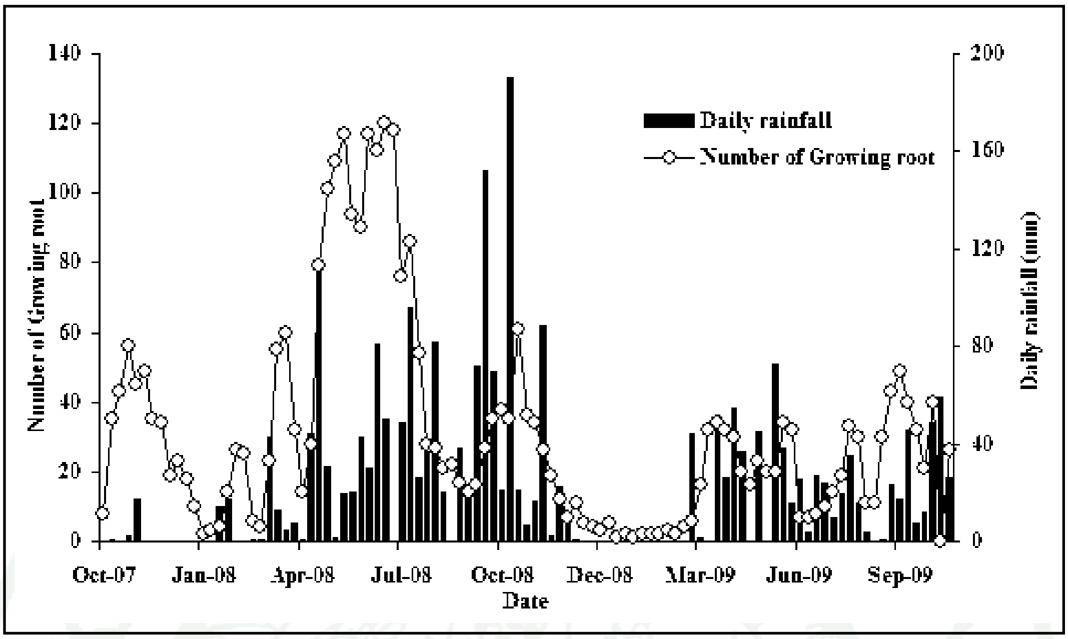

Figure 38 Relationship between number of growing root and daily rainfall (mm) from October 2007 to October 2009

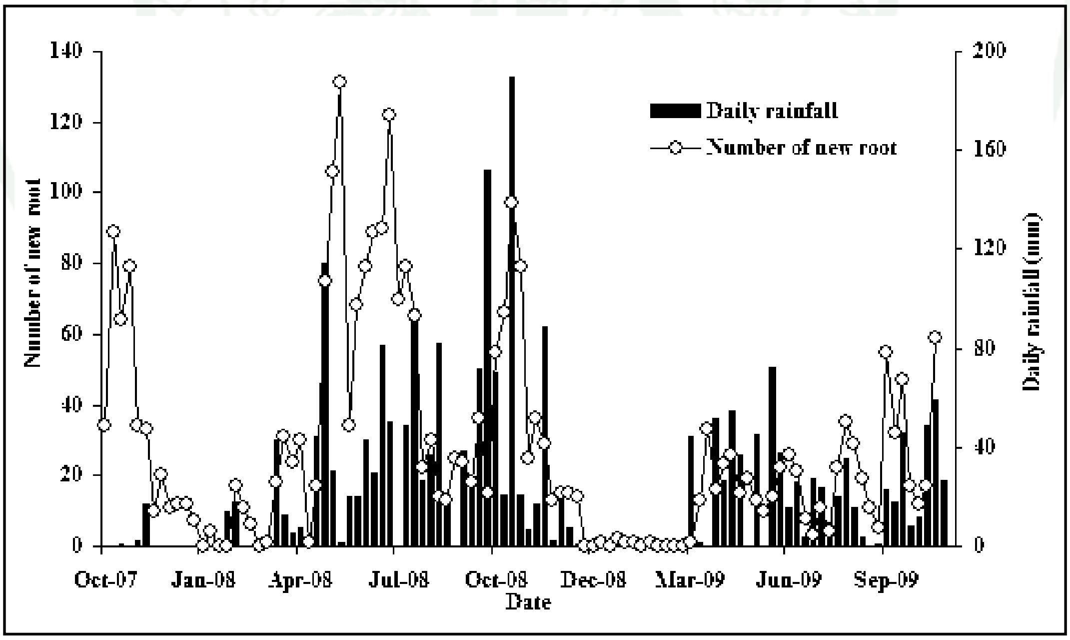

Figure 39 Relationship between number of new root and daily rainfall (mm) from October 2007 to October 2009

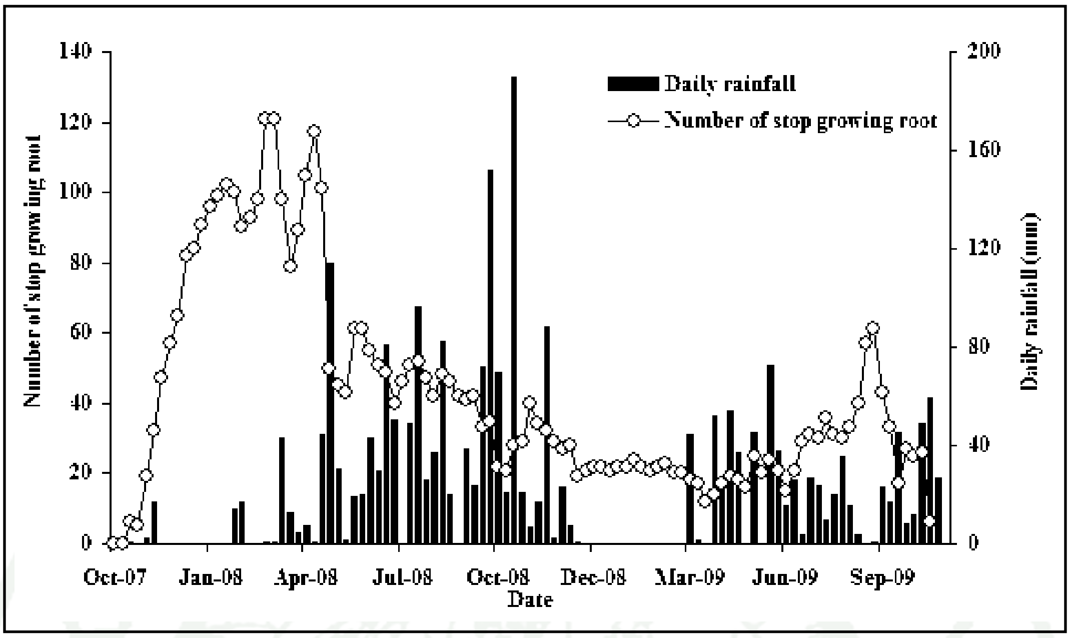

Figure 40 Relationship between number of stop growing root and daily rainfall (mm) from October 2007 to October 2009

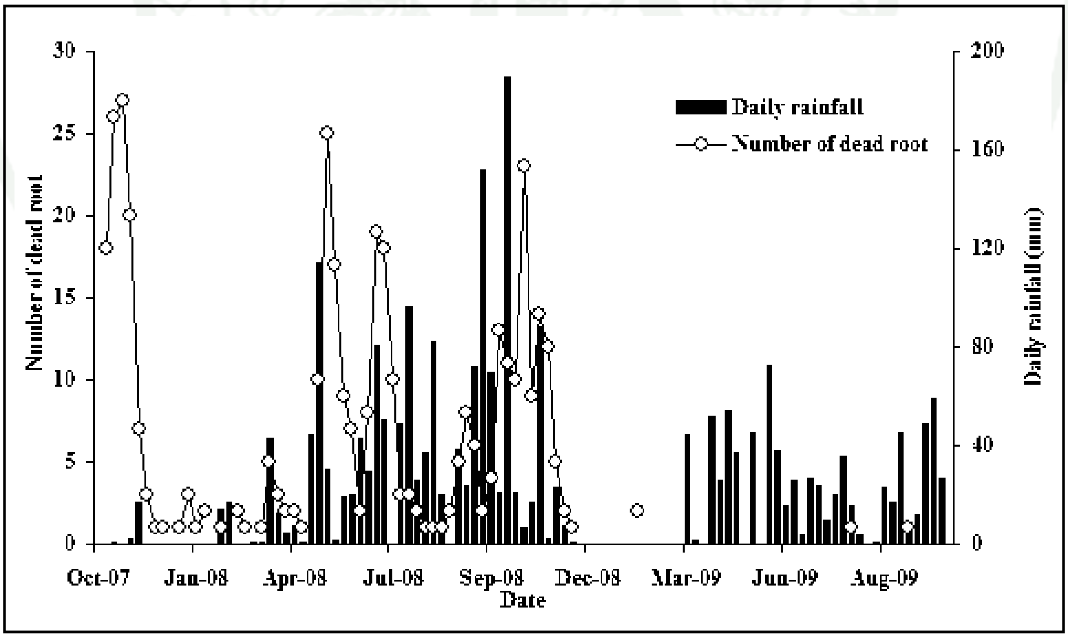

Figure 41 Relationship between number of dead root and daily rainfall (mm) from October 2007 to October 2009

The number of dead root increased rapidly after rhizotron installation then decreased to near zero during October 2007 to March 2008 corresponded to very low rainfall. After rain resumed in late March 2008, the number of dead root increased and syncronized with the pattern of rain fall (Figure 41).

(3) Plant Area Index (PAI)

In the early December 2007, root elongation rate decreased with the rapid decrease of PAI from 3 to 0.95. During refoliation period from late January to February, root elongation remained low until late April 2008 while PAI increased rapidly from 0.95 - 2.48.Root elongation rate increased rapidly after PAI reached maximum value in May 2008. While, PAI varied from 2.2 to 3.17 from May to November 2008 root elongation rate did not relate to PAI. Both PAI and root elongation rate decreased significantly during December 2008 to late January 2009 and it was evident that reduction in root elongation rate occurred before PAI. One week after that, PAI started to increase rapidly from 0.8 to 2.2 while the root elongation rate increased relatively slowly (Figure 42).

(4) Leaf litterfall

One month after rhizotron installation, root elongation rate started to decrease rapidly in November 2007, and reached the minimum in January 2008. Peak of leaf litterfall came later in December 2007. No relationship between root elongation rate and leaf litterfall was found during rainy season of 2008. The pattern in 2009 was similar to 2008 (Figure 43).

h) Fine root biomass, production and turnover from sequential and ingrowth cores

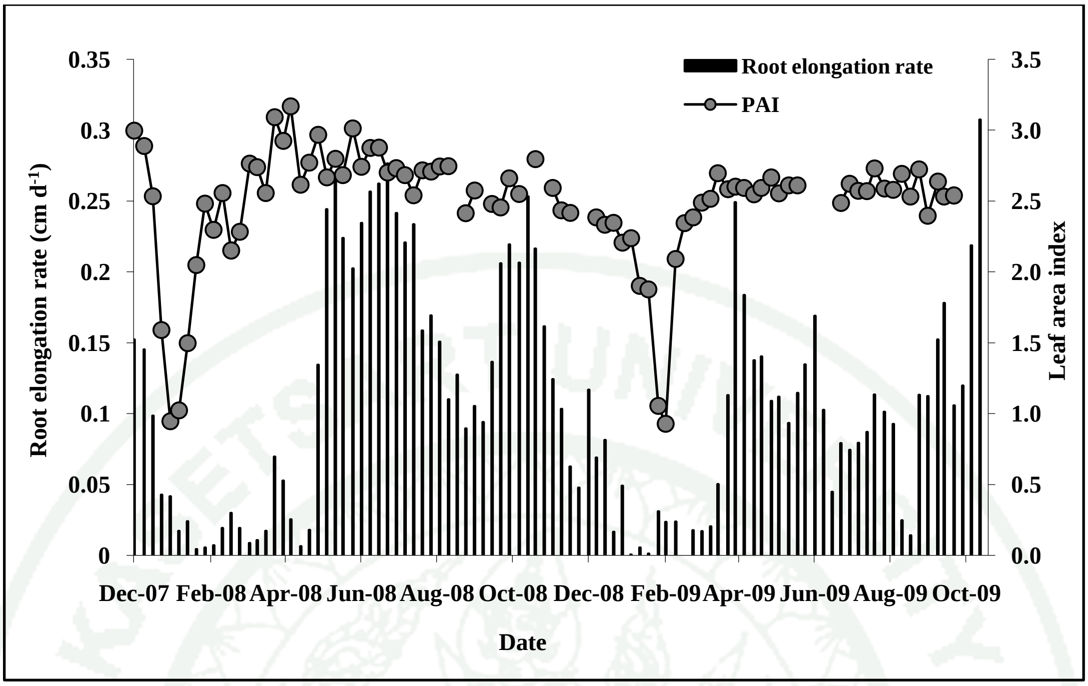

Figure 42 Relationship between root elongation rate (cm d^{-1}) and leaf area index from October 2007 to October 2009

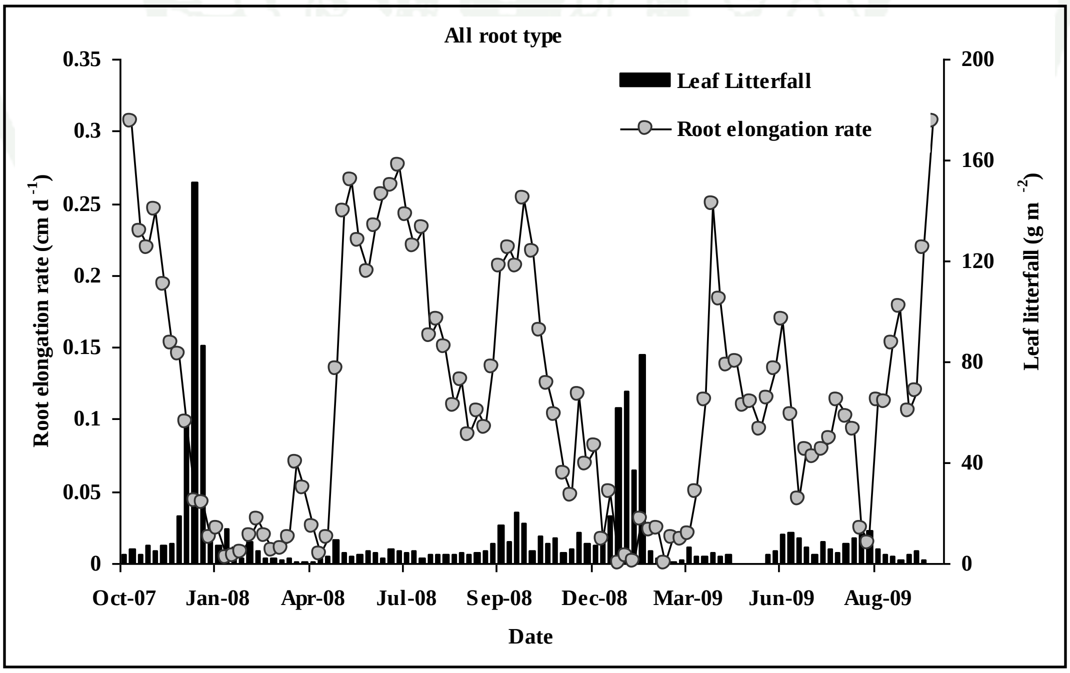

Figure 43 Relationship between root elongation rate (cm d^{-1}) and leaf litterfall(g m^{-2}) from October 2007 to October 2009

(1) Sequential coring method for fine root biomass and necromass estimation

Standing fine root biomass ranged from 1.6 to 2.1 t ha^{-1}and mean fine root biomass was 1.80 t ha^{-1} from November 2007 to 2008 (Figure 44). The maximum standing root biomass was observed in November 07 (the end of rainy season) and decreased gradually from this period until it reached its minimum value (1.6 t ha^{-1}) in August 2008. The pattern for fine root necromass followed a similar trend as fine root biomass. The maximum necromass was found in November 2008 (0.87 t ha^{-1}) before a decrease to the minimum in August 2008 (0.33 t ha^{-1}) and the mean of fine root necromass from November 2007 to 2008 was 0.7 t ha^{-1} (Figure 44). Standing fine root biomass and necromass in 0-10 cm soil layer showed higher value than in 10-30 cm in all 5 sampling dates which a highest value in November 2007 and decrease gradually until August 2008, thereafter slightly increased in November 2008 (Figure 45).

(2) Ingrowth core method

Fine root biomass collected from 5 sampling dates ranged from 0.76 to 4.19 t ha^{-1}. The highest biomass was found in 1 month of re-growth period with PVC method followed by 3, 6 and 2 months of re-growth period and the lowest were found in 1 month without PVC (Table 10).

Annual fine root production from ingrowth cores ranged from 1.07-4.63 t ha^{-1}y^{-1}. Fine root production of each installation date increased exponentially with regrowth period upto 3 months (Figure 46). In non-PVC treatment, the maximum fine root production was found in 6 months of re-growth of each installation date except on the third installation date during dry season where fine root production decreased in 6 months and lower than the value at 3 months of re-growth period (Figure 46). Fine root necromass increased during dry season and decreased during wet season (Figure 47). Fine root necromass increased with the increasing of re-growth period. Fine root necromass ranged from 0.30-0.55 t ha^{-1}. It decreased from

0.31 at 1month of re-growth period to 0.30, 0.53 and 0.55 t ha^{-1} at 2, 3 and 6 months of root re-growth (Figure 48 and Table 9).

The annual fine root production and turnover rate varied due to different study methods. Annual fine root production and turnover rate calculated from sum of mean biomass in short term bags (3 months) was lower than calculated from positive increment method (Table 10).

III. Net primary productivity of rubber plantation

Net primary productivity of rubber plantation in this study shows the difference between two study years. Total NPP of rubber plantation was 13.68 t ha^{-1}y^{-1} in 2008 and 10.36 t ha^{-1}y^{-1} in 2009. The allocation of carbon was different between tree components. In 2008, rubber tree allocated about 43.5% of NPP to aboveground litter, 35% for aboveground component, 9.4% for belowground litter, 8.9% for latex and only 3.2% located in belowground component. In 2009, total NPP was about 25% smaller than from 2008. Biomass allocation was about 51.2% in aboveground litter, 21.7% in aboveground component, 13.3% in latex, 12.4% in belowground litter and only 1.4% in belowground component (Table 12).

Aboveground biomass increment in 2008 was 4.79 t ha^{-1} y^{-1} and decreased to 2.25 t ha^{-1} y^{-1} in 2009. Belowground biomass increment in 2008 was higher than in 2009 (0.44 and 0.15 t ha^{-1} y^{-1}). The total biomass in 2008 was 13.68 t ha^{-1} y^{-1} and decreased to 10.36 t ha^{-1} y^{-1} in 2009 (Table 11).

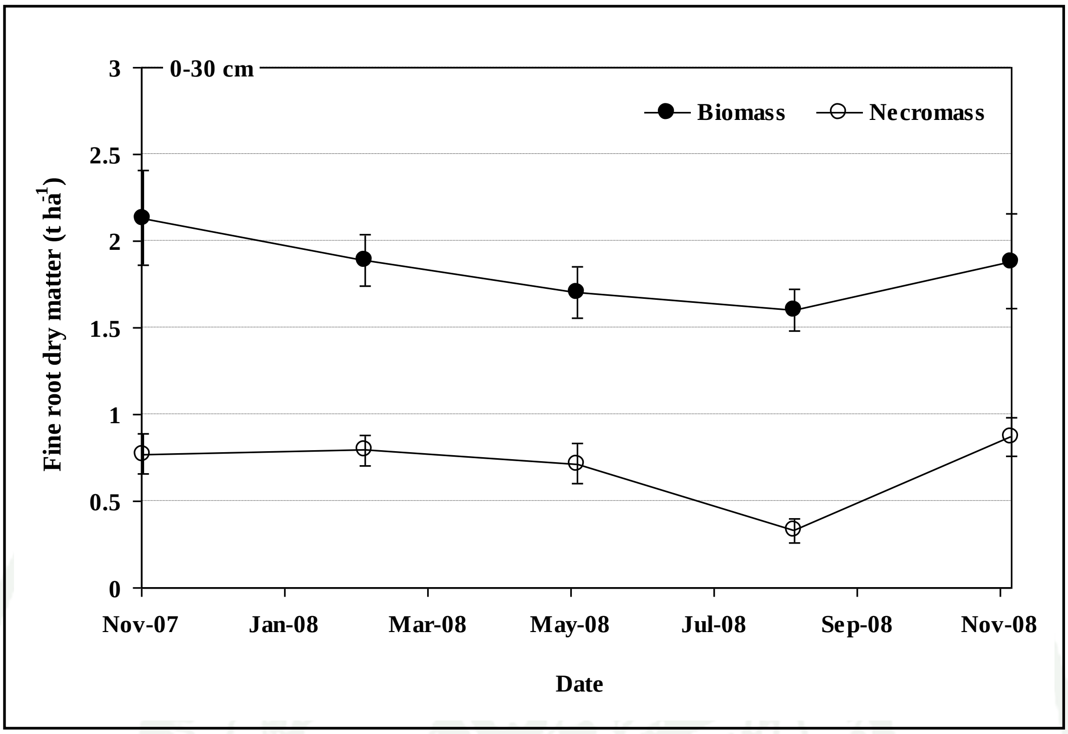

Figure 44 Fine root biomass production (t ha^{-1}) at 5 sampling dates at 0-30 cm from soil surface estimated from sequential cores method. S.E. are indicated by bars (n=10).

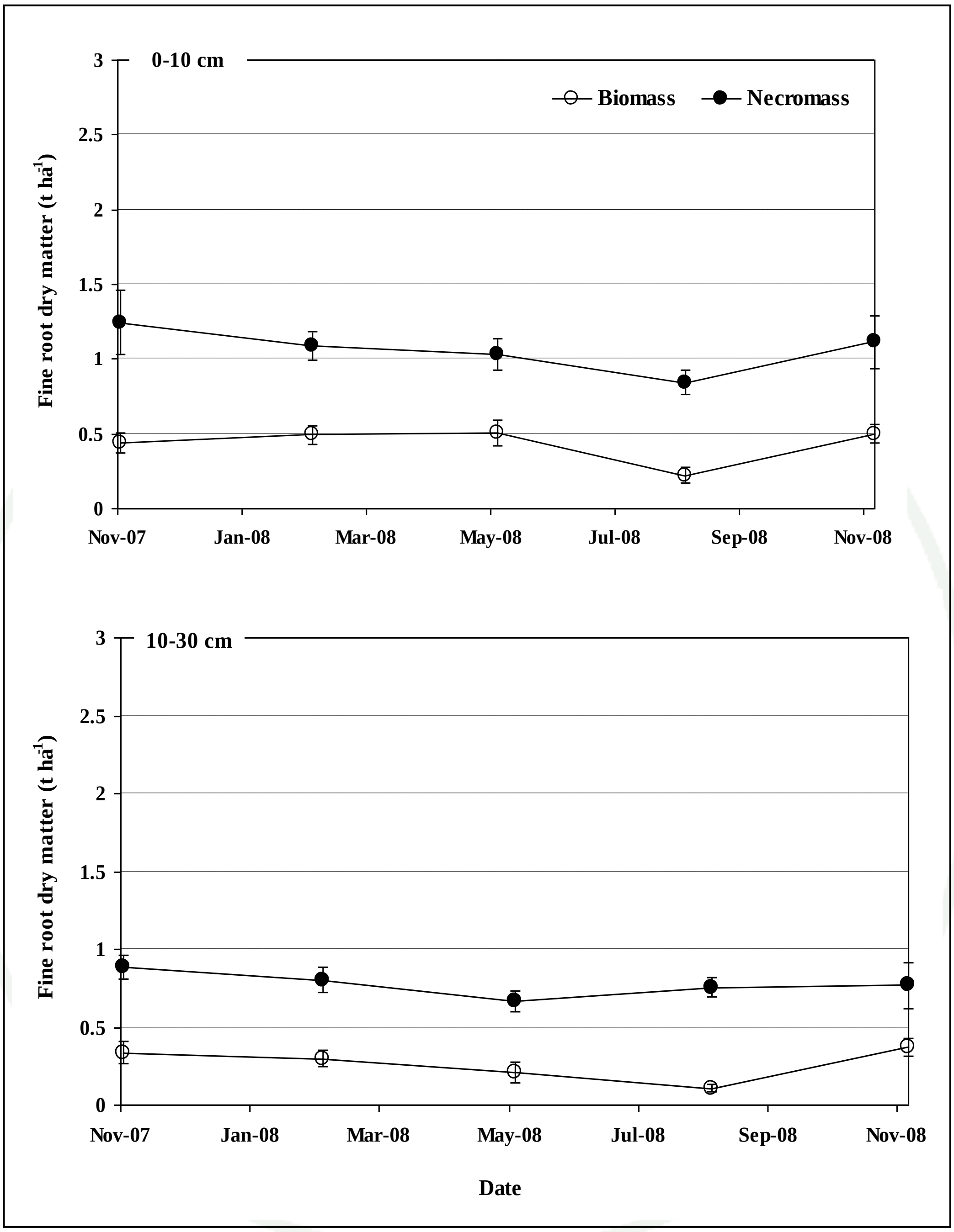

Figure 45 Fine root biomass production (t ha^{-1}) at 5 sampling dates at 0-10 and 10-30 cm from soil surface estimated from sequential cores method. Bar represent standard error of mean S.E. (n=10)

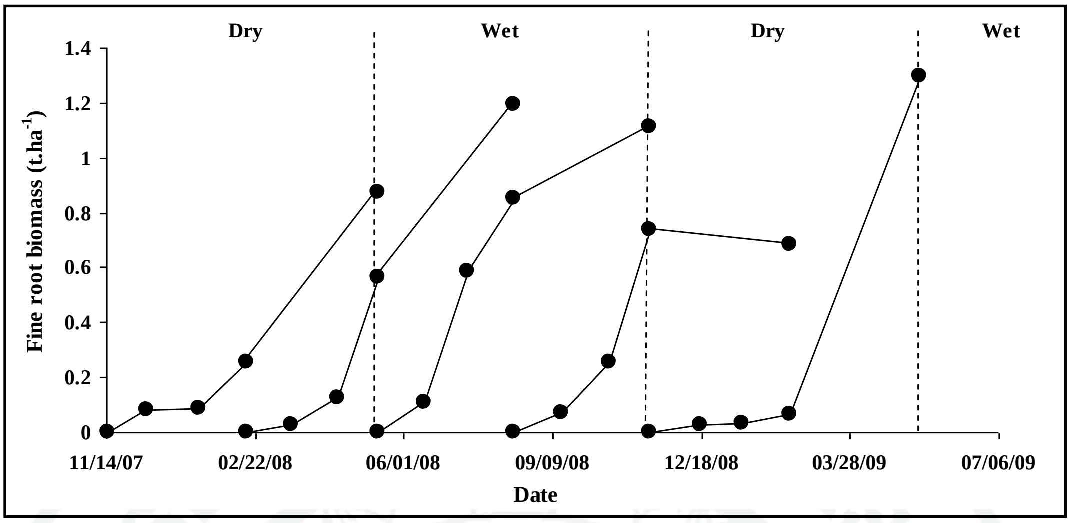

Figure 46 Seasonal variation on fine root biomass production in 5 installation dates at 0, 1, 2, 3 and 6 months of re-colonization

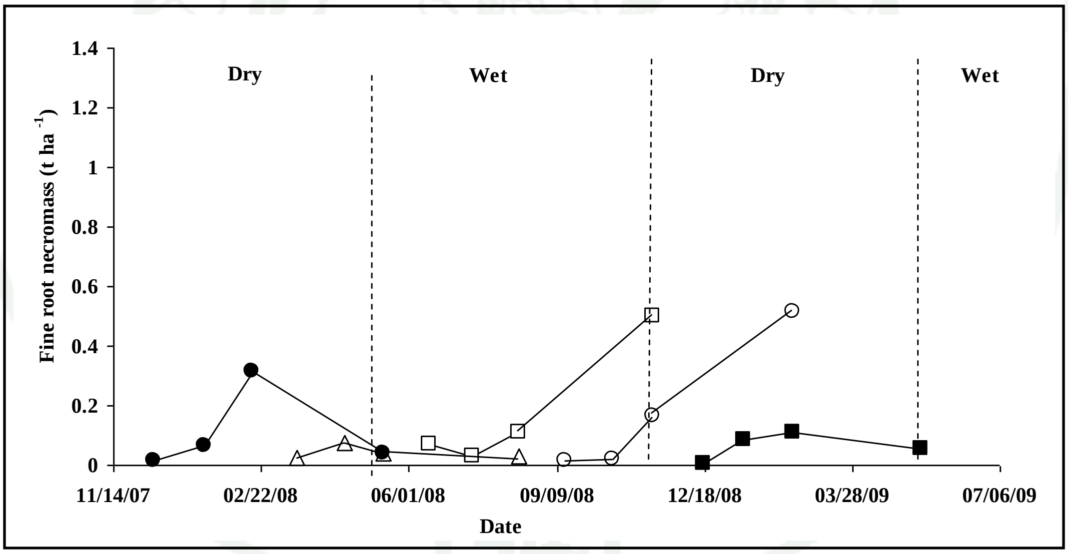

Figure 47 Seasonal variation on fine root necromass in 5 installation dates at 0, 1, 2, 3 and 6 months of re-colonization

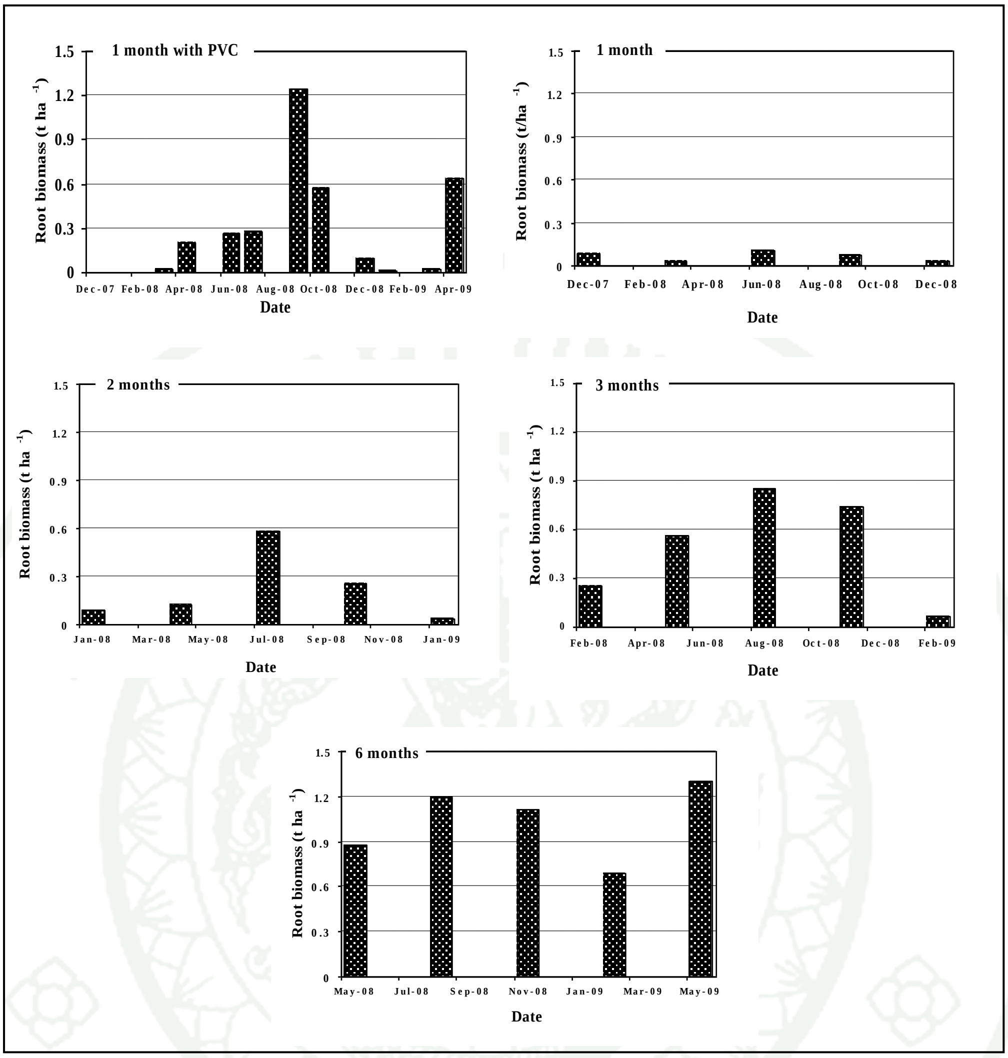

Figure 48 Fine root biomass production (t ha^{-1}) estimated from ingrowth cores method at 1+PVC, 1, 2, 3 and 6 months of re-colonization period.

Table 9 Annual fine root production (t ha^{-1} year^{-1}), mean standing biomass (t ha^{-1}) and necromass (t ha^{-1}) estimated from ingrowth method in a rubber plantation

Root mass	Re-colonization period (month)				
	1+PVC	1	2	3	6
Biomass (t ha^{-1})	4.19	0.76	1.54	2.31	2.09
Necromass (t ha^{-1})	0.43	0.31	0.30	0.53	0.55
Fine root production (t ha^{-1} year^{-1})	4.63	1.07	1.84	2.84	2.64

Table 10 Annual fine root production (t ha^{-1} $year^{-1}$) mean standing biomass (t ha^{-1}) and turnover rate ($year^{-1}$) in a rubber plantation on different root observations and calculation procedures.

Method	Calculation	Production (t ha^{-1} $year^{-1}$)	Biomass (t ha^{-1})	Turnover ($year^{-1}$)
Sequential cores	ΣFine root mass at 4 sampling periods	2.47	1.80	1.37
Ingrowth cores	Σ Fine root mass (3 months of recolonization period	2.84	2.31	1.23
	ΣShorterm cores (3 months)	3.04	1.84	1.65
	ΣPositive increment	3.93	1.84	2.13

Table 11 Net primary productivity (NPP) of rubber plantation in 2008 and 2009.

Tree components	Biomass (t ha^{-1} yr^{-1})	
	2008	2009
Above-ground biomass increment (ΔBm_a)	4.79	2.25
Below-ground biomass increment (ΔBm_b)	0.44	0.15
Above-ground litter (L_a)	5.95	5.3
Below-ground litter (L_b)	1.28	1.28
Exportation of latex (E)	1.22	1.38
Total	13.68	10.36

Discussion

I. Aboveground biomass increment and litterfall production

A. Tree height

The low relationship between measured tree height and circumference might be due to the effect of tapping that caused changes in partitioning and growth pattern of rubber tree. In addition, the trees in this plot are tapped using different systems. The study of Silpi *et al*. (2006) on effect of tapping activity on the dynamics of radial growth of *Hevea brasiliensis* trees found that tapping significantly affected radial growth of rubber stem. After resumption of tapping, the radial growth rate decreased sharply within two weeks and the effect persisted throughout the whole season, so that the cumulative growth of tapped trees was about half that of untapped trees. In addition, wound responses and bark regeneration of tapped tree are carbon consuming processes, and hence should be considered as sink functions, that compete with both radial and vertical growth.

B. Biomass estimation from allometric equation

The proposed regression models for estimating aboveground biomass and tree components showed that tree diameter (d), tree height and combination of these two variables could be used as effective predictor variables. The allometric equation was relatively satisfactory for predicting aboveground biomass, but not for the below ground component. These might be due to (i) the narrow range of rubber age and tree sizes.(ii) the belowground component sampling procedure might have a great influence on regression parameters and their reliability because of the difficulties of excavating and measuring accurately the root system(Saint-Andre *et al*.,2005).

Biomass estimation of rubber plantation from our research was lower than the study of Wauters *et al*. (2007) in rubber tree plantations in Western Ghana. Wauters' (2007) research showed that 14 year-old rubber plantation stocked 135 and 153 t C ha^{-1}or 270 and 306 t ha^{-1}.

C. LAI estimation by 2 methods

A simple measure of the amount of foliage present in a forest is leaf area index, which can be determined by optical estimation (gap fraction method) with an instrument such as fisheye photography, the Li-Cor LAI-2000 Plant Canopy Analyzer. However, optical instruments such as the fisheye photo cannot directly differentiate between foliage and woody components of the canopy (Kalacska *et al*., 2004).

The difference between these estimates and the leaf-collection LAI provides an estimate of woody plant element area index.The estimated LAI from fisheye photograph method in this study, however, was lower than from leaf litter collection method even though LAI estimated from photographs represent a total plant area index (PAI) (Huchison *et al*., 1986). Musshe *et al*.(2001) suggest that the underestimation of LAI from photograph was due to that the weather conditions have a large influence on the LAI images. Technically, measurements should only be made under a uniform overcast sky. When measurements are made under conditions of fast moving clouds or a sunny sky, this will underestimate the LAI. Furthermore, the influence of the sky conditions is different depending on the canopy structure. With a clumped, non-homogeneous canopy structure the underestimation of the LAI will even be larger, due to the very local penetration of rays of radiation through the canopy. In addition, manual thresholding can be another relevant source of error because it is somewhat arbitrary and subjective (Chan *et al*., 1986; Rich, 1990; Machado and Reich, 1999; Frazer *et al*., 2001; Diaci and Thormann, 2002; Jonckheere *et al*., 2004). Therefore, fisheye photography method should be used for dynamics of LAI. But it a study that require high accuracy LAI, measurement method should be litter fall.

II. Below ground biomass

Table 12 compaires dry root mass from 3 methods. The best method to estimate tap and coarse root mass is total excavation which can collect most large roots from the individual tree. The disadvantages of this method are high labor, high cost and time consuming for root collection and root classification, therefore, it is not possible to use for study of fine and medium roots in tree plantation. Voronoi trench method is less accurate than total excavation but this method use less labor, cost and time. For soil cores method, the data shows under estimation for coarse root when compare to total excavation and Voronoi trench method and over estimation for medium and fine root when compare to Voronoi trench method. But this method use the lowest labor, cost and time.

A. Fine root biomass and necromass

High percentage (approximately 70%) of fine root biomass estimated trench excavation methods was located within the organic and mycorrhizal rich top soil layer (0-30 cm). This might be related to the fact that fine roots fulfilled mainly nutritional, metabolic and symbiotic functions (Hendrick and Pretziger, 1996). Sayer *et al*. (2006) and Jinenez *et al*. (2009) found that standing crop fine root mass and fine root production decreased with soil depth. Fine roots allow the direct cycling of nutrients from organic matter, which probably is an adaptation to low nutrient supply in infertile soils. Ford and Deans (1977) stated that high concentration of fine roots in the surface soil layers of the forest are related to higher nutrient concentrations, providing that there is enough moisture, because of the decomposition of the organic litter and release of nutrients on the surface soil, particularly during periods of active growth. The soil concretion (hard pan) combined with the organic and nutrient poor soil content found at depth of 1 m would undoubtedly reduce root growth in the deeper layer. Our results were inagreement with those of George *et al.* (2008). We found that 55% of rubber root activity was confined to the top 10 cm soil layer and declined with increasing depths. Moreover George *et al.* (2008) found that

Table 12 Root dry mass estimation with different methods.

Sampling method	Root mass (kg tr^{-1})			
	Tap root	Coarse root	Medium root	Fine root
Total excavation	38.9	14.2	x	x
Voronoi trench	x	9.2	8.1	2.7
Soil cores	x	6.8	11	4.2

concentration of physiologically active roots at 90 cm depth was only 6%, which is closed to our results of 4% from Voronoi trench method of fine roots within the 70-100 cm soil layer. The coring method within Voronoi trench with the 8.4-cm-inner-diameter auger allowed us to get better information of root spatial distribution spread out vertically and horizontally from the base of the tree trunk to the middle row of the rubber plantation compared. It is note worthy that random sampling with smaller cores (4 cm in diameter) have usually been used in earlier root studies. Oliveira *et al*. (2000) suggested that the core must large enough to obtain a reasonable sampled volume. Too small diameter cores can be a particular problem where there are low rooting densities and the most commonly used cores diameters range from 5 to 8 cm (Van Noorwijk, 1993).

Fine root biomass estimated from sequential coring decreased from the maximum during the end of wet season in November 2007 to the minimum in the mid of rainy season in August 2008. This was probably due to moderate soil water stress that could enhance root growth, shifting assimilate allocation below ground to reduce water limitation for overall plant growth (Freeman and Smart, 1976; Richards, 1983; van Zyl, 1984; Bloom *et al*., 1985). Another explanation could be that, during the end of rainy season, rubber tree allocated carbohydrate and nutrients from leaf to trunk or belowground component before leaf shedding in dry season. After leaf shedding, allocated carbohydrates and nutrients might be mobilized from trunk and belowground parts to produced new leaves, twigs and flowers. During leaf expansion and flowering, carbohydrates stored in fine roots of rubber tree might be depleted (Silpi *et al*., 2007). Silpi *et al.* (2007) demonstrated that high concentration of total nonstructural carbohydrates (TNC) increased to the maximum before leaf shedding in dry season and decreasing during the bud break and re-foliation. The similar pattern of distribution of assimilates was found in northern red oak seedling (deciduous tree) according to the flush-cycle with most of the assimilates (i.e.,>90%) directed upward to the flush during the flushing episode, and conversely most of assimilates (i.e.,> 95) are directed downward to the lower stem and roots during lag stage in between flushing episodes (Dickson R.E., 1989). Research of Thaler and Pages (1996a) on rubber seedlings (*Hevea brasiliensis*) showed that both apical diameter and elongation rates of roots were depressed during the period of root growth.

The results of this study was similar as those found on Eucalyptus plantations in Brazil where the maximum biomass production occurred in the hot-wet season and the minimum was found in the coolest and driest period (Jourdan *et al.,* 2008). Six months sampling intervals performed using ingrowth core method might be introduced errors of calculation due to simultaneous birth and death of fine roots during the sampling interval which were not detected. In addition, the very fine roots probably die within weeks, not months according to Wells and Eissenstat (2001).

After 1 month period with PVC pipe method, the fine root biomass estimation was very high. Possible explanation may be the modifications of environment between PVC and soil during 1 month of PVC insertion. Air and humidity might be decreased along the soil-PVC contact and root flushes should be enhanced after PVC removal and replaced by mesh bag with root free-soil volume. The high rate of fine root production could result from soil disturbance that could increase water and nutrient availability by increasing decomposition and reducing root competition (Eissenstat, 1991). Similar result was found in the research of Populus clones of Lukac and Godblod (2001). They showed that root production from using PVC technique after 13 weeks of re-growth period was higher than that of without PVC for two clones of Populus (Beaupre and Ghoy) by 33% and 53% respectively. For the fast-growing rubber clone use in our research, the result suggest that 4 weeks for re-growth period of PVC technique might be adequate to reach the equilibrium (high number of root production and low number of root mortality) as 13 weeks of PVC technique was needed in poplar clones. In addition, Oliveira *et al*. (2000) that cutting of the roots stimulates root production. Rytter (1999) suggested that the recovery phase of root growth after coring can be eliminated using the spacer-tubes. This method might be considerable advantages for estimation of root growth in fast growing species which require high temporal resolution. Moreover, it was suggest that use of PVC pipe might allow more accurate estimates of root production before onset of root turnover (Lukac and Godblod, 2001).

Fine root necromass estimated from sequential coring was quite steady along the studying period ranging from 0.77 to 0.87 t ha^{-1} except in August where root necromass reached its lowest value (0.33 t ha^{-1}) corresponding to lowest value of fine root biomass at that the same time.

Fine root necromass estimated from ingrowth cores was high during the dry season and low in wet season. This pattern was similarly showed in previous studies conducted in forest where highly seasonal rainfalls strongly influenced root growth during the rainy season (Kavanagh and Kellman 1992, Lopez *et al.*, 1998) and root mortality during the dry season (Srivastava *et al.*, 1986, Kummerow *et al.*, 1990).

B. Fine root production

Fine root production in our study was 2.84 t ha^{-1} y^{-1}, which is higher than previous studies (2.09 t ha^{-1} y^{-1}) in a tropical natural forest in Indonesia (Hertel *et al.*, 2009) , 2.42 t ha^{-1} y^{-1} in young Eucalyptus plantation in Brazil (Jourdan, 2008) and 1.04-1.17 t ha^{-1} y^{-1} in two tropical dry evergreen forest in India (Visalakshi, 1994). Our result fit the range of values found in tropical perennial biomes (Gill and Jackson, 2000) and is greater than those of temperate forests or other tree plantations.

Makkonen (1999) suggested that soil core method can be used to study both the annual and seasonal biomass variations. For estimating of fine root production, sampling should be done at short intervals. Jourdan *et al*. (2008) demonstrated that monthly sampling by the sequential coring method made it possible to take into account seasonal variations in fine root biomass that were not accurately detected by fine root sampling every 3 months performed on installation of the mesh bags.

Fine root production estimated from ingrowth cores were strongly affected by seasonal variation of soil water content. This is probably due to both adequate moisture content of the soil and adequate aeration in that period. Indeed root growth is positively related to the abundance of water and negatively to the soil impedance, which is typical at high soil water contents (Richards, 1983).That the lowest value of fine root production of rubber tree was found in the dry season (December- February) and the highest was found in early wet season (May) is a similar pattern previously described in studies of tropical forest in which rainfall is highly seasonal and roots grow mostly in the rainy season (Kavanagh and Kellman 1992, Lopez *et al.*, 1998). Although these patterns suggest direct control by soil water availability, growth also coincides with leaf flush in the canopy and a very sharp increase in soil nutrient availability as the rains begin (Singh *et al.*, 1989, Roy and Singh 1995). However, in this study it is clearly show that root grow after leaf growth.

For the re-colonization period in this study, 1 or 2 months of regrowth period might not be enough for rubber tree to produce new roots and fine root development was likely to be highly influenced by mesh bag installation.This study selected 3 months of regrowth period because it was expected that 6 months of regrowth period might not effectively detect the very fine roots that died and decomposed within few weeks.

C. Fine root turnover

The chosen re-growth period used for estimating fine root production and turnover was 3 months. It was expected that this period would better allow observing the short lifespan roots when comparing with 6 months of fine root re-growth. For 1 and 2 months of re-growth periods, fine root biomass and necromass productions were too low probably because 1 or 2 months was too short periods to compensate root recovering due to root cuttings during mesh bags installation. That values of fine root turnover calculated from 3 and 6 months of re-growth period of rubber tree were similar (1.23 and 1.26 y^{-1} respectively) indicates that average fine root lifespan is at least more than 6 months. These values obtained for an adult rubber tree plantation are lower than those found for a young Eucalyptus plantation estimated by the same method and which ranged from 2.97 to 3.43 y^{-1} (Jourdan *et al.* 2008). The high variability in root turnover estimations might partly be explained by methodological constraints. The methods used to measure and calculate belowground biomass and production can play a strong impact on determining estimates of root turnover (Gill and Jackson, 2000). Rapid fine root turnover of Eucalyptus constitutes a large energy and nutrient cost for plant, while long lifespans result in reduced rates and lower efficiency of resource uptake (Schoettle and Fahey, 1994) In the other hand, fine root turnover at our site was higher than fine root turnover in the temperate trees such as an 60 year-old Asia white birch in China (0.39 to 0.63 y^{-1}) (Xiao *et al*., 2007), 0.77 y^{-1} in old Scots pine forest (Janssens *et al*., 2004) and also the tropical forest in Colombian Amazon (0.51-0.84 y^{-1}) (Jimenez *et al*., 2009). Turnover increased from boreal zones to the tropics, possibly reflecting the influence of seasonality and implying that if tropical systems are to maintain the same belowground biomass as temperate of boreal systems then their belowground biomass must be higher (Gregory, 2006). Rapid root turnover may be advantageous in nutrient-rich environments, where resource capture efficiency is likely to be maximized by reducing root longevity, thus simultaneously increasing nutrient uptake capacity and reducing root maintenance costs (Crick and Grime, 1987). Turnover rate of deeper root might be lower than the top 30 cm. This might be due to deeper roots being exposed to smaller fluctuations in soil moisture levels and temperature, or reduced levels of herbivory. However, the exact cause of this pattern in unknown (Baddeley and Christine, 2005).

The seasonal timing of production may influence root longevity, since roots produced before tree bloom in the spring have shorter lifespan than those produced later. This may be due to the fact that trees have lower carbohydrate reserves (Anderson *et al*., 2003). Moreover, root longevity is enhanced by mycorrhizal colonization and negatively correlated with nitrogen concentration, root maintenance respiration and specific root length (Eissenstat *et al*., 2000).

D. Fine root dynamics and the relationship with environment factors

This study is the first detailed assessment of fine root dynamics – root elongation rate, fine root production and fine root status- in a rubber tree plantation. The average root elongation rate of rubber trees in wet season 2008 was 0.16 cm d^{-1} and only 0.12 cm d^{-1}in October 2009 with a maximum value of 0.30 cm d^{-1} both years. These rates are lower than common tree roots (0.3 to 0.5 cm d^{-1}) (Kramer and Boyer,

1995) and lower than other tropical trees such as Eucalyptus grown in the plantation in Congo (0.6 cm d^{-1} in the 9-month-old stand; M'bou. *et al*., 2008) or oil palm grown in Ivory coast (0.3 cm d^{-1}; Jourdan and Rey 1997), or for 4-month-old Eucalyptus seedlings grown under controlled conditions (0.6 to 1.5 cm d^{-1}) (Misra, 1999). The lower rate of root elongation of rubber tree might be due to the depressing effect of tapping for latex production on tree growth (Silpi et al., 2007). Comparing tapped and untapped trees would be relevant to confirm such hypothesis, as the depressing effect of tapping has been showed only on trunk growth so far.

There was a strong decrease of every measured parameters (number of the different type of roots, fine root elongation rate and fine root production) between the first (2008) and the second (2009) year of experiment. This may be due to the rhizotron methodology. Disturbance of roots and of the rooting environment during rhizotron installation may be offset by an overproduction of roots during weeks or months after the installation (De Ruijter et al., 1996; Vogt et al., 1998). Consequently, it is generally recommended to wait a certain period of time after the installation of the rhizotron before starting any measurement of fine root dynamics along the glass surface. Nevertheless, our results clearly showed that the development pattern of the fine roots was remarkably similar the two years. Therefore, we can conclude that despite a possible impact on the number of roots, the rhizotrons used in our study provided reliable data on the dynamics of fine roots of rubber trees.

Rainfall and soil water status clearly appeared as the main drivers of fine root dynamics, whereas other climatic factors had less effect. This is consistent with previous works on tree plantations (M'bou *et al*., 2008), or forest stands in tropical conditions (Green et al., 2005). First, we observed a similar seasonal trend in fine root growth and development the two different years which is consistent with the succession of dry and rainy seasons. Root growth almost stopped during the dry season and quickly resumed at the onset of the rainy season. This was linked to the proportion of growing roots and the production of new roots, similarly to results on fine root dynamics in tropical forest (Green et al., 2005). However, during the dry season, a large proportion of root (up to 100%) stopped growing but did not die, as they resume growing at the next rainy season. Secondly, we also observed significant differences in root growth between the two rainy seasons with 25% reduction in average root elongation rate of the rainy season 2009 compared to 2008. The 2009 rainy season was remarkably dryer than 2008 with 36% less rainfall (952 mm in 2009 vs 1500 mm in 2008), resulting in a 3% reduction of the average soil water content. These results are consistent with those of Meier and Leuschner (2008) who found a 30% decrease in fine root biomass when rainfall is reduced by 40%. However, the weekly variations of RER during the rainy seasons, characterized particularly by a sharp decrease of root elongation rate in August of both years, were more surprising. These variations could be explained neither by the rainfall events at this time step nor by the evolution of soil water content, which remained rather high during all the second part of the rainy season in 2008. It is likely that there are other factors influencing root elongation rate during that period. Root growth is not only influenced by exogenous parameters but also by endogenous ones (Tierney *et al*. 2003, Moroni *et al*. 2003). Root and shoot phenology could be closely related because of physiological coupling, with shoots dependent on roots for soil resources and roots dependent on shoots for photosynthates (Steinaker and Wilson, 2008). Rubber tree is a deciduous tree shedding leaves in dry season. Leaf regrowth in late January could create a large sink for carbohydrates and nutrients that could reduce root growth. The observed patterns could fit the shoot-root opposition showed by Thaler and Pagés (1996a) in young seedlings, as root started to grow mainly after the end of the refoliation. However, this could not be unraveled from the concomitant restart of rainfall despite the positive correlation found between PAI and root parameters on a monthly time step. During the rainy season, leaf area did not vary much suggesting that fine root experienced structural and functional changes that were not reflected on the aboveground parts, or at least responded to water stress earlier than aboveground. This finding is not in line with common theories stating that leaf growth is more sensitive to water stress than root growth (Hsiao and Xu, 2000), and that trees allocate more carbon to roots at the expense of aboveground parts during water stress period (Meier and Luschner, 2008). However, it is not easy to compare leaf growth and fine root growth in mature rubber trees because the production and growth of new leaves mostly occurred during the dry season when there was no growth of fine roots. Moreover, our data do not tell anything about the behavior of fine roots below the maximum depth explored by the rhizotrons used in this study (i.e. 75 cm). Meier and Luschner (2008) found a shift with decreasing precipitations of fine root growth from the top soil to deeper layers in European beech stands. In soil and climatic conditions close to those in this study, Gonkhmadee et al. (2009) showed that fine root growth below 75 cm of rubber trees in a 12 years old rubber stand occurred mostly between July and November after fine root had stopped growing in the upper layers. Thereby, fine root growth at deeper layers could compensate for water stress limited growth in upper layers.

The average lifespan of primary and secondary root were rather short comparing to other species. Some available data suggest that root longevity of deciduous tree species (<1 year) is shorter than that of evergreen species (<1-12 years). Furthermore, root lifespan was not related to root diameter but it might be related to other factors such as tissue density, N concentration, basal respiration rates or mycorrhizal infection (Eissenstat *et al.*, 2000). Waisel *et al*.(1991) report that roots longevity is also directly affected by the development of mirorrhizals. Roots not colonized by micorrhizal fungi have a life span limited to a few weeks, whereas mycorrhizal roots may be alive for years.

After leaves emergence in late January, the root elongation rate was low and remain low until May. This was possibly related to the movement and competition for food reserved from belowground part to aboveground part. Carbohydrates and nutrients from belowground was used to produce the new flushes until leaves become mature. The mature leaves then started to produce carbohydrate and supplied to other components included root system. Thus root growing started after refoliation was completed when leaves need more water and nutrient to produced carbohydrate.

Rubber root mortality increased with the number of new roots, in both dry and wet seasons. The result was different from previous study of forest in which roots grow mostly in rainy season (Kavanagh and Keiiman 1992, Lopez *et al.,* 1998) and die during the dry season (Srivastava *et al.,* 1986, Kummerow *et al.,* 1990)

III Above and belowground biomass and net primary productivity

A. Biomass distribution

Allometric relationships are commonly used to estimate tree biomass in forest systems and involve destructive techniques in combination with the application of regression equations. The best fitting equation is often an exponential function ($y = ax^b$) where y is biomass and x is diameter or circumference at breast height (Baskerville 1972, Beauchamp, 1973; Sprugel, 1983). This method has been used successfully by several authors. Dey *et al*. (1996) studied on rubber tree clone RRIM 600 and found that exponential regression equations fitted with all classes of girth from 45 to 93 cm. The studied of Chaudhuri *et al*. (1995) showed that a power function of girth had a good fit from 16 cm or more girth and can be applied efficiently in estimating biomass of rubber tree.

The above and belowground carbon stock in our study 141.41 t ha^{-1} was higher than the research of Wauter *et al.*(2008) which stated that the predicted tree carbon stock for 14-year-old rubber stands was 76.3 t ha^{-1}.

B. Net primary productivity

The estimated total NPP of two studied year were 24% different. NPP in 2008 (13.68 t ha^{-1}) was much higher than in 2009. This could be explained partly by much lower rainfall in 2009 (925 mm) than in 2008 (1,500 mm). The lower rainfall in 2009 caused the reduction of soil water content that affects both above and belowground growth and development especially for trunk and fine root growth. Binkley *et al.*, 1997 suggested that productivity of tropical plantation varies widely, depending on site resources (water, nutrient, and light), species, favourable environmental conditions and intensive management to control spacing, genetics and competition. These features affect both the rate of GPP and the allocation of NPP to stem wood.

Our results showed that about 91-92% of total NPP was allocated to aboveground components and only 8-9% was located to belowground components. The constant of the porportion of above and belowground NPP could be explain by “constant allocation” hypothesis that total NPP increases as resource availability increases, but the proportion of total NPP allocated to foliage, wood and fine roots remains relatively constant (Aber *et al*., 1985; Nadelhoffer *et al*., 1985; Raich and Nadelhoffer,1989).

CONCLUSION

Rainfall and its distribution during the two successive years showed strong differences with 1500 in 2008 and 950 mm in 2009. Aboveground and belowground standing biomass were 271.6 t ha^{-1} in 2008 and 35.9 t ha^{-1} in 2009. Approximately 95% of aboveground biomass was in trunk and coarse branches while 61% of belowground biomass was in tap roots. Moreover, 64% of fine, medium and coarse root biomass was in the top 30 cm of soil. Fine root production completely stopped during the dry season and resumed quickly after the first rains. During the rainy seasons, fine root production and the daily root elongation rate were highly variable and exhibited strong annual variations with an average root elongation rate of 0.16 cm day^{-1} in 2008 and 0.12 cm day^{-1} in 2009. The positive correlations found between fine root production, root elongation rate, the appearance of new roots, and rainfall indicated significant impact of rainfall seasonality on fine root dynamics. However, the rainfall patterns failed to explain the weekly variations of fine root dynamics observed during rainy seasons. Total NPP of rubber plantation were 13.68 t ha^{-1} y^{-1} in 2008 and 10.36 t ha^{-1} y^{-1} in 2009, respectively. Aboveground litter ranged from 44% to 51%, aboveground biomass increment varied from 35% to 22%, belowground biomass increment were from 3% to 14% and belowground litter were 9% to 12% of NPP in 2008 and 2009, respectively. Latex production was 9% of NPP in 2008 and 13% in 2009.

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