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THESIS

# NUTRIENT AND CARBON STORAGE IN FOREST PLANTATION, PRACHUAP KHIRI KHAN PROVINCE, THAILAND

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the Requirements for the Degree of
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This research aims to determine the appropriated tree species for forest rehabilitation in Prachuap Khiri Khan Province, Thailand by analyzing the tree growth, above- and belowground biomass in term of carbon sequestration into the biomass, and soil carbon pool; and to emphasize the nutrient dynamics of the forest plantation by identifying structure characteristics of plantation stands and distinguishing the nutrient dynamics in each part of plantation.

Survivals of tree species were varied from species to species from less than 10 % to more than 90%. The six selected species included both native- and exotic tree species i.e. *Acacia crassicarpa*, *Azadirachta indica* (exotic), *Pterocarpus macrocarpus*, *Shorea roxburghii, Tectona grandis* and *Xylia xylocarpa* (native). The exotic tree species showed greater growth rate than native tree species. Approximately two times differences in $D_0$, DBH and Ht were found when compared between the best and the worst species. Monthly amount of litter fall was fluctuated that depended and strongly related to climatic conditions. In addition, total amounts of litter fall depended on their leaf mass. All species showed the rapid decomposition in the first four months after fall down. On the other hand, slow decomposition rate appeared in the dry season. There were very few differences in soil nutrient concentration both through soil depth and among species plots. However, soil nutrient concentration trended to slightly decrease with increasing soil depth. The carbon pool in a plantation ecosystem depended on the relative biomass of components. Fast growing species, i.e. *A. crassicarpa* and *A. indica*, could store more carbon than slow growing species. The results revealed that the major factors affecting nutrient return to forest ecosystem were the amount of litter fall and nutrient concentration in litter. However, only slight difference of nutrient concentration was found. Therefore, litter mass was the main factor that played an important role on the nutrient return rate. According to the result of the study, massive stock of nutrient was remained in tree biomass. Hence, forest logging programme caused nutrient loss and nutrient deficiency. Plantation management should be intensively done for nutrient conservation aspect. Residuals included some parts of remained trunk, branches and leaf should be leave on the ground after logging. In conclusion, two exotic i.e. *A. crassicarpa* and *A. indica*, appeared to be the appropriate species for commercial forest plantation programs while, *T. grandis* and *X. Xylocarpa* were the alternative choices for rehabilitation in degraded forest land.

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Student's signature Thesis Advisor's signature

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## INTRODUCTION

History has shown that human beings have most often considered the forest as a space that must be cleared in order to develop activities other than forestry, particularly farming and use, eventually beyond its capacity to regenerate itself, as a wood and forage resource. It was only in the face of serious shortages in timber and wood energy, or the degradation of forest lands caused by deforestation or over exploitation. Thus, the decline of forest area is very important of natural resource problems in the world. The total net loss of the countries with a negative change was 8.9 million hectares per year during 1990-2000. After that, during the period of 2000-2005, the total net change in forest area is estimated decrease at 7.3 million hectares or equivalent to a loss is 200 $km^2$ of forest per day, with few signs of a significant decrease over time (FAO, 2009). In Thailand, the natural forest cover changed from 221,707 $km^2$ (43.21 %) to 171,585 $km^2$ (33.44 %) during the period of 1973-2009 or the deforestation rate was estimated 1,392 $km^2$ per year (Office of the Forest Land Management, 2010). The promotion of short-rotation plantations, as a solution to the chronic wood shortages faced by hundreds of millions of people in tropical regions has raised concerns about their sustainability (FAO, 1981). Of particular concern is the risk that frequent harvest-related nutrient losses could result in soil fertility and biomass productivity declines over successive rotations, particularly on inherently infertile or otherwise degraded soils where such plantations are often established (Wise and Pitman, 1981; Jorgensen and Wells, 1986; Goncalves *et al*., 1997). Earlier research has clearly shown that tree species differ widely in their nutrient uptake, storage and recycling patterns (Lugo, 1992; Cuevas and Lugo, 1998). As a result, harvest related nutrient costs per unit of wood or total biomass production also greatly vary (Wang *et al*., 1991; Toky and Singh, 1995; Foelster and Khanna, 1997). In order for these managed forest systems to continue to provide social, economic and environmental benefits over successive harvest rotations, a better understanding of tree species impacts on various aspects of soil fertility, including nutrient cycling processes, is therefore essential (Parrotta, 1999).

Reduction of tropical forest area has a great impact on the amount of carbon dioxide ($CO_2$) stored in the atmosphere, because the forest is the great essential source of the world producing oxygen ($O_2$) and storing $CO_2$, importantly, $CO_2$ is an influential gas leading to climate change and global warming (IPCC, 2006). Forest plays important roles in the carbon cycle. It is not only a source but also a sink and reservoir of $CO_2$ that absorbed by the forest and stored in standing biomass. They will be released to the atmosphere when the forest is transformed into non-forested land such as agricultural land, residential area, etc. Deforestation and forest burning are the prominent factors result on an increasing level of $CO_2$ emission. $CO_2$ sequestering capacity of the earth's biotic system therefore depends on the changing

rate of land-use change, density of forest and patterns of land use of previous forestland. Forestry activities design to store carbon is often purposed to the tropics, as tropical climates supported rapid vegetation growth rates. Several studies of forestation potential suggest that the tropics may offer a good opportunity to fix and store large amounts of carbon, and thereby reduce the area required to store a given amount of carbon (Marland, 1988; Myers, 1989; Sedjo, 1989; Schroeder and Ladd, 1991). Forest rehabilitation of these areas would be capture significant amounts of atmospheric carbon, and would be expected to contribute to soil quality and conservation (Schroeder, 1997). Although there are several estimates of carbon storage in various forest types, few estimates of individual species carbon storage potentials have been published. In this context, it is important to characterize various traits which influence carbon storage on a species basis to allow informed choices between species when establishing carbon storage projects (Kraenzal *et al*., 2003).

# OBJECTIVES

The objectives of this study aimed to emphasize;

1. To analyze the tree growth, above- and belowground biomass in term of carbon sequestration into the biomass, litter and soil carbon pools in the individual tree species.

2. To emphasize the nutrient dynamics of the forest plantation by identifying structure characteristics of plantation stands and distinguishing the nutrient dynamics in each part of plantation.

3. To determine the appropriated tree species for forest rehabilitation in Prachuap Khiri Khan Province, Thailand.

# LITERATURE REVIEW

## 1. Forest degradation and green house gas emission

Forest land degradation will remain an important global issue for the 21st century, because of its adversely impact on the environment, and its effect on the quality of life. Forest area impacts of land degradation are due to a decline in land quality on site where degradation occur e.g. erosion, and off site where sediments are deposited. When tropical forests are clear-cut, the deforested soil begins almost immediately to lose organic matter. Depending on how the soil is managed, the loss of organic matter can be fast and trigger a series of soil degradation processes (Tiessen *et al*., 1994). In tropical region, most of natural forests grow on highly weathered soils that contain low activity clays and have low natural fertility and pH (Whittaker, 1975). Because of this, these systems depend on efficient nutrient cycling based on litter deposition and decomposition (Vitousek, 1988). In addition, in these soils, soil organic matter plays an important role in the soil's cation exchange capacity (CEC), retention of base ions, soil aggregation and is directly related to nutrient availability, especially soil nitrogen (Craswell and Lefroy, 2001; Six *et al*., 2002). In addition to being a major factor contributing to good soil functioning, soil organic matter represents the third largest terrestrial carbon reservoir, with an estimated global total of 1550 Pg C (Lal, 2004). Many studies have shown that tropical forests store large quantities of carbon in their biomass and soil (Brown and Lugo, 1992; Pregitzer and Euskirchen, 2004).

Tropical forest is the great source of $CO_2$, which is the dominant greenhouse gas, affecting the global temperature. The amount of $CO_2$ is influenced by the balance between the reaction of $CO_2$ formation and the $CO_2$ sequestration. The amount of $CO_2$ in the atmosphere is assumed that it will increase by about 0.5% a year. Moreover, it is forecasted that the rate of $CO_2$ emission will be greater than the $CO_2$ sequestration. If the rate of $CO_2$ increment is still unchanging, the amount of $CO_2$ would be double increasing by the 21st century. The earth's temperature would consequently rise about 1.5 - 4.5 $C^o$ (IPCC, 2006). The amount was marginal, compared to the world total. Of this total, greenhouse gas emissions in Thailand, $CO_2$ contribute about 71% while $CH_4$ and $N_2O$ contribute about 23 and 6%, respectively (Ministry of Science, Technology and Environment, 2002). However, impacts of forest land degradation are marked due to use of forest rehabilitation program (Eswaran *et al*., 1999). There are three broad categories of forestry-related interventions that will help stabilize greenhouse gas emissions: managing the existing forest resource better, expanding the area of forest cover, and using wood fuel as a substitute for fossil fuels. Expanding the area of forest cover not only re-creating natural forests (reforestation) and avoiding deforestation, but also monoculture tree farming on plantations for logging, biodiesel production, or other commercial purposes. The term "reforestation" is nevertheless often applied to monoculture tree farming as well as re-creating natural forests. There is also afforestation, which can produce higher carbon sequestration rates because it mean establishing forests particularly on land not previously forested, for example on agricultural lands where

baseline carbon levels are comparatively low (Roper, 2006). However, the role of forests and soil as sink and/or source of greenhouse gases are still a matter of discussion (Brown and Lugo, 1992; Hugues *et al*., 2002; Bellamy *et al*., 2005; Keppler *et al*., 2006).

## 2. Forest biomass

Biomass is the dry mass of living organisms and dead organic matter contained in a define area, usually one square meter or a hectare ($g.m^{-2}$ or $kg.ha^{-1}$ respectively) (Field *et al*., 1998). In forest ecosystem, biomass is located in five major pools: the aboveground and below-ground tissues of over-story and under-story, woody debris consisting of dead and fallen tree stems, forest floor, mineral soil and the tissues of heterotrophic organisms (decomposers and consumers) (Barnes *et al*., 1998). The biomass productivity of ecosystem differs from one geographic location to another. Clearly, biomass and productivity differ markedly among forest types. Several approaches provide ecologist with insight into the biomass and productivity of forest ecosystem. One approach is based on relationships that exist between the dimension of forest tree and their weight. These species-specific or allometric relationships are typically expressed in from of mathematical equation in which the diameter at breast height (DBH) and height of a particular tree is used to predict the weight of leaves, branches, stems and sometime roots. Allometric equation development is a very intensive task in which individual trees spanning a range of DBH and height are harvested, divided into components, and weighted. Because of the great difficulty of collecting tree roots from soil, most allometric biomass equations are used to predict the aboveground biomass and productivity of forest ecosystems. The laws of allometric relations formulate the relation between the amount of two different parts of a plant, X and Y as follows (Satoo and Senda, 1958):

$$Y = aX^b \quad \text{or} \quad \log Y = \log a + b \log X$$

Where;

a and b are specific constant.
X is dimension of tree (diameter or height).
Y is biomass of tree.

Since the above equation represents the linear regression between the logarithms of X and Y. The dominance or importance of any species can be expressed as the percentage of total biomass. The aboveground biomass of the tree can measure by stratified clip technique method (Monsi and Saeki, 1953), which is based on allometric relation as mentioned above. However, for small quadrants in herbaceous vegetation, biomass may be measured by clipping all aboveground matter, oven drying and weighing (Barbour *et al*., 1988). The aboveground biomass of each

forest (both natural and plantation is widely different. On average, woody tissue (trunk, branches, twigs and coarse root) made up 95% of tree's mass and these woody tissues have significantly higher carbon concentrations than the soft tissues (leaves, flowers and fine root) (Kraenzel *et al*., 2003).

The biomass of each forest type is widely different. There are many studies about the production of aboveground biomass in various types of natural forest and forest plantations e.g. Yamakura *et al*. (1986) found that the biomass of stem branch and leaf of trees (DBH > 4.5 cm.) in tropical rain forest, East Kalimantan, Indonesia were 414.20, 78.86 and 5.72 ton $ha^{-1}$, respectively. Jamroenprucksa (1981) revealed that the biomass of stem, branch and leaf of trees in dry evergreen forest, Nam Phom dam, Chaiyaphum province, Thailand were 194.15, 68.92 and 4.50 ton $ha^{-1}$, respectively. Furthermore, in hill evergreen forest, Doi Inthanon, Chiang Mai province, Thailand the biomass of woody part (stem and branch) and leaf of trees were 163.45 and 14.50 ton $ha^{-1}$, respectively. Sahunalu and Jamroenprucksa (1980), who were studied in dry dipterocarp forest in various regions of Thailand, and found that the average biomass of stem, branch and leaf were 87.85 ± 34.97, 36.98 ± 17.66 and 1.28 ± 0.28 ton $ha^{-1}$. In forest plantation, 8-54.7 ton $ha^{-1}$ of aboveground biomass was found in forest plantation exist on opencast coal mine spoil (Dutta and Agrawal, 2003), 0.15-45.24 ton $ha^{-1}$ of *Casuarina equisetifolia* (Taylor and Zisheng, 1987), 29.5 ton $ha^{-1}$ of *Albizia procera* (Singh, 1999). According to Petmark and Sahunalu (1980) used the harvesting method to estimate biomass content in various ages of teak plantation at Ngao district, Lampang province, the result showed that teak plantations at the ages of 5-19-years-old were 19.63 - 110.88 ton $ha^{-1}$. Petmark (1978) carried on net primary production of the 14-years-old stands of thinned and un-thinned teak plantations at Ngao district, Lampang province, in thinned plantation where trees were removed at 45% of the total basal area and has been cut 6 years before the study carried out. The finding of the study revealed that the biomass content of the thinned teak plantation was approximately 78.97 ton $ha^{-1}$, whereas the un-thinned teak plantation appeared 81.79 ton $ha^{-1}$. Viriyabuncha *et al.* (1997) carried out the study on aboveground biomass, leaf area index and evaluation on diameter by determination of growth ring increment method of teak at 21-years-old with spacing of 4x4 $m^2$ at Mae Chaem plantation, Chiang Mai province. The result presented that the mean DBH of 21 years old teak was 18.61 cm and the total aboveground biomass showed around 70.09 ton $ha^{-1}$ and the aboveground biomass of stem, branch and leaf were 50.11, 16.42 and 3.56 ton $ha^{-1}$, respectively. Chittachumnonk *et al*. (2002) found that the average of tree aboveground biomass in the teak plantation at the age of 4-31-years-old were 8.91 - 113.84 ton $ha^{-1}$. Dhammanonda (1981) found that the above ground biomass of 3 × 3, 4 × 4 and 6 × 6 $m^2$ spacing of teak plantation were 23.95, 13.73 and 2.53 ton $ha^{-1}$, respectively. Visaratana (1993) undertook the study on aboveground biomass of *Eucalyptus camaldulensis* and *Acacia mangium* planted alternately in the same row with 2 × 4 $m^2$ spacing, with agro-forestry system. The outcome presented that above ground biomass were 27.18 and 19.18 ton $ha^{-1}$, respectively. Pranslip and Nongnueng (1993) found the aboveground biomass was 97.60 ton $ha^{-1}$ in 6-years-old *Acacia mangium* planted with 3 × 3 $m^2$ spacing. Peawsa-ad and Viriyabuncha (2002) carried out the research of growth and

aboveground biomass of 7-year-old *Acacia mangium* plantation at Ladkrating, Chachoengsao province. The findings presented that the total aboveground biomass was 95.80 ton $ha^{-1}$.

## 3. Litter production and decomposition

In forest ecosystem, litter means the small fractions of leaves, branches, flowers, fruits and others parts of plant including debris of insects on leaf blade, which fall in forest floor (Tsai, 1974). Forest litterfall is associated with the transfer of energy and nutrients from the living biological component to the soil and is the starting point for nutrient cycling. Accumulation of organic matter, produced by litterfall and its decomposition, is an important factor in both soil formation and nutrient cycling processes (Wesemael, 1993). Thus, litter production affects tree nutrition, growth patterns, and forest production (Newbould, 1967). Litterfall serves three main functions in the ecosystem: energy input for soil micro flora and fauna, nutrient input for plant nutrition, and material input for soil organic matter building up. The first two functions are completed through decomposition and mineralization, and the third one through decomposition and huminication. Those functions are related to the main soil processes, such as biological ativity, nutrient cycling and soil structure (Bernhard-Reversat and loumeto, 2002). Factors which affect the rate of litter fall in each forest are ages, species of plants (Thaiutsa *et al*., 1978), stand density, crown cover, silvicultural systems (Bray and Gorham, 1964), climatic condition such as annual rainfall, maximum temperature, dry season (Comforth, 1970), storm (Prachaiyo *et al*., 1980), water deficit in plants physiology (Heald, 1971), topography such as the differences of latitude and longitude, aspect, elevation and climatic region (Bray and Gorham, 1964). Panly *et al*. (2007) suggested that relative humidity, maximum temperature, population of fungi and actinomycetes were the best predictor variables for litter mass loss rate. Furthermore, soil quality and site quality are the most important factors that affect litter fall (Thaiutsa *et al*., 1978). Semwall *et al*. (2003) initiated that the species with the three-phase decomposition pattern (initial slow phase, intermediate first phase and terminal slow phase of decomposition) incubated before rainy season and species with two-phase pattern (initial fast followed by a slow phase) incubated in the beginning of rainy season.

Plantations are generally exploited, resulting in nutrient losses by wood exportation and supplying a great amount of residues to the litter system (Nwoboshi, 1980). Silvicultural practice is one of the important factors related to litter system. Those practices require nutrient cycling study in order to obtain a nutrient balance (Miller, 1984, Bouillet *et al*., 1997). Weeding is generally practiced in young plantations and may change the litter system by burying the stand litter (Bouillet *et al*., 1997) or by spreading herbicides which may alter the microbial populations (Andariese and Vitousek, 1988). There are many publications of litter production which differ greatly thought out the world. Some conclusion of annual litterfall recorded from natural and man-made stand were shown in Table 1.

**Table 1** Annual litterfall in each forest type and localities.

| Forest/Localities | Annual litterfall (ton $ha^{-1}$ $year^{-1}$ ) | Source |
|---|---|---|
| Mountain montane forest, New Guinea | 7.55 | Edward (1977) |
| Lowland montane forest, Malaysia | 8.80-12.00 | Protoc *et al*. (1983) |
| Tropical rain forest, Malaysia | 10.60 | Spain (1984) |
| Tropical low land forest, Indonesia | 8.44-11.74 | Hardivinoto *et al*. (1996) |
| Evergreen forest, Hokkaido, Japan | 3.52-3.59 | Hardivinoto *et al*. (1991) |
| Deciduous forest, Kyoto, Japan | 4.05 - 4.86 | Sakai and Tsutsumai (1986) |
| Dry evergreen forest, Nakhon Ratchasima, Thailand | 7.71 | Chunkaew and Boonyawat (1980) |
| *Robinia pseudoacacia* forest | 3.1 | Tateno *et al*. (2007) |
| Hill evergreen forest, Chiang Mai, Thailand | 6.88 | Boonyawat and Ngampongsai (1974) |
| Moist evergreen forest, Thailand | 23.22 | Kira *et al*. (1967) |
| Dry dipterocarp forest, Nakhon Ratchasima, Thailand | 4.67 | Paovongsa (1976) |
| Deciduous forest with Teak, Lampang, Thailand | 7.92 | Thaiutsa *et al*. (1978) |
| Mangrove forest, Ranong, Thailand | 8.90 | Kooha (1983) |
| Peat forest, Narathiwat, Thailand | 6.70 | Bunyavejchewin and Nuyim (1996) |
| Bamboo forest, Kanchanaburi, Thailand | 4.81 | Thaiutsa *et al*. (1978) |
| 10–years-old *T. grandis* plantation, Lampang, Thailand | 11.65 | Aksornkaew *et al*. (1972) |
| *T. grandis* plantation, Western region, Thailand | 4.5-6.7 | Sumantakul and Viriyabuncha, 2007) |
| 12 years old Pinus plantation, Chiang Mai, Thailand | 11.35 | Thaiutsa *et al*. (1978) |
| 5-year-old *Acacia crassicarpa* plantation, Tanzania | 4.86 | Raphael *et al*. (2004) |
| *Azadirachta indica* plantation, India | 36.2 | Singh *et al*. (1999) |

Litterfall and decomposition are two primary mechanisms by which the forest ecosystem's nutrient pool is maintained. In most forest the major source of nutrients for trees is the process of decomposition. Decomposition refers to the processes that convert dead organic matter into the smaller and simpler compounds. The products of complete decomposition are carbon dioxide, water and inorganic ions i.e. ammonium, nitrate, phosphate and sulfate). Decomposition is mainly a biological processes carried out by insects, worm, bacteria and fungi both on the soil surface and in the soil (Kuers and Simmons, 1998). Decomposition of litters has been studied in various localities from arctic to tropical regions. Ecologists have paid considerable attention on litter decomposition in relation to nutrient cycling and soil productivity. The obvious reason is that litter decay has a pronounced effect on the availability of nutrients, and nutrient availability is a basic determinant of tree growth and timber production (Thaiutsa and Granger, 1979). In temperate forests, decomposition of leaf litter has been studied for the dominant species composing the forest crown layer. While in tropical forest, the decomposition of leaf litter have been studied for mixed leaf litter collected in the study area, because of a diversity of tree species (Takeda *et al*., 1984). There were rather few studies on the decomposition rates for individual tree species in tropical forests, especially small branch litter decomposition was rarely.

Many factors developed decomposing state of forest litter e.g.; Byard *et al*. (1996) found the slow decomposition rate of *Callophylum brasiliense* because of the leaf characteristics with thick waxy and contained the lowest level of N, P and Mg may retard decomposition, as same as Tateno *et al*. (2002) noted that N content was major factor influences on decomposition rate. On the other hand, *Stryphodendron microstachyum* has the high level of leaf K and P and it also has soft and small leaf which probably favored decomposition. The species with high leaf N content do not always decompose faster than those with lower N concentration; lignin and polyphenol concentration may be more important factors for determining decomposition rates. Semwall *et al*., (2003) concluded that monthly mass loss was positively related with rainfall and temperature and annual decomposition constants of mass and N were positively related with C and N concentration but negatively correlated with C/N, lignin/N, polyphenol/N and lignin-polypheno ratio of fresh litter. Raich *et al*., (2007) concluded that litter decay rates increased with increasing lignin content. Between plantations compared to natural forests, the characteristics of tree plantations may result in different litter forming processes as compared to natural forests. Tree plantations are generally mono-specific and litterfall is dominated by one species. Consequently, the litter quality in forest plantations may lead to nutrient deficiency, extreme decomposition rates, or the accumulation of organic constituents resulting in toxicity for soil living organisms. (Bernhard-Reversat and Loumeto, 2002).

Litter decomposition rate or weight loss was expressed by use k constant. The slopes (k constant) of the regression $X/Xo = e^{-kt}$ (Olson, 1963). There were several reports of decomposition rate e.g. temperate forest in Korea, k constant ranges from 0.33 - 0.82 (Yang and Shim, 2003). Tateno *et al*.(2007) found that k constant of exotic black locust plantation and indigenous oak forest in China ranges from 0.15 to 0.48. Bubb *et al*., (1998) found the k value of hoop pine (*Araucaria cunninghamii*) planted in Queensland, Australia is 1.7. In radiate pine plantation forest, after 13 years, log-wood, log-bark and side branches lost 59, 55 and 24% of their initial mass, respectively (Ganjegunte *et al*., 2004), multipurpose tree species plantation in Central Himalaya, India, k constant ranged from 0.63 to 1.16 (Semwall *et al*., 2003). In tropical region, 2.01 and 3.09 of k constant were found in 7 and 3 years-old forest plantation, and 2.28 in hill evergreen forest at Huay Kogma watershed research station in Northern region of Thailand (Gawinchan *et al*., 2004). In West Africa, Attignon *et al*., (2004) found that, k value ranged from 1.3 in teak plantation to 4.7 of *Afzelia africana* in natural forest. Deborah *et al*., (2000) found that k constant of agro-forestry system in Amazonian ranged from 0.4 to 2.1. The k values of tropical tree plantation in Brazil ranged from 0.39 (*Pinus caribaea*) to 1.13 (Leguminosae) (Smith *et al*., 1998), 0.24 to 1.96 of k constant was found in fast growing tree plantation in Congo (France and Schwartz, 1997). According to Olson k constant, ranged from slightly more than 1 to slightly more than 4 in any given stand (Thaiutsa and Granger, 1979).

## 4. Nutrient distribution and their cycling in forest ecosystem

There are differently nutrient content among each tree part. Many results reveal that generally, percentage of nutrient concentration in tree changed from highest to lowest as leaf > bark > branch > stem > root (Curlin, 1970). For litter, concentrate of nutrient in litterfall will change with the composition of plants, fertility of soil and season of litterfall (Katagiri and Tsutsumi, 1983). Percentage of N, P, K and Ca in various kinds of litter are in the following order; other litter > leaf litter > flower litter > branch litter except Mg which is the highest concentration in leaf litter. Concentration of nutrient in branch litter is higher in small branches than that in big branches (Tsutsumi *et al*., 1983). Jutikidecha (1996) found that in 9 years old *Eucalyptus camaldulensis* Dehn. plantation, planted with density 1,100 tree $ha^{-1}$, the amount of litter production on soil surface (Ao layer) is 5.86 ton $ha^{-1}$ $year^{-1}$ and the content of N, P, K, Ca and Mg are 32.82, 0.94, 18.34, 55.67 and 6.62 kg. $ha^{-1}$ $year^{-1}$, respectively, and in 10 years old teak plantation is 7.90 86 ton $ha^{-1}$ $year^{-1}$ and the content of N, P, K, Ca and Mg that accumulate in litter are 52.60, 7.10, 49.10, 154.00 and 16.69 kg. $ha^{-1}$ $year^{-1}$, respectively, and in 12 years old Pine plantation, the production of litter is 11.30 ton $ha^{-1}$ $year^{-1}$ and the content of N, P, K, Ca and Mg that accumulate in litter are 62.40, 5.70, 47.60, 28.40 and 12.50 kg. $ha^{-1}$ $year^{-1}$, respectively (Thaiutsa *et al*., 1978). In teak plantation, on average 13.1% of tree's carbon was stored in their roots and 86.9% in their shoots. The mean carbon storage in tree roots of the plantation is 15.7 ton $ha^{-1}$, while 104.5 ton $ha^{-1}$ distributes in their shoot. The mean total tree carbon storage at the plantation level is 2-120 ton $ha^{-1}$ (Kraenzel *et al*., 2003). Lengh and Windsor (1982) found that litterfall in most

lowland tropical forest range between 6 and 8 ton $ha^{-1}$ $year^{-1}$. Kraenzel *et al*., (2003) found that average dry mass of litter which accumulated over the floor in dry season was 79 ton $ha^{-1}$, containing 34 ton Carbon $ha^{-1}$ (the mean total tree carbon concentration of the litter was 43.3 %).

There are many pathways of nutrient accumulation in litter and soil system i.e. from litterfall, weathering of parent materials, atmospheric deposition, nutrients fixing by plants and microorganisms and leaching from rainfall. Therefore, the amount of nutrient in soil and litter depended on those factors. The amount of nutrient that accumulated on soil surface depends on nutrient supply to soil in from of litterfall which release nutrient to the soil by decomposition of litter on soil surface. The concentration of nutrient in litter that accumulates on soil surface was vary with classes of decomposition and quality of litterfall (Tsuami, 1971), such as C/N ratio value, base content (K, Ca, Mg) in litter. William and Gray (1974) said that high concentration of K, Ca and Mg in leaf litter conduct to rapid decomposition because these nutrient conduct and increase pH value of environment. The litter on temperate forest that composes of high Ca concentration will rapidly decompose. Tsunami *et al*., (1983) found that the amount of nutrients that accumulates to soil surface in dry evergreen forest on soil surface in dry evergreen forest , Thailand, of which N, P, K, ca and Mg were 52.00, 2.90, 12.00, 116.00 and 17.00 kg $ha^{-1}$ $year^{-1}$, respectively. Jutikidecha (1996) found that the accumulation of N, P, K, ca and Mg in 9 years-old *Eucalyptus camaldulensis* plantation, planted with density 1,100 trees $ha^{-1}$ were 32.82, 0.94, 18.34, 55.67 and 6.62 kg $ha^{-1}$, respectively. Generally, forest soil contains high nutrient content especially on surface soil and declines with soil depth (Jutikidecha, 1996). Puriyakorn (1982) found that the content of N, P, K, Ca and Mg in soil 70 cm depth of dry evergreen forest are 11,900, 32.71, 705.87, 326.18 and 2,985.65 kg $ha^{-1}$ $year^{-1}$, respectively. While, the content of N, P, K, Ca and Mg in soil 70 cm depth in the same type of forest reported by Tsunami *et al*., (1983) are 5,930, 140.70, 418, 8,341 and 11,019 kg $ha^{-1}$ $year^{-1}$, respectively. Sahunalu *et al*. (1984) reported that the content of these nutrients in soil 55 cm depth of dry dipterocarp forest are 8,117.90, 22.70, 294.12, 293.04 and 173.88 kg $ha^{-1}$ $year^{-1}$, respectively. Jutikidecha (1996) reveal that the content of these nutrient in 5 cm soil depth of 9 year-old *Eucalyptus camaldulensis* plantation are 384.46, 9.93, 16.36, 97.86 and 46.13 kg $ha^{-1}$ $year^{-1}$, respectively. These results as mentioned above pointed the difference view of nutrient content in soil between the natural forest and forest plantation. The higher of tree density and species richness of the natural forest compare to the mono-specific species plantation were the main causes of the higher amount of nutrient content in the soil.

The natural nutrient cycling in forest ecosystems consists of three important processes i.e. input process, the process that nutrients flow to ecosystem to increase nutrients of the cycling system by releasing nutrients from soil and rocks, and the constituent of nutrients with rainfall and fixed from atmosphere, retention process, the process that nutrients accumulate in living biomass in soil and litter of various living things and loss process, the process that nutrients are lost from cycling system by soil erosion, leaching, producing by man, animals and natural disaster (Brown, 1978).

These three processes as mentioned above are called “nutrient cycling”. Petmark (1983) suggested that in nutrient cycling study, the necessary data used for analyzing nutrient cycling process are; the amount of nutrient accumulates in biomass of plants and soil, the amount of nutrient releases from plants to soil per year (annual return) and rate of annual nutrient uptakes from soil by plants. Nutrient dynamic is a function of the ecosystem. It can make the forest come alive and has sustainable yield (Cole, 1986). In general, forest ecosystem would develop the mechanism of nutrient retaining in system. The general processes that control nutrient flux in ecosystem are composed of; 1) Nutrient that concern with plant uptake. 2) Translocation and reuse by plants. 3) Return of nutrients to soil. 4) Mineralization and Immobilization of nutrients by microorganism, and 5) Leaching of nutrients through soil profile (Cole, 1986). Tsutsumi (1971) cited that the pattern of nutrient cycling and nutrient balance in forest ecosystem are nutrient uptake from soil by plants, return of nutrient to soil in the form of litterfall, leaching from crown of trees by rainfall and lost of nutrients by leaching through soil profile and surface runoff. The estimation of these values may be lower than true values because of insufficient data about nutrient leaching from rainfall and lost of nutrient out of cycling by various processes (Tsunami *et al.*, 1983).

Many papers indicate those nutrient uptakes are greater than nutrient return to soil according to Sahunalu *et al*., (1984). They studied in dry dipterocarp forest in Thailand and found that uptakes of N, P, K, Ca and Mg by plants are 168.97, 5.47, 58.73, 117.65 and 20.23 kg $ha^{-1}yr^{-1}$, respectively. In the other hand, the return of those to soil is 96.53, 3.16, 18.47, 69.33 and 10.45 kg $ha^{-1}yr^{-1}$, respectively. Jutikidecha (1986) studied in 9 year-old *Eucalyptus camaldulensis* plantation and found that uptakes of N, P, K, Ca and Mg are 44.54, 2.85, 74.40, 78.90 and 10.62 kg $ha^{-1}yr^{-1}$, respectively. The returns of those nutrients are 35.20, 2.10, 54.76, 52.38 and 8.01 kg $ha^{-1}yr^{-1}$, respectively. In forest area, most nutrients are retain in soil and the turnover rate of nutrient can be calculate from the ratio of nutrients increase to the system and nutrients that accumulate in litterfall, nutrients that dissolve in rain water and fall to the ecosystem. Katagiri *et al*., (1978) studied about turnover rate in board leaf deciduous forest, Japan and found that turnover rate of N, P, K, Ca and Mg in total soil system are 1, 19, 8, 57 and 1.7% $yr^{-1}$, respectively. Chinsukjaiprasert (1996) found that turnover rates of N, P, K, Ca and Mg in dry evergreen forest are 0.91, 10.39, 4.07, 22.99 and 0.39% $yr^{-1}$, respectively. While, Jutikidecha (1986) studied in 9 year-old *Eucalyptus camaldulensis* plantation and found that turnover rates of these nutrients are 0.93, 0.024, 0.224, 0.081 and 0.022 $yr^{-1}$, respectively. Glumphabutr (2004) was studied about turnover rate of total soil system in moist evergreen forest (MEF), dry evergreen forest (DEF) and Hill evergreen forest (HEF) located in Eastern region of Thailand. He reported that, in MEF site, turnover rates of N, P, K, Ca and Mg of total soil system are 1.14, 23.18, 8.09, 6.75 and 5.99 kg $ha^{-1}$ $year^{-1}$, respectively. While, in DEF plot, turnover rates of these nutrients are 0.79, 61.74, 5.03, 1.30 and 0.25 kg $ha^{-1}$ $year^{-1}$, respectively. In addition, for HEF plot, turnover rates of these nutrients are 0.89, 25.13, 1.51, 2.91 and 2.71 kg $ha^{-1}$ $year^{-1}$, respectively.

## 5. Forest plantation development in Thailand.

The first forest plantation was established by the Royal Forest Department (RFD) in 1906 using teak (*Tectona grandis*). After 1910, teak plantations were developed for wood production and forest restoration after logging. In 1939, the RFD created the Forest Plantation Division. By 1960, forest plantations covered about 6,000 ha. Private sector involvement in plantation development was insignificant, although mangrove plantations have been established since 1932 to meet demand for charcoal. (Mahannop, 2004). Forest plantation development has been mentioned in all the National Economic and Social Development Plans and the RFD promoted forest plantations particularly for watershed protection between 1965 and 1975. Between 1975 and 1978, *Eucalyptus* spp. and *Acacia auriculiformis* were introduced to rehabilitate the national reserve forest lands. In addition, the global energy crisis drew attention to the need to promote fast-growing trees to produce fuelwood. Between 1978 and 1987, many community forestry plantations were established throughout Thailand. Towards the end of this period, the government intended to increase the area of forest plantations by about 80,000 ha per year, while at the same time decreasing the area deforested annually from 768,000 ha to 80,000 ha. The promotion of private sector participation in forest plantations on national reserve forest lands and private lands increased in subsequent National Economic and Social Development Plans between 1981 and 1996. On the national reserve forest lands, a shortage of available land limited the planting target to 48,000 ha per year (Pousajja, 1996; Mahannop, 2004).

Department of Silviculture (1994) reported that many exotic tree species were introduced and planted through Thailand in both government and private sectors. Most of them was *Acacia* spp. e.g. *A. aulacocarpa*, *A. auriculiformis*, *A. confuse*, *A. crassicarpa* and *A. indica*; E*ucalyptus* spp. e.g. *E. camaldulensis*, *E. citriodora*, *E. cloeziana*, *E. deglupta*, *E. grandis*, *E. globules* and *E. robusta*; *Pinus* spp. e.g. *P. caribaea* and *P.oocarpa*; *Paulownia taiwaniana*, *Casuarina junghuhniana*. Exactly when *Eucalyptus* spp. was introduced to Thailand is not clearly recorded. However, information from some records could be assumed that these trees were introduced by foreigners who lived in Bangkok around 1900-1903 (Pousajja, 1996). In the late 1980s, eucalyptus became the favored species for private plantations. Opposition by local villagers and NGOs against the use of eucalyptus grew when environmentalists declared that "commercial eucalyptus plantations are incompatible both with forest conservation and with village livelihood (Lohmann, 1990; Lang, 2002). Despite this opposition to Eucalyptus and commercial plantations, the RFD maintained a strong interest in agroforestry and community forestry throughout this period. Most recent data from Royal Forest Department (2009) concluded that; both government and private sectors; there were 2.86 million hectare of forest plantation consist of both native species through rehabilitation in forest degraded area, and exotic tree species mainly by E. *camaldulensis* and *A. mangium* for commercial purposes in private sector.

**6. Selected species information.**

*Acacia crassicarpa* A. Cunn. ex Benth. Family: Fabaceae – Mimosoideae. *Acacia crassicarpa* is a small- to medium-sized tree 25 to 30 m height; bole often straight and branchless for about 13-18 m; up to 50-60 cm in dbh; crown heavily branched and spreading. Bark is dark or grey brown, hard with deep vertical furrows; inner bark is red and fibrous. Phyllodes falcate, 8-27 x 1-4.5 cm, greyish-green, glabrous; primary veins 3-5, prominent, longitudinal, tending to run into the lower margin at the base; secondary veins parallel, not anastomosing, crowded; pulvinus, 4-20 mm long with a circular gland at the top. Inflorescence is bright yellow spike, 4-7 cm long, clustered in groups of about 2-6 in the upper axils; peduncle is 5-10 mm long, rachis thick; flowers pentamerous, bisexual; calyx broadly cupular, 0.5-0.7 mm long, lobes concave, lobed to about halfway down; corolla widely spreading, glabrous, 1.3-1.6 mm long, 2-3 times as long as the calyx; stamens are 2-3 mm long; ovary shortly pubescent, more densely hairy at the top. Pod woody, ovoid-oblong, flat, 5-8 x 2-4 cm, glabrous, dull brown, transversely veined but hardly reticulate. Seed oblongoid, 5-6 x 2-3 mm, black, arranged separately in separate compartments; areole large and almost closed; funicle folded and thickened, forming a long, pale creamy-yellow aril below the seed (Thomson, 1994; Hong *et al*., 1996; Doran and Turnbull, 1997).

The species is found in warm to hot humid and sub-humid zones in the lowland tropics. In Australia, it is commonly found immediately behind beaches, on coastal plains and foothills. It appears to be tolerant of salt spray and soil salinity. In Papua New Guinea and Irian Jaya, Indonesia, *A. crassicarpa* is found on the gently undulating terrains on well-drained, strongly acid soils, and on imperfectly drained soils that flood in the wet season. In the southern coastal lowlands of Queensland the species occurs in the understory of open forest and in open woodland dominated by *Eucalyptus pellita*, *E. tereticornis* or *E. tessellaris*. On frontal sand dunes it is found as a wind-sheared shrub or small tree, behind *Casuarina equisetifolia* and associated with *Alphitonia exelsa*. On Cape York Peninsula, it is associated *with Eucalyptus tetrodonta*, *Allocasuarina littoralis* and Melaleuca spp. In Papua New Guinea, northern wattle occurs frequently with *Acacia aulacocarpa*, *A. auriculiformis* and *A. mangium.* Altitude: 0-200 m (max. 450), Mean annual temperature: 15-22 to 31-34 deg. C, Mean annual rainfall: 500-3,500 mm Soil type: Red wattle occurs on a wide variety of soil types, from calcareous beach sands, yellow earths derived from granite, red earths on basic volcanic rock to alluvial and colluvial soils (Turnbull, 1986; Lemmens *et al*.,1995; Faridah and Maesen, 1997).

**Figure 1** *Acacia crassicarpa* A. Cunn. ex Benth.

*Azadirachta indica* A. Juss. Family: Meliaceae. *Azadirachta indica* is a small to medium-sized tree, usually evergreen, up to 15 - 30 m height, with a round, large crown up to 20 m in diameter; branches spreading; bole branchless for up to 7.5 m, up to 90 cm in diameter, sometimes fluted at base; bark moderately thick, with small, scattered tubercles, deeply fissured and flaking in old trees, dark grey outside and reddish inside, with colourless, sticky foetid sap. Leaves alternate, crowded near the end of branches, simply pinnate, 20-40 cm long, exstipulate, light green, with 2 pairs of glands at the base, otherwise glabrous; petiole 2-7 cm long, subglabrous; rachis channeled above; leaflets 8-19, very short petioluled, alternate proximally and more or less opposite distally, ovate to lanceolate, sometimes falcate 3.5-10 x 1.2-4 cm, glossy, serrate; apex acuminate; base unequal. Inflorescence an axillary, many-flowered thyrsus, up to 30 cm long; bracts minute and caducous; flowers bisexual or male on same tree, actinomorphic, small, pentamerous, white or pale yellow, slightly sweet scented; calyx lobes imbricate, broadly ovate and thin, puberulous inside; petals free, imbricate, spathulate, spreading, ciliolate inside. Fruit 1 (max. 2)-seeded drupe, ellipsoidal, 1-2 cm long, greenish, greenishyellow to yellow or purple when ripe; exocarp thin, mesocarp pulpy, endocarp cartilaginous; seed ovoid or spherical; apex pointed; testa thin, composed of a shell and a kernel (sometimes 2 or 3 kernels), each about half of the seed's weight. *A. indica* trees may start flowering and fruiting at the age of 4-5 years, but economic quantities of seed are produced only after 10-12 years. Pollination is by insects such as honeybees. Certain isolated trees do not set fruit,

suggesting the occurrence of self-incompatibility. The flowering and fruiting seasons largely depend on location and habitat. In Thailand for instance, neem flowers and fruits throughout the year whereas in East Africa (with pronounced dry and wet season) flowering and fruiting are restricted to distinct periods. Fruits ripen in about 12 weeks from anthesis and are eaten by bats and birds, which distribute the seed (Baumer, 1983; National Research Council, 1992; Lemmens *et al*., 1995; Kausik, 2002; Zhang, 2008).

In India, A. *indica* is present in mixed forest with *Acacia* spp. and *Dalbergia sissoo*; in Indonesia, it is naturalized in lowland monsoon forest. In Africa, it is found in evergreen forest and in dry deciduous forest. *A. indica* tolerates some frost, but seedlings are more sensitive. It quickly dies in waterlogged soils. *A. indica* requires large amounts of light, but it tolerates fairly heavy shade during the first few years. Altitude: 0-1500 m, mean annual temperature: Up to 40 $^{0}$C, mean annual rainfall: 400-1200 mm, A. *indica* grows on a wide variety of neutral to alkaline soils but performs better than most species on shallow, stony or sandy soils (Randhawa and Parmar, 1993)

**Figure 2** *Azadirachta indica* A. Juss.

*Pterocarpus macrocarpus* Kurz. Family: Fabaceae. *Pterocarpus macrocarpus* is an important timber species of Southeast Asia, with a natural distribution extending from Myanmar through Thailand, Laos, and Cambodia to southern Vietnam (Rojo 1977; Forest Inventory and Planning Institute, 1996). Trees are generally found scattered in mixed deciduous forest, dry dipterocarp forest, and hill evergreen forest with altitudes ranging from 100 to 600 m. *P. macrocarpus* has a perfect flower that relies on insects as pollinators. Although individual flowers have a short blooming period lasting only a few hours in the morning, individual trees generally produce abundant flowers and the flowering episode within each tree lasts for 2 to 3 weeks (Liengsiri *et al*., 1995).

It is a light-demanding, drought tolerant tree that is suitable for well drained, light textured soils with shallow depths and little humus (Khorn, 2002). It is a medium to large tree, reaches from 25-30 m high and produces boles from 70-90 cm in dbh (Cambodia Tree Seed Project, 2001). The trunk is straight and cylindrical, and the bark is dark brown and longitudinally fissured. The crown is a dense and globosely. New twigs are covered with dense hairs, and become glabrous after development. Leaves are compound, alternate, bi-pinnate, with densely hairy on the petiole. 5-11 alternate are oblong-ovate and taper into a hard point at their tips. The bases of leaflets are rounded and the edges are smooth. The leaflets are glossy-green above and dull below. About 20 densely reticulate pairs of nerves from 7-9 mm long. Small flower, yellow, aromatic flowers are concentrated on axillaries flowering stalks from 10-15 cm long. These are covered with dense brown hairs. The bell-shaped calyx exhibits 5 prominent tips and an outer covering of hairs. The standard petal (or 'flag') is oval and 12-14 mm long. The flower has 10 stamens, and the ovary is densely hairy. Immature fruits contain 2-4 ovules. The fruit is surrounded by thin wing which is flat and round, and around 8 cm in diameter. It has 1-2 chambers and bears 1-2 seeds in each (Forest Inventory and Planning Institute, 1996).

**Figure 3** *Pterocarpus macrocarpus* Kurz.

*Shorea roxburghii* G. Don. Family: Dipterocarpaceae. *Shorea roxburghii* G. Don is a tropical rainforest tree species belonging to the white meranti group of Dipterocarpaceae, and is commonly used for plywood, construction timber, and furniture. It is distributed from Eastern India to Southeast Asia, and grows to over 40 m in height and 1 m in trunk diameter (Soerianegara and Lemmens 1994). This species is useful for silviculture in the tropics, because of its tolerance to heavy drought and high survivorship after forest fire (Nakamura, 2006)

**Figure 4** *Shorea roxburghii* G. Don.

*Tectona grandis* Linn. Family: Lamiaceae. *Tectona grandis* is indigenous to the continental asia on moist and dry mixed deciduous forest types below 1000 m MSL in India, Mynmar, Lao and Thailand. Its distribution is not continuous. The northern limits are: India, Rajputana 24' 42''N, Jhansi 25' 33''; Mynmar 25'30''N and southern limits are India, Travancore 9'N ; Mynmar 15-16'N (White, 1991). Kasoa-ard (1991) suggested that *T. grandis* naturally occurs in India, Mynmar, Lao and Thailand but it is not natural occurs in Indonesia. It was introduced to Indonesia 400-600 years ago. Evans (1986) suggested that *T. grandis* was successfully introduced into Sri Lanka by the Dutchman throughout the eighteenth and early nineteenth. In 1829 *T. grandis* was successfully planted in Java and the first plantation of *T. grandis* in India was established in 1840. Perhutani (1992) suggested that *T. grandis* forests in Indonesia were planted by Hindu merchants in the beginning of the 14$^{th}$ century.

*T. grandis* is a large deciduous tree with a rounded crown, large leaf, entire and a long clear bole often buttressed at the base, sometime fluted. *T. grandis* produces a large deep root system, a thick taproot is formed which may persist or disappear, but strong laterals are formed. *T. grandis* is pronounced light demander and seedling are intolerant of shade and thrive best in the open. They are very sensitive to any suppression by weeds. Growth of sapling under the light shade will be slower than open grown trees. In natural, seedling is frequently killed back for

year in succession while the root system develops until it attains sufficient vigor to produce a permanent stem. Young *T. grandis* has a power of recovery to damage from fire. *T. grandis* coppice and pollards vigorously sometimes retaining coppicing ability to considerable size (White, 1991).

Gyi (1992) suggested that, in Myanmar most *T. grandis* forests are found in hilly or undulating country and noticeably more growth of *T. grandis* represent in deep, well drained alluvium found along the banks of river and the foot of ridge. Growth of *T. grandis* in Myanmar is poor on the upper slope and top of the ridge according to the natural forest with *T. grandis* in Thailand, its growth in deep and well drained alluvial soil with an optimum range of soil pH between 6.5 and 8.0 with relatively high calcium (Ca) and Phosphorus (P) content (Kaosa-ard, 1992). In India, the most suitable soil for *T. grandis* as deep and well-drained alluviaum high percentage of calcium (Ca) and Phosphorus content of 5 to 7 mg per 100 g soil. On lateritic soils *T. grandis* growth deteriorate and other factors that inhibit regeneration are water-logging and low lime content (Kumaravelu, 1992). In Vietnam, the best soil type for plated *T. grandis* is basaltic soil originating from volcanic rock which is very fertile and moist with good drainage (Forest Science Sub-Institute of Southern Vietnam, 1998).

Research Institute of Tropical Forestry (1992) was divided the natural distribution of *T. grandis* in China in three climatic zones, the middle tropics, the edge tropics and the south sub-tropics. Phompate (1993) suggested that *T. grandis* can grows in dry regions approximate rainfall 500-5,000 mm./year; however, *T. grandis* have a better growth in moist climate areas than dry climate areas. The appropriate rainfall for *T. grandis* is 1,250-2,500 mm/year in 118 day/years. *T. grandis* can grow in temperature ranges from 2 to 40 $C^0$ but appropriate temperature ranges from 20-30 $C^0$ in daytime and 20-30 $C^0$ in night time. In addition, light intensity of 75-95 % is required for seedling establishment. In India, *T. grandis* grows under a variety of precipitation ranges from 800 to 2,500 mm and base on rainfall. *T. grandis* forests in India can classified into five types as very dry (<900 mm), dry (901-1,200 mm.), semi-moist (1,201-1,600 mm.), moist (1,601-2,500 mm.) and very moist (>2,500 mm) (Kumaravelu, 1992). In Mynmar, Gyi (1992) suggested that *T. grandis* of the best quality, producing cylindrical and sound logs occurs in the zone where the rainfall range from 1,270 to 1,650 mm; however, it can still occur within the extreme limit of 760 and 5,080 mm. *T. grandis* cannot tolerant severe drought, but needs at least 2 months of dry season for normal development. In Thailand, Kaosa-ard (1992) observed that the range of rainfall in Thai *T. grandis* region is from 1,000 to 1,800 mm, the most favorable amount of rainfall for better growth and timber qualities is about 1,200 mm.

*T. grandis* plantations were recognized many centuries ago, leading to its relatively wide spread distribution and cultivation throughout the tropics. In Myanmar, the area of *T. grandis* plantation has been established about the year 1700, in Thailand the pioneer plantations of *T. grandis* were established from 1906. Establishment of *T. grandis* plantation in India commenced in 1842 and in Indonesia,

*T. grandis* was introduced into Java in the fourteenth century. Plantation of *T. grandis* also widespread in the tropical Americas, where it was introduced early in the twentieth century. In the Pacific region, *T. grandis* was introduced by the Germans to Papua New Guinea in the early 1900 (Krishnapillay, 2000).

**Figure 5** *Tectona grandis* Linn.

*Xylia xylocarpa* (Roxb.) Taub. Family: Leguminosae Mimosoideae. *Xylia xylocarpa* is a large deciduous tree to over 18 m high by 60 cm trunk diameter, native of eastern India, Burma and Thailand. Leaves are double-compound, carried on stalks 3-6 cm long. Leaflets are 2-4 pairs - lowest leaflets are 3-4 cm long, with a pointed tip. End leaflet is 7-15 cm long. Stalkless tiny white flowers arise in round heads 2 cm in diameter, carried in slender 7 cm long stalks. Pod is 10-16 cm long, 6 cm wide, woody, rusty velvety, shaped like a boomerang, splitting into two twisted segments. Flowering between March-April. *Xylia xylocarpa* is a medium-sized deciduous tree usually reaching up to 20 m in height and 2 m in girth. On dry and poor sites the tree may be smaller and the trunk crooked. The timber is very hard and used for house and bridge construction. It is often found on areas of abandoned cultivation and on low hilly country. It is fire resistant.

**Figure 6** *Xylia xylocarpa* (Roxb.) Taub.

# MATERIALS AND METHODS

## Materials

1. Diameter tape
2. Balance
3. Electronic relay scope model Criterion RD 100
4. Atomic absorption spectrophotometer; model J-Science Thermo S Series
5. Digestion apparatus
6. CN micro corder; model JM 1000 CN
7. UV-VIS Spectrophotometer; model Shimadzu UV-1800
8. Flame photometer; Perkin Elmer Inc.
9. Litter traps
10. Vinyl bags
11. Computer and software packages

## Site description

### 1. Location of study area

Prachuap Khiri Khan Province covers an area of 6,367 $km^2$ and locates at 300 km southern of Bangkok. The district is located on the narrow land bridge connecting the Malay Peninsula with mainland Asia. The province contains the narrowest part of Thailand - directly south of the capital it is just 13 kilometers from the coast of the Gulf of Thailand to the border with Myanmar (Figure 7). In 1993, the Prachuap Khiri Khan Silvicultural Research Station was established in Kui Buri district, Prachuap Khiri Khan Province. Originally, this research area was covered by dry evergreen forest. However, in 1980, it was disturbed by migrants and converted to agricultural land dominated by pineapple plantations. The Royal Forest Department acquired and established PSRS in 1990. The study plot covered 1 hectare which was 100 m x 100m, planted with 19 species, included both native and exotic species (Table 3). Completely randomized block design which 25 treatments and 4 replications were used for experimental stand. In each 10 m x 10 m sub-plot contained 25 trees planted with 2 m × 2 m spacing. The unplanted control plot was set in abandoned crop fields nearby the study plot. The control plot was abandoned and changed to grasslands in 1990 after the Royal Forest Department acquired the land. The grasslands have been sustained by wildfires, which were mainly accidental. The study was carried out from August 2007 to July 2008, when the trees were 14-15 years-old.

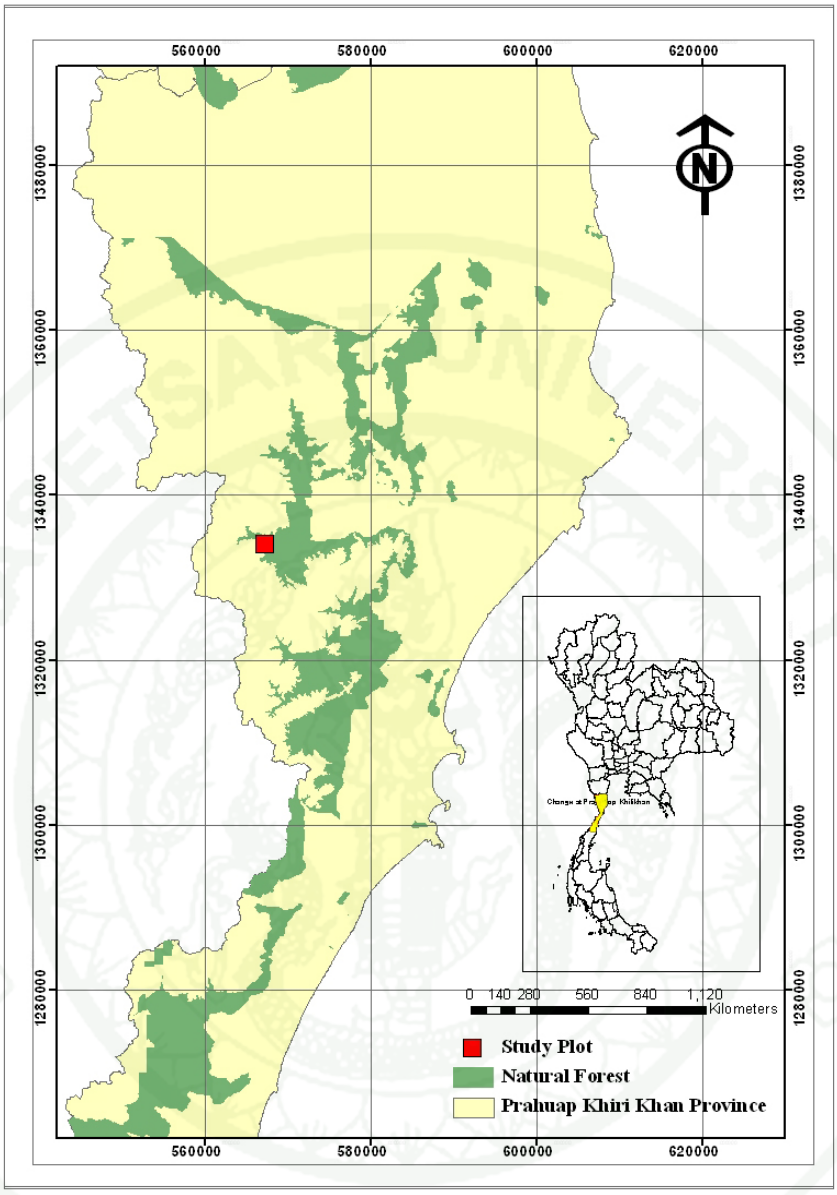



**Figure 7** Location of the study site, Prachuap Khiri Khan Silvicultural Research Station.

## 2. Climatic data

Prachuap Khiri Khan Province is located on the peninsula approaching to the gulf of Thailand on the eastern and Tanao Sri range on the western. Thus, Tanao Sri range, highly ridge mountain which was laid down from north to south on the western side influenced on climatically of this Province, especially the amount of rainfall. Climatic information indicated that average rainfall between 1961 and 1990 in Prachuap Khiri Khan was 1,153 mm $year^{-1}$. That seem to be inferior from southern region climate i.e. in the same period, Chumporn, the nearby southern Province rainfall was 1,962 mm $year^{-1}$ (Thai Meteorological Office, 2011). From all information that mentioned above, Prachuap Khiri Khan Province seem to be the drought area and distinctively different climate from other area of southern region.

In the period of study (August 2007-July 2008), annual rainfall was 1,049.40 mm. The rainy season (when average monthly rainfall exceeded 100 mm) occurred twice a year, firstly between August 2007 and October 2007, and then between March 2008 and May 2008. The averages maximum and minimum temperatures were 35.52 and 23.18 ˚C, respectively. The average temperature was 27.85˚C. The average relative humidity was 83.8%. All information were shown in Table 2 and Figure 8.

**Table 2** Climatic data of Prachuap Khiri Khan Silvicultural Research Station between August 2007 and July 2008.

| Month | Rainfall (mm.) | Average temperature ($^oC$) | Relative humidity (%) |
|---|---|---|---|
| August 2007 | 214.8 | 28.2 | 85.5 |
| September | 192.3 | 28.9 | 86.4 |
| October | 98.1 | 28.1 | 89.1 |
| November | 12.8 | 28.1 | 85.2 |
| December | 36.5 | 26.2 | 76.0 |
| January 2008 | 27.2 | 26.5 | 83.4 |
| February | 57.8 | 27.2 | 87.8 |
| March | 113.5 | 27.8 | 89.2 |
| April | 98 | 29.5 | 88.7 |
| May | 134.8 | 28.8 | 82.1 |
| June | 63.3 | 28.7 | 84.3 |
| July 2008 | 0.3 | 26.2 | 68.1 |
| Total | 1,049.40 | | |
| Average | 87.45 | 27.85 | 83.82 |

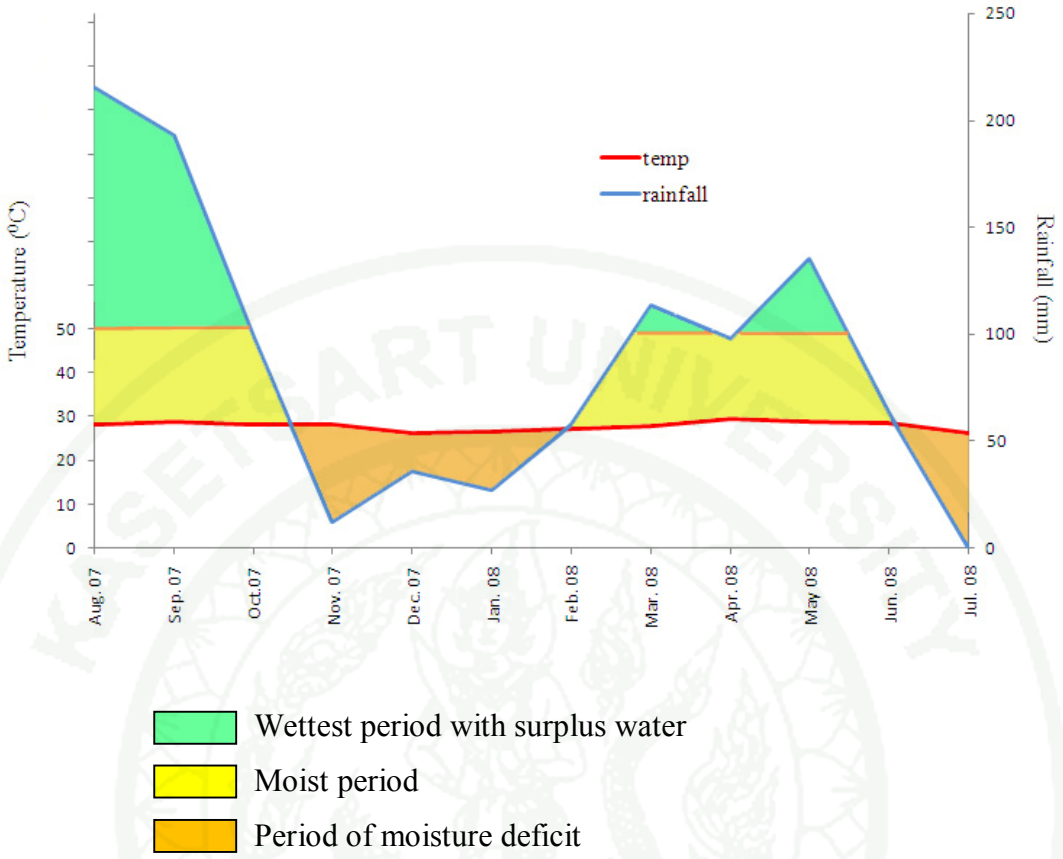



**Figure 8** Walter's climatic diagrams of Prachuap Khiri Khan Silvicultural Research Station between August 2007 and July 2008.

### 3. Layout of sample plot

The 1 hectare sample plot was contained both native and exotic tree species planted in 1993 A.D. The native tree species included; *Dipterocarpus alatus, Intsia palembanica*, *Pterocarpus macrocarpus*, *Tectona grandis*, *Fagraea fragrans*, *Shorea roxburghii*, *Dalbergia cochinchinensis*, *Xylia xylocarpa*, *Sterculia foetida*, *Alstonia macrophylla*, *Casuarina equisetifolia* and *Fermandoa adenophylla*. While, the exotic species were *Acacia mangium*, *A.auriculiformis*, *A. crassicarpa*, *Casuarina junghuniana, Azadirachta indica*, *Acrocarpus fraxinifolius*, and *Eucalyptus camaldulensis*. *A. auriculiformis* and *C. equisetifolia* have unique number and code which were difference via provenance of seed sources. Arrangements of study plot and species information were shown in Figure 9 and Table 3.

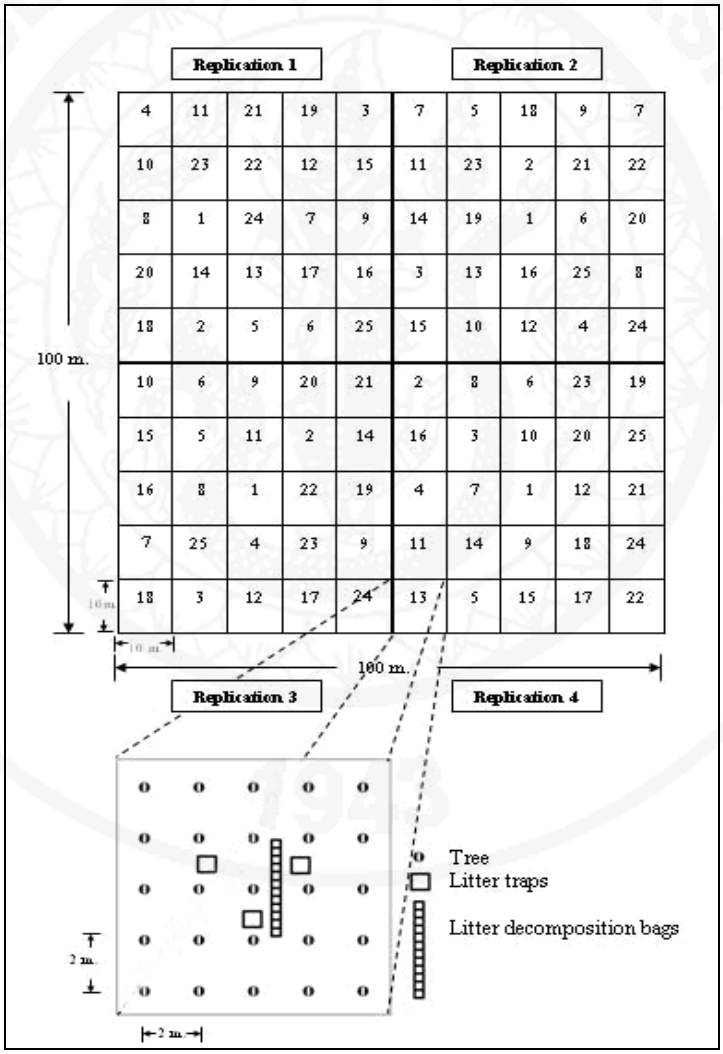



**Figure 9** Permanent 1 hectare sample plot (100 m x 100 m), numbering labels show the number of subplots. Litter bags placing and litter decomposition bags laid down were shown as the square shape below.

**Table 3** Planted tree species in the study plot.

| No. | Scientific name | Common name | Thai name | Family | Status |
|---|---|---|---|---|---|
| 1 | *Acacia mangium* Wild. | Black Wattle, Hickory Wattle, Mangium | Krathin Tae Paa กระถินเทพา | Fabaceae | exotic |
| 2 | *Acacia auriculiformis* Cunn. | Northern black wattle, Darwin black wattle, Ear-pod wattle, Wattle | Krathin Narong กระถินณรงค์ | Fabaceae | exotic |
| 3 | *Acacia crassicarpa* A.Cunn. ex Benth. | Northern wattle, Papua New Guinea red wattle, Red wattle | Krathin Crassicarpa กระถินคราสสิคาป้า | Fabaceae | exotic |
| 4 | *Dipterocarpus alatus* Roxb. | Yang, Gurjan, Garjan | Yaang Naa ยางนา | Dipterocarpaceae | native |
| 5 | *Casuarina junghuniana* Miq. | Beef wood | Son Pradipat สนประดิพัทธ์ | Casuarinaceae | exotic |
| 6 | *Azadirachta indica* A. Juss. | Nim, Neem | Sadao India สะเดาอินเดีย | Meliaceae | exotic |
| 8 | *Intsia palembanica* Miq. | Malacca teak | Lumphor หลุมพอ | Leguminosae | native |
| 7 | *Pterocarpus macrocarpus* Kurz | Burma Padouk, Burmese Ebony | Pra Duu Paa ประดู่ป่า | Papilionaceae | native |
| 9 | *Acrocarpus fraxinifolius* Wight ex Arn. | Pink Cedar, Red Cedar, Shingle tree | Sadao Chaang สะเดาช้าง | Fabaceae | exotic |
| 10 | *Tectona grandis* L.f. | Teak | Sak สัก | Labiatae | native |
| 11 | *Eucalyptus camaldulensis* Dehnh. | Red Gum, River Red Gum | Eucalyptus ยูคาลิปตัส | Myrtaceae | exotic |
| 12 | *Fagraea fragrans* Roxb. | Tembusu | Kan Krao กันเกรา | Loganiaceae | native |

**Table 3** (Continue)

| No. | Scientific name | Common name | Thai name | Family | Status |
|---|---|---|---|---|---|
| 13 | *Shorea roxburghii* G.Don. | Common sal, Indian dammer, Sal tree, Yellow balau | Pha Yom พะยอม | Dipterocarpaceae | native |
| 14 | *Dalbergia cochinchinensis* Pierre | Siamese Rosewood | Pha Yuung พะยูง | Leguminosae | native |
| 15 | *Xylia xylocarpa* Taub. | Iron wood | Daeng แดง | Mimosaceae | native |
| 16 | *Sterculia foetida* Linn. | Bastard Poon, Pinari | Sam Rong สำโรง | Sterculiaceae | native |
| 17 | *Alstonia macrophylla* Wall. | Devil tree | Thung Faa ทุ้งฟ้า | Apocynaceae | native |
| 18 | *Fernandoa adenophylla* Steenis | - | Khae Hang Khaang แคหางค่าง | Bignoniaceae | native |
| 19 | *Acacia auriculiformis* A. | As above | | | |
| 20 | *Acacia auriculiformis* B. | As above | | | |
| 21 | *Casuarina equisetifolia* J.R. | Common Iron wood, Beefwood, Sea oak | Son Thale สนทะเล | Casuarinaceae | native |
| 22 | *Casuarina equisetifolia* no.13 | As above | | | |
| 23 | *Casuarina equisetifolia* no.14 | As above | | | |
| 24 | *Casuarina equisetifolia* no.21 | As above | | | |
| 25 | *Casuarina equisetifolia* no.16 | As above | | | |

## Field methodology

### 1. The study of above and below ground biomass

At first, all trees were measured by using diameter tape for diameter at ground level ($D_o$), diameter at breast height (DBH) and Electronic relay scope for total height (Ht). All remaining trees of each species were calculated into survival rate. Only the 6 highest survived species (include both indigenous and exotic tree species) were selected for this study. Tree census was re-measured in annual period. After finished tree census, 5 trees of each selected species, which covered all size classes, were selected for studying above and below ground biomass. The above ground biomass was studied by using stratified clip technique (Monsi and Saeki, 1953). Harvested tree was separated into different above ground component. Stem and branch were cut into 1 meter segments as fresh weight was recorded. Above ground were separated into stem, branch and leaf. An approximately 1 kilogram of fresh sample of each component was collected for nutrients analysis.

Below ground biomass was studied by excavation method. Root system of the sample tree was excavated from a 1m × 1m pit set up around the sample tree. The soil pit was separated into 5 vertical stratums, at the interval 10 cm. (Figure 10). The excavated soil was spread on plastic sheets and roots in the soil were collected by the hand sorting method. (Kanzaki *et at*.,1991; Kraenzel *et at*., 2003). As the tree density was high, it was difficult to distinguish between fine root systems of different trees sharing the space. To deal with this problem, pits were established around each sample tree from which all soil was removed to isolate the fine and coarse roots. The perimeters of these pits were set halfway between the sample trees and their neighbors (1 m from the sample tree) to balance for the foreign fine roots which were collected from within the pit (Kraenzel *et al*., 2003). The soil was manually washed using a low-pressure water source over a 1 mm mesh. After washing soil off, the roots were separated into fine- and coarse root. Fine root was the root with less than 2 mm in diameter, and coarse root was larger than 2 mm diameter.

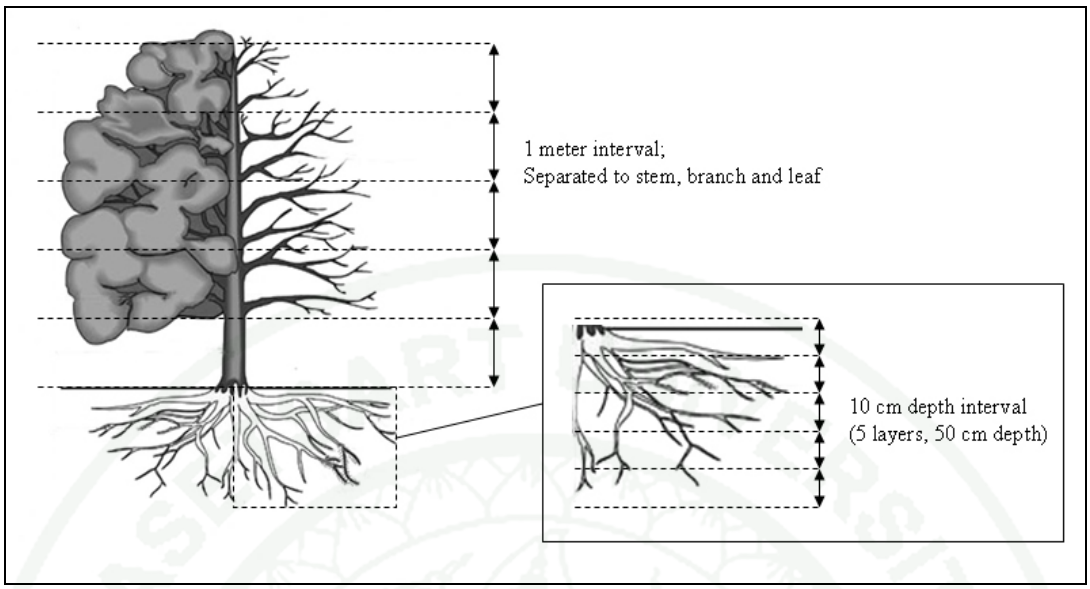



**Figure 10** Schematic diagram of tree sampling with stratified clip technique**.**

## 2. Litterfall

Litter production or litterfall was observed for one year. In order to collect litterfall, 12 square litter traps of each species (3 traps x 4 replications) were set up at the middle most of sub-plot. Trap made from plastic net with 1m x1m size was set up of approximately 1 m high above ground level, by using plastic pole. All accumulated litterfall in traps were collected monthly at the end of month during one year period. The collected litter was air dried and sorted into leaf, other leaf, branch and miscellaneous (bark, seed, flower, bud scale, insect bodies and feces and unidentified fraction). Sub-sample was collected monthly for oven dry. The oven temperature was set at 85 $^{o}$C in 48 hours for find out constant weight. Chemical analysis in each type of litter was investigated in laboratory.

## 3. Litter decomposition

Litter decomposition; nylon mesh bag technique was used to monitor the litter decomposition (Bernhard-Reversat, 1982). Nylon bags with a 2 mm mesh was used because this mesh size is small enough to prevent major losses of fragmented leaves, yet large enough to allow aerobic microbial activity and the entry of small soil invertebrates. The nylon bag of 30 cm x 30 cm size was filled with 10 grams of air dried leaf litter. In every sub-plot of each selected species, 12 litter bags were carried out. Before laid down the litter bags on the forest floor, top litter layer that covered forest floor was moved aside. The removed litter was set on the top of the litter bags (Byard *et al*., 1996). At the end of the month, 4 litter bags per species were brought

back to laboratory monthly. The litter bags were air dried and brushed for cleaning soil contamination. The residual litter in each litter bag was weighted for calculated the litter decomposition rate (k constant). Remaining litter was oven dried for chemical properties analyzed.

**4. Soil sampling**

After root sampling by excavation method, soil sampling was conducted in each soil trench. Soil samples were taken from 5 depths differently, 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm. In each horizon, disturbed and undisturbed soil samples were collected for 1 kg. Undisturbed sample was conducted by using 100 cc soil core samplers. Soil samples were collected for physical and chemical properties analysis.

**Laboratory Methodology**

**1. Nutrients content in plant samples**

Plant samples were brushing for replacing contamination e.g. soil, sawmill etc. Nutrient content in plant samples; Sample of each tree component and litter was sorted and oven dried at 80 $^{o}$C until the constant weight were achieved. The component dry matter was calculated from its fresh weight and percent dry weight. Contents of organic and mineral constituents in all samples were analyzed in laboratory. The air-dried sample was ground with laboratory mill to pass 0.5 mm. screens. Some parte of sorted samples were used as the samples for analyzing nutrient content. Total nitrogen (total N) and total carbon (total C) was analyzed by using CN micro corder model JM 1000 CN. $HNO_3$-$HClO_4$ wet digestion and atomic absorption spectrophotometer was used for analysis of Potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na). Total phosphorus (P) was analyzed by using $HNO_3$-$HClO_4$ wet digestion and Vanadomolybdate yellow color method. Nutrient concentration was calculated in each kind of sample and the value of nutrient concentration was transformed to nutrient accumulation in each kind of sample per unit area (kg $ha^{-1}$).

**2. Soil sample analysis**

Soil sample from the sampling trenches was brought back to laboratory and air-dried at the room temperature and used for analyzing the physical and chemical properties of soil as follows; bulk density of each soil sample was determined by weighing the sample after oven dry at 105 $^{o}$C for 48 hours and expressed as g $cm^{-3}$. The available P was determined by using Bray II method and Spectrophotometer (Alexander and Robertson, 1970). The exchangeable K, Ca, Mg and Na were

determined by 1 N. $NH_4Oac$ extraction method and measured by using Atomic absorption spectrophotometer (Jackson, 1967). All elements were expressed as kilogram per unit area ($kg.ha^{-1}$). The details of plant and soil analysis were shown in Table 4.

**Table 4** Nutrient analysis method in plant and soil samples**.**

| Elements | Tools/Methods | Cited |
|---|---|---|
| Plant | | |
| Total N | Dry combustion method | Steward *et al*. (1964) |
| Total C | Dry combustion method | Steward *et al*. (1964) |
| Total P | $HNO_3$-$HClO_4$ wet digestion and Vanadomolybdate yellow color method | Olsen and Sommers (1982) |
| K, Ca, Mg and Na | $HNO_3$-$HClO_4$ wet digestion and Atomic absorption spectrophotometer | Sumner and Miller (1996) |
| Soil | | |
| Bulk density | Oven dried method | Natural Resources Conservation Service (2007) |
| Total C | Dry combustion method | Steward *et al*. (1964) |
| Total N | Dry combustion method | Steward *et al*. (1964) |
| Available P | Bray ll method and Spectrophotometer | Hesse (1971) |
| Exchangeable K, Ca, Mg and Na | 1 N. $NH_4O_{ac}$ extraction method and Atomic absorption spectrophotometer | Sumner and Miller (1996) |

## Data analysis and calculation

### 1. Above- and below ground biomass

To study the above and below ground biomass, all data from stratified clip technique was calculated as follow;

1.1 Survival percentage of tree; remaining tree was calculated into survival percentage by using the formulae as follows:

$$\text{Survival percentage (\%)} = \frac{[D_0 - D_t] \times 100}{D_0}$$

Where;

$D_0$ is density of tree in established year (trees $ha^{-1}$).
$D_t$ is density of tree at the period of study (trees $ha^{-1}$).

1.2 Tree growth evaluation; any given tree growth parameter i.e. $D_0$, DBH and Ht data were used to generate the tree growth model by using logistic growth curve as follows;

$$Y = \frac{L}{1+ae^{-bt}}$$

Where;

Y is growth parameters i.e. $D_0$, DBH (cm) and Ht (m)
L is the upper limit to the growth parameter
e is the base of the natural logarithms
t is tree age (year), and
a and b are the coefficients obtained by fitting the curve to the data

1.3 Dry weight; all samples of each tree parts and litter component were sorted and weighted before and after oven dry for calculate percentage of moisture content by using the formula as follows:

$$\text{Moisture content (\%)} = \frac{\text{Fresh weight (g) - oven dry weight (g)} \times 100}{\text{Oven dry weight (g)}}$$

$$\text{Dry weight (kg)} = \frac{100 \times \text{fresh weight (g)}}{\text{moisture content (\%)} + 100}$$

1.4 Allometric relationship of estimated component dry matter; allometric relationship of estimated component dry matter on DBH were developed from the harvested sample trees for each components separated by using the formula as follows;

$$Y = aX^b \text{ or } \log Y = \log a + b \log X \text{ (Satoo and Senda, 1958)}$$

Where;

a and b are specific constant
X is diameter at breast height (DBH; cm.)
Y is biomass of tree (kg tree$^{-1}$)

1.5 Belowground biomass was calculated by mean tree method (Satoo, 1970). Sample of root achieve from 3 sample trees by using excavation method were categories to coarse root (>2 mm in diameter) and fine root (≤ 2 mm in diameter). After all, belowground biomass was obtained from multiplying number of tree of each size class with belowground biomass of sample tree in the same size class

$$\text{Belowground biomass (kg ha}^{-1}) = \sum Wi\ Ni$$

Where;

Wi is biomass of sample tree obtained from i size class (kg tree$^{-1}$)
Ni is number of tree of i size class (tree ha$^{-1}$)

1.6 The component biomass values of the plantation stands were obtained by applying DBH (cm) to the Allometric equation developed for each component, after that, multiplying by the number of remaining tree density (tree ha$^{-1}$). The sums of aboveground biomass components in the plantation stands were converted to total aboveground biomass.

Total aboveground biomass (kg.ha$^{-1}$)

= biomass of each tree (kg tree$^{-1}$) × tree density (tree ha$^{-1}$)

**2. Litterfall mass and litter decomposition**

Annual amount of litterfall (kg.ha$^{-1}$) was calculated by sum of monthly litterfall. Decomposition rate of leaf litter of each species was estimated by using exponential decay model derived from Olson (1963). The data used for the calculation of decomposition constants was the mean value of weight remaining at each collection time.

$$\frac{X_t}{X_o} = e^{-kt}$$

Where;

$X_o$ is the initial weight of litter (g)
$X_t$ is the weight of litter at given period (g)
k is decomposition rate constant
e is natural logarithm
t is period of decomposing (year)

3. Nutrient content in plant and soil

3.1 Total nutrient content in biomass; the total nutrient contents of aboveground biomass, roots, and litter were estimated on a unit-area for each species as the sum of the products of estimated biomass (by component) and their respective nutrient concentrations by using the formula as follows:

Nutrient content in biomass (kg $ha^{-1}$) = Nutrient concentration × Biomass of each plant part

3.2 Total nutrient in soil; the masses of nutrients in the soil were calculated by multiplying the mean concentration of each nutrient in each layer by the corresponding mean soil bulk density (Ma *et al*., 2007) by using the formula as follows:

Soil nutrient storage (kg $ha^{-1}$) = nutrient concentration × soil bulk density

The bulk density of each soil sample was determined by weighing the sample after oven drying at 105 $^{o}$C for 48 hours. Then the bulk density was calculated as follows;

$$D_b = \frac{M_s}{V_b}$$

Where;

$D_b$ is bulk density (g $cm^{-3}$)
$M_s$ is soil weight (g)
$V_b$ is soil volume ($cm^3$)

**4. Nutrient Dynamics**

Nutrient dynamics of the forest plantation were estimated by considering the amount of nutrient content in each part of the forest plantation as the studies of Sahunalu *et al*. (1984), Chinsukjaiprasert (1984), Suksawang (1988), Jutikidecha (1996), Pansatha (2002) and Glumphabutr (2004) as follows;

4.1 Annual return rate. The annual returns of nutrients were derived from the content of nutrients that accumulated in litterfall. The annual return values in each species plot were calculated by multiplying the amount of annual litterfall with the concentration of nutrient of litter.

Annual return rate (kg $ha^{-1}$ $yr^{-1}$)

= total amount of litterfall (kg $tree^{-1}$) × nutrient concentration of litter (%)

4.2 Rate of nutrient release to soil. Rates of nutrient released from plant to soil were estimated from nutrient that released from decomposition of both litter fall and litter on soil surface.

Rate of nutrient release to soil (kg $ha^{-1}$ $yr^{-1}$)

= {nutrient concentration of litterfall (%) × weight loss of litter (kg $ha^{-1}$ $yr^{-1}$}
+ {nutrient concentration of litter on soil surface (%) × total amount of litter on soil surface (kg $ha^{-1}$ $yr^{-1}$)}

4.3 Uptake rate. The amounts of annual nutrient uptake by trees were estimated by considering the summing value of nutrient content in annual increment of the tree biomass with nutrient that release in the form of litterfall in one year period.

Annual uptake rate (kg $ha^{-1}$ $yr^{-1}$) =

= annual retain by plant (kg $ha^{-1}$ $yr^{-1}$) + annual return by litterfall (kg $ha^{-1}$ $yr^{-1}$)

4.4 Retain rate. The annual retain of nutrient in aboveground biomass of trees was estimated from the amount of nutrient that accumulated in the annual increment of aboveground biomass. The annual nutrient retain was estimated by using nutrient content in the annual increment of tree biomass plus with the concentration of nutrient in each part of the trees in each species plot.

Annual retain rate (kg $ha^{-1}$ $yr^{-1}$)

= nutrient content in the annual biomass increment (kg $ha^{-1}$ $yr^{-1}$)
× concentration of nutrient in each part of tree (%)

4.5 Turnover rate. The turnover rate of nutrient was calculated by dividing the value of nutrient in the form of nutrient uptake, nutrient return, nutrient release to soil with the content of nutrient that accumulated in each part of the forest i.e. plant system, litter on soil surface, mineral soil and total soil system. The processes of nutrient dynamic study were carried out as in Figure11.

Turnover rate in plant system (% $yr^{-1}$)

$$= \frac{\text{Total uptake by plant (kg ha}^{-1}\text{ yr}^{-1}\text{)}}{\text{Total storage in tree biomass (kg ha}^{-1}\text{)}} \times 100$$

Turnover rate of litter on soil surface (% $yr^{-1}$)

$$= \frac{\text{Annual return by litterfall (kg ha}^{-1}\text{ yr}^{-1}\text{)}}{\text{Storage of litter on soil surface (kg ha}^{-1}\text{)}} \times 100$$

Turnover rate of mineral soil system (% $yr^{-1}$)

$$= \frac{\text{Total released by litter decomposition (kg ha}^{-1}\text{ yr}^{-1}\text{)}}{\text{Total storage in mineral soil (kg ha}^{-1}\text{)}} \times 100$$

Turnover rate of total soil system (% $yr^{-1}$)

$$= \frac{\text{Total return (kg ha}^{-1}\text{ yr}^{-1}\text{)}}{\text{Total storage of litter on soil surface + Total storage in mineral soil (kg ha}^{-1}\text{)}} \times 100$$

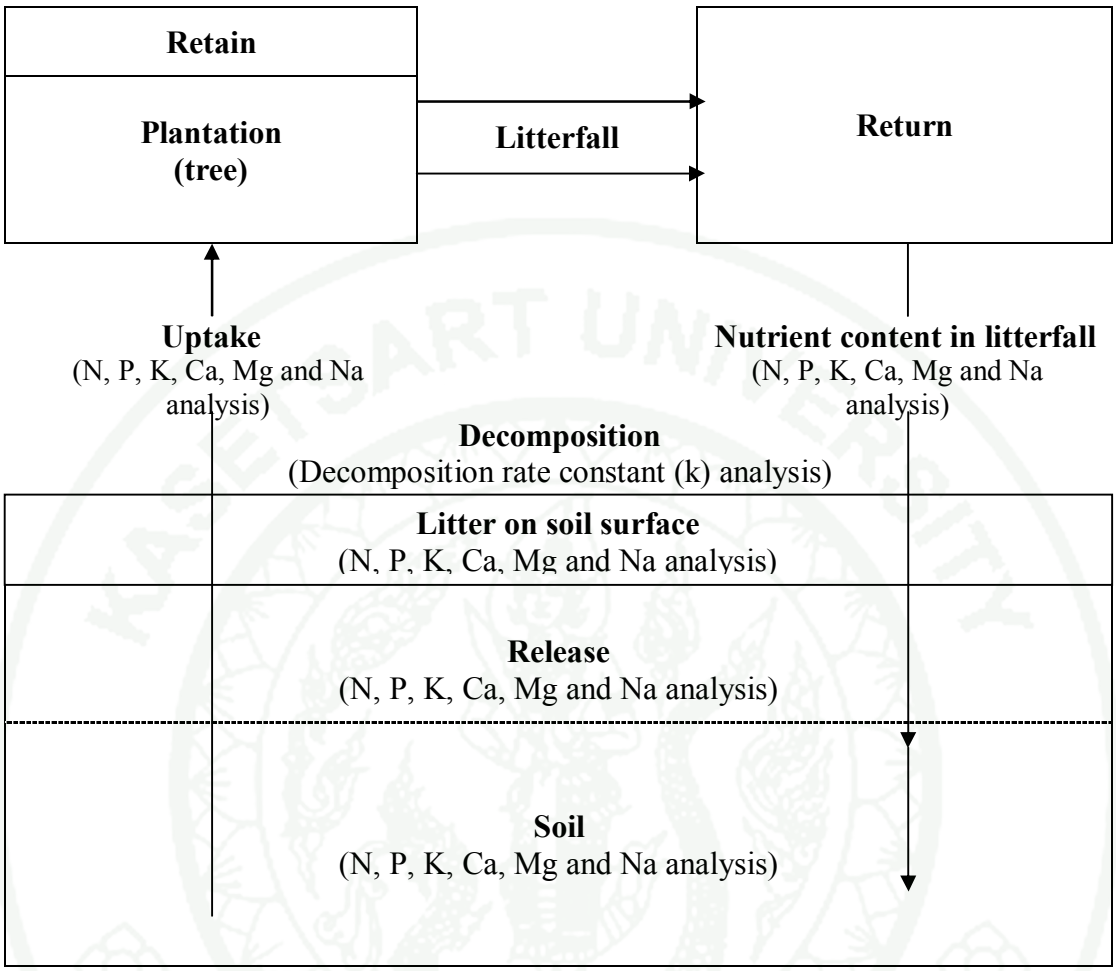



**Figure 11** Diagram of nutrient dynamic study.

**5. Mathematic analysis**

Differences between treatments and blocks in tree and stand characteristics were tested by using one way analysis of variance (ANOVA). The probability level used to determine significant was P, 0.05. When the ANOVA indicated significant effect, the mean were compared with Duncan's New Multiples range test by using SPSS. 11.5 statistical software (SPSS Inc.). Tree growth estimation was calculated from logistic growth model by using Curve Expert 1.4. Biomass equations were fit using the data collected from the harvested trees. Biomass prediction models were evaluated by using exponential models. Cluster analysis by Sorensen (Bray-Curtis) distance was used to measured, and the group average method by PC-ORD version 5.10 generated a dendrogram, which separated into groups of the plant nutrient concentration from each tree part.

# RESULTS AND DISCUSSION

The results of this study were conducted both on field experimental and laboratory works. The results were divided into parts including the studied of survival rate and species trials, tree growth characteristics, biomass of tree, litter production and decomposition, soil and plant properties, soil and plant nutrient pools and carbon concentration and pools in plant and soil system. All results and their discussion were as follows;

## 1. Survival rate and species trials

Tree survival rate was calculated when the trees were 15- years-old. Survival varied significantly between tree species (Table 5 and Figure 12). Survival rate ranking showed that, a couple of exotic tree species; *Azadirachta indica* and *Acacia crassicarpa* expressed the highest survival rate, 94.45%, while native tree species showed the survival rate between 69.45 and 83.34%. The highest survival rate of native tree species was *Shorea roxburghii*; 83.34%. The second was *Pterocarpus macrocarpus*, 72.23%. In addition, *Tectona grandis* and *Xylia xylocarpa* were similar, 69.45%. Other *Acacia* species including *A. mangium* was 58.34%, *A. auriculiformis* were ranged from 25.00 to 52.78%. *Casuarina junghuniana* was 55.56%. On contrast, *C. equisetifolia* was ranged from 5.56 to 30.56%. There were 3 species showed the results below 10% of survival including; *E. camaldulensis*, *C. equisetifolia* and *Intsia palembanica*. The lowest survival rate was *C. equisetifolia* and *Intsia palembanica*, 5.56%. Tree survival rates were grouped by using Duncan multiple range test (Table 5). The results demonstrated that *A. crassicarpa* and *A. indica* were distinctly higher different results from other species. In addition, *Intsia palembanica* and *C. equisetifolia* were also distinctly lower values than other species. Anyhow, there are 13 plots showed the results more than 50% of survival. *Acacia* spp. (i.e. *A. crassicarpa*, *A. mangium* and *A. auriculiform*) were the exotic tree familiar that could adapted and survived very well. The statistical results and status of tree derived from Table 5 were distributed to 2 group e.g. *A. crassicarpa* and A. *indica* as the same group, while, other species including *P. macrocarpus*, *S. roxburghii*, *T. grandis* and *X. xylocarpa* were another group. These species which included both native and exotic tree were selected for biomass and nutrient circulation study. Either native or exotic will appropriate for such forest rehabilitation proposes.

The greatest survival of *A. crassicarpa* in the present trial mirrors the good results achieved by Nyadzi *et al*. (2003). He reported that the survival of *A. crassicarpa* planting in Malawi was reached up to 81%. According to 93.3 % survival was found in 2.5-year-old *A. crassicarpa* plantation in western Tanzania (Nyadzi *et al*., 2002). However, it was higher than *A. crassicarpa* planted in the same country that ranged from 36 to 81% (Ngulube, 1993). Roongrattanakul *et al*. (1999-a) revealed that *A. crassicarpa* which introduced to plant in western part of Thailand was 72.08-74.47% of survival in 5-year-old plantation. Awang *et al*., (1997) reported that the survival of 2-year-old of *A. crassicarpa* planted in Malaysia was more than 94 %.

On the contrary, Rarivoson *et al*. (2007) revealed that *A. crassicarpa* was the lowest survival species when compared to other *Acacia* spp. and *Eucalyptus camaldulensis* planted in Madagascar. Anyway, many articles indicated *A. crassicarpa* was a good adaptability to a wide range of site conditions especially in dry land and acid soils (National Research Council, 1983; Meekaew *et al*., 1990; Ngulube *et al*., 1993; Roongrattanakul *et al*., 1999-b; Nyadzi *et al*., 2003; Rarivoson *et al*., 2007). All results from this present studied showed the lower results of both native and exotic tree species when compared to Nualngam (2002). He studied in 14-year-old plantation, north eastern, Thailand and found that survival rates of native tree species *P. macrocarpus* and *Xylia xylocarpa* were 94.50 and 80.00%, respectively. In addition, survival rates of exotic tree species, *A. auriculaeformis*, *A. mangium* and *E. camaldulensis* were 69.50, 52.60 and 75.20%, respectively. In incredibility, *Eucalyptus camaldulensis*, the most favorite species for plantation program in Thailand showed only 8.33% survival. Actually, *E. camaldulensis* have planted throughout Thailand, even the most drought area of the north-eastern area. According to Watanabe *et al.* (2009) speculated that the majority of *E. camaldulensis* sites with low survival rates were located on hilltops, ironstone outcrops or near ironstone hills, where shallow soils less than 60 cm deep were present. In addition, some paper indicated that *E. camaldulensis* exhibits a deep root system (Sun and Dickinson 1995). Some Eucalyptus species roots could grow to 30 m. in depth (Jacobs 1955) and extracedt water from 6 to 15 m deep (Peck and Williamson, 1987). That may be the course of mortality of *E. camaldulensis* in this present study. The low survival of *C. equisetifolia* was explained by Elfers (1988) that the species naturally present in the beach vegetation and restricted on foreshore dunes and sandy flats. It did not grow well on other areas. From that reason, *Casuarina* spp. in the experiment plot, which displace on the evergreen forest, could not adapt and survive in this area. The survival of *C. equisetifolia* of the present study was on the same range reported by Papa *et al*. (1993) between 11 and 60%. Comparing the survival of *X. xylocarpa*, the result was lower than some those were reported e.g. Jongsuksuntigool and Lertnitiwong (1999). They reported that survival of 10 years-old-plantation of *X. xylocarpa* was 98.8% that was higher than 69.45% of this present studied. Punsatha (2001) reported that the survival of 14-15 year-old *A. indica* plantation was ranged from 78.63 and 100.00%. That result was greatly varied via tree planting density. Anyway, the result reported by Punsatha (2001), as the same planting density of this study (2500 tree $ha^{-1}$) was 96.88% survival. That result was comparable to this present result. The 6 most ranking of highest survival species, including both native and exotic species were selected for the experimental procedures.

**Table 5** Survival rates of 15-year-old planted tree species and their ranking.

| Ranking | Scientific name | Status | Survival rate (%) | Group | tree/ha |
|---|---|---|---|---|---|
| 1 | *Acacia crassicarpa* | exotic | 94.45 | a | 2,361 |
| 2 | *Azadirachta indica* | exotic | 94.45 | a | 2,361 |
| 3 | *Shorea roxburghii* | native | 83.34 | abc | 2,084 |
| 4 | *Pterocarpus macrocarpus* | native | 72.23 | abc | 1,806 |
| 5 | *Tectona grandis* | native | 69.45 | abc | 1,736 |
| 6 | *Xylia xylocarpa* | native | 69.45 | abc | 1,736 |
| 7 | *Alstonia macrophylla* | native | 63.89 | abcd | 1,597 |
| 8 | *Dalbergia cochinchinensis* | native | 61.12 | abcd | 1,528 |
| 9 | *Acacia mangium* | exotic | 58.34 | bcde | 1,459 |
| 10 | *Casuarina junghuniana* | exotic | 55.56 | bcdefg | 1,389 |
| 11 | *Fermandoa adenophylla* | native | 55.56 | bcdef | 1,389 |
| 12 | *Acacia auriculiformis* B | exotic | 52.78 | bcdef | 1,320 |
| 13 | *Acacia auriculiformis* | exotic | 50.00 | bcdefg | 1,250 |
| 14 | *Acrocarpus fraxinifolius* | exotic | 47.23 | cdefgh | 1,181 |
| 15 | *Sterculia foetida* | native | 41.67 | cdefghi | 1,042 |
| 16 | *Casuarina equisetifolia* no.14 | exotic | 30.56 | defghij | 764 |
| 17 | *A. auriculiformis* A | exotic | 25.00 | efghij | 625 |
| 18 | *Casuarina equisetifolia* no.13 | exotic | 25.00 | efghij | 625 |
| 19 | *Casuarina equisetifolia* no.16 | exotic | 22.23 | fghij | 556 |
| 20 | *Dipterocarpus alatus* | native | 16.67 | ghij | 417 |
| 21 | *Fagraea fragrans* | native | 13.89 | hij | 347 |
| 22 | *Eucalyptus camaldulensis* | exotic | 8.33 | ij | 208 |
| 23 | *Casuarina equisetifolia* | exotic | 8.33 | ij | 208 |
| 24 | *Intsia palembanica* | native | 5.56 | j | 139 |
| 25 | *Casuarina equisetifolia* no.21 | exotic | 5.56 | j | 139 |

**Remark**: ANOVA results; the same letter in each column denotes groups that were not significantly different ($p$>0.05).

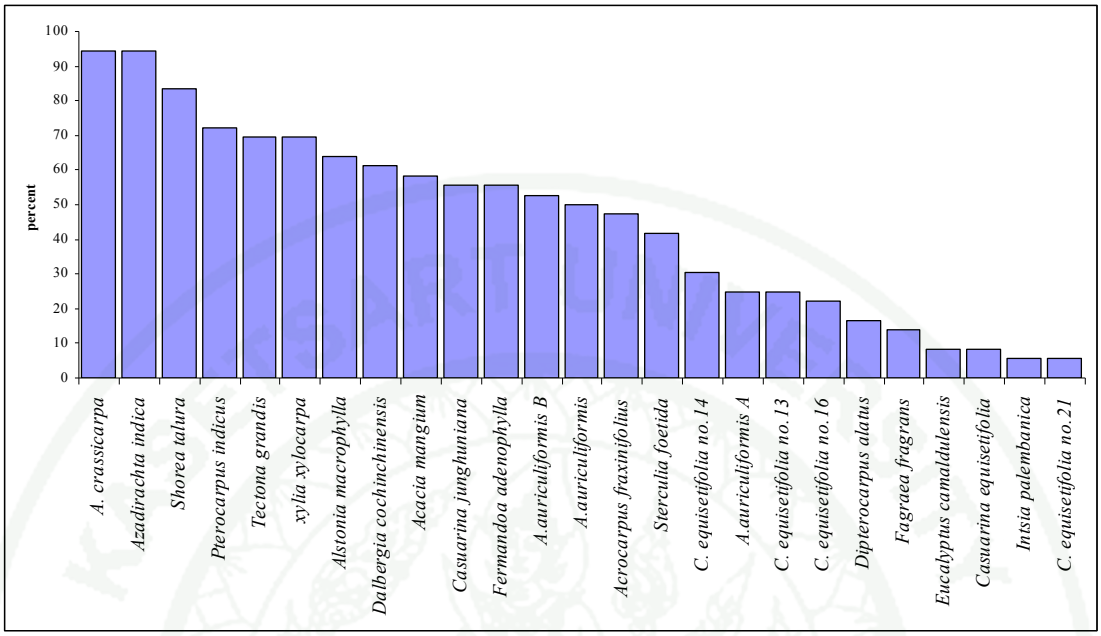



**Figure 12** Remaining of planted tree (percent) after 15-year planting.

**2. Tree growth characteristics**

Tree growth measurement was undertaken by Prachuap Khiri Khan Silvicultural Research Station from the first year until the trees were 4 years-old. Afterward, no data was collected until the trees were 14 and 15 years-old. Diameter at ground level ($D_0$), diameter at breast height and height of all trees, except border rows were measured yearly. All details were shown as follows;

2.1 Diameter at ground level ($D_0$)

Diameter at ground level was measured at the base of stem. Exotic, *A. crassicarpa* showed the greatest annual growth of diameter at ground level. From the established year, *A. crassicarpa* expressed 4.54 cm and reached to 20.60 cm when the trees were 15-years-old. *A. indica* and *T. grandis* were shown the similar trend of annual increment. When the trees were 15-years-old, $D_0$ of *A. indica* was 14.37 cm. It was closely to 15.02 cm of *T. grandis*. The annual growths of both species were 0.96 and 1.00 cm year$^{-1}$, respectively. Likewise, *P. macrocarpus* and *Shorea roxburghii* showed the similar trend of annual increment of diameter at ground level, that was 11.02 and 10.99 cm, respectively. The highest annual growth was *A. crassicarpa*; 1.37 cm year$^{-1}$. *A. indica*, *T. grandis* and *X. xylocarpa* shown the results nearly to 1.00 cm year$^{-1}$. *P. macrocarpus* and *S. roxburghii* were showed the poorest growth. Annual growth of these species were similar; 0.73 cm year$^{-1}$. *A. crassicarpa* showed remarkably good growth when compared to other species. The present results conform to Ngulube *et al*. (1993). They reported the diameter at ground level of 1- and 2-years-old *A. crassicarpa* were between 0.3 and 3.0 cm, and 4.0 and 6.8 cm, respectively. Nevertheless, higher results reported by Nyadzi *et al*. (2003); 9.2 and 18.6 cm when *A. crassicarpa* were 2.25- and 4-years-old, respectively. In addition, 18.64 cm $D_0$ were found in *A. crassicarpa* plantation in western Tanzania (Nyadzi *et al*., 2002). A result of *A. indica* represent above was higher than the result of Punsatha (2001). He revealed that $D_0$ of 13- and 14 year-old *A. indica* planted with 2,500 tree ha$^{-1}$ was between 11.5 and 11.7 cm. While, the result of this present studied was range from 14.17 and 14.37 cm.

Data of $D_0$ from Table 6 were used for generating logistic growth model. All results were shown in Table 7. Data from 15 years-old plantation, "L" coefficient indicated the upper limit of $D_0$ growth under present situation. The highest possible results of $D_0$ was *A. crassicarpa* came after by *T. grandis* and *A. indica* which 20.69, 14.33 and 14.20 cm, respectively. For *X. xylocarpa*, the highest possible $D_0$ was 13.96 cm. *P. macrocarpus* and *S. roxburghii* were 10.59 and 9.53 cm, respectively. All r values were ranged from 0.97 to 1.00, which were highly correlation between parameter (age) and $D_0$ size. The infection point indicated the point of maximum growth rate. Data from Table 7 showed that *A. indica* and *T. grandis* reached to the inflection point in 2.40 and 2.55 year, respectively. While, *A. crassicarpa*, *S. roxburghii* and *X. xylocarpa* were 3.44, 3.85 and 3.87 year, respectively. The lowest growth rate species, *P. macrocarpus* met the inflection point in 4.34 years. After that,

the growing rates of all species were slowdown. The infection point typically appeared at half of upper limit. Hence, the time to steady of growing state of tree was calculated from multiply the time of inflection state by 2. The results from Table 7 showed that the fastest growing rate was *A. indica*, and it took 4.80 years to reached up the steady stage of $D_0$. While, *T. grandis*, *A. crassicarpa*, *S. roxburghii*, *X. xylocarpa* and *P. macrocarpus* were 5.11, 6.88, 7.71, 7.74 and 8.67 years, respectively. Ground level diameter growth curves were shown in Figure 13.

**Table 6** Diameter at ground level of each individual tree species (cm).

| Tree age (years) | Ac | | Ai | | Pm | | Sr | | Tg | | Xx | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $D_0$ | sd | $D_0$ | sd | $D_0$ | sd | $D_0$ | sd | $D_0$ | sd | $D_0$ | sd |
| 1 | 4.54 | 1.16 | 3.29 | 0.80 | 1.34 | 0.82 | 1.46 | 0.45 | 3.50 | 1.78 | 1.19 | 0.62 |
| 2 | 7.47 | 1.64 | 6.74 | 1.37 | 2.42 | 1.73 | 2.43 | 0.99 | 5.27 | 2.27 | 2.60 | 1.61 |
| 3 | 10.10 | 1.93 | 9.10 | 1.64 | 3.91 | 2.10 | 3.91 | 1.52 | 9.15 | 2.70 | 5.32 | 2.65 |
| 4 | 10.99 | 2.08 | 9.83 | 2.20 | 4.62 | 2.42 | 4.83 | 1.76 | 10.08 | 2.19 | 7.03 | 3.30 |
| 14 | 20.53 | 5.98 | 14.17 | 4.96 | 10.06 | 6.24 | 8.02 | 5.70 | 13.72 | 4.52 | 13.07 | 7.85 |
| 15 | 20.60 | 6.02 | 14.37 | 4.81 | 11.02 | 5.11 | 10.99 | 4.76 | 15.02 | 3.13 | 14.86 | 6.75 |
| AGR | 1.37 | | 0.96 | | 0.73 | | 0.73 | | 1.00 | | 0.99 | |

**Remark**: Ac: *Acacia crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa* and AGR: Absolute growth rate (cm $year^{-1}$)

**Table 7** Coefficient of logistic model of annual growth of diameter at ground level.

| species | L | a | b | r | infection point (years) | steady state (years) |
|---|---|---|---|---|---|---|
| *Acacia crassicarpa* | 20.69 | 4.70 | 0.45 | 1.00 | 3.44 | 6.88 |
| *Azadirachta indica* | 14.2 | 4.99 | 0.67 | 0.99 | 2.40 | 4.80 |
| *Pterocarpus macrocarpus* | 10.59 | 9.54 | 0.52 | 1.00 | 4.34 | 8.67 |
| *Shorea roxburghii* | 9.53 | 8.65 | 0.56 | 0.97 | 3.85 | 7.71 |
| *Tectona grandis* | 14.33 | 6.45 | 0.73 | 1.00 | 2.55 | 5.11 |
| *Xylia xylocarpa* | 13.96 | 18.2 | 0.75 | 1.00 | 3.87 | 7.74 |

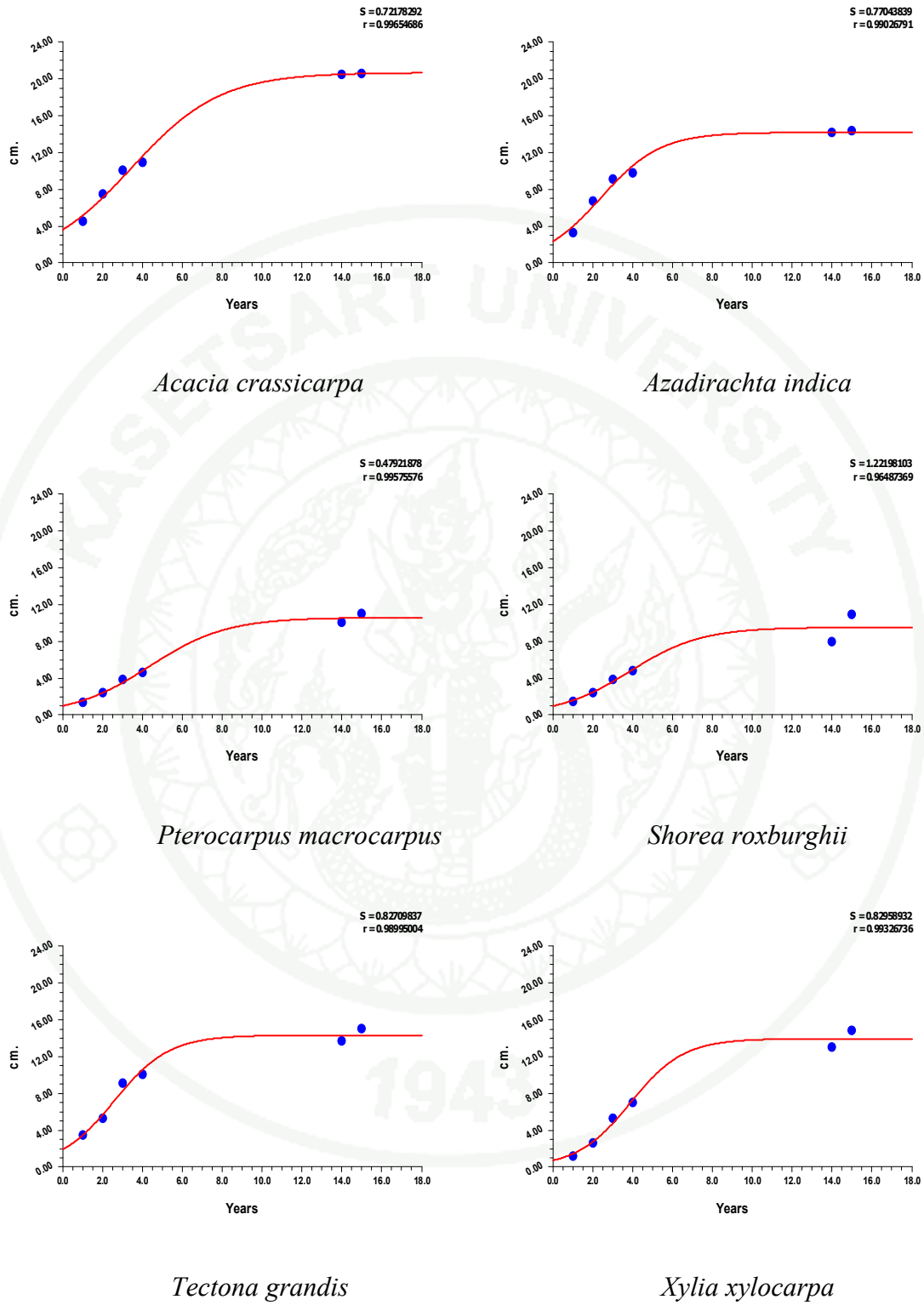



**Figure 13** Ground level diameter growth curves of each tree species.

2.2 Diameter at breast height (DBH)

As same as data of diameter at ground level, data in Table 8 showed the differences of DBH among tree species. *A. crassicarpa* expressed the greatest size of 16.28 cm DBH when the trees were 15-years-old. In addition, *A. indica* and *T. grandis* showed similarly sizes of 11.57 and 11.73 cm, respectively. Even the first four year, *A. indica* showed the larger size of DBH when compared to *T. grandis*, but after that, more rapid growth rate was found in *T. grandis*. Annual growth rate of *T. grandis* was higher than *A. indica* (0.78 vs. 0.77 cm $yr^{-1}$). Hence, there were the similar sizes of DBH in this present period. *X. xylocarpa* was 10. 84 cm, and its annual growth rate was 0.72 cm $year^{-1}$. A couple of native tree species, *S. roxburghii* and *P. macrocarpus* showed the lowest results of DBH size when they compared to other species. DBH of these species were 8.18 and 7.97 cm, and annual growth rate were 0.55 and 0.53 cm $year^{-1}$, respectively. According to annual growth rate of *A. crassicarpa*, 1.09 cm $year^{-1}$, approximated 2 times higher was found when it compared to these native species.

Roongrattanakul *et al.* (1999) reported the average DBH of 5-year old *A. crassicarpa* was ranged from 13.70 to 14.01 cm. Nydzi *et al*. (2002) reported that *A. crassicarpa* reached to 10.16 cm DBH in 4 years. That result was comparably higher than the present studied. The important reason was the spacing differences (4 m x 4 m vs. 2 m x 2 m of this present study). The DBH of *A. indica* of this present study was higher than the result was reported by Punsatha (2001). He revealed that DBH of 14-15 year-old *A. indica* plantation was ranged between 7.9 and 8.1 cm. For *T. grandis* showed lower results when it compared to other results i.e. 14-years-old plantation with 20.95 cm DBH reported by Sumanakul and Viriyabuncha (2007); 13-14-years-old plantation that ranged between 20.50 and 27.29 cm, which reported by Piananurak (1995); 15-years-old plantation with 15.88 cm DBH, reported by Petsri (2006). Furture more, many results from other countries also showed higher results e.g. 20-years-old plantation in Panama with 24.4 cm DBH, reported by Kraenzel *et al*. (2001). Annual growth rate of *T. grandis* from present study (1.09 cm $yr^{-1}$) was comparable to other countries i.e. 0.40-1.26 cm $year^{-1}$ in China (Research Institute of Tropical Forestry, 1992); 0.40-1.34 cm $year^{-1}$ in Lao PDR (Department of Forest,1998); 0.60-1.20 cm $year^{-1}$ in Vietnam (Forest Science Sub-Institute of Southern Vietnam, 1998); 1.00-3.10 cm $year^{-1}$ in Panama (Varmola,1998). In the other hand, some reports showed higher e.g.1.27 cm $year^{-1}$ in Bhutan (Droji, 1998); 1.50-2.00 cm $year^{-1}$ in Brazil (Bhat and Whan, 2001); 1.50-2.50 cm $year^{-1}$ in Honduras (Varmola, 1998). In case of *X. xylocarpa*, this native species expressed the higher growth trend when it compared to the results reported by Jongsuksuntigool and Lertnitiwong (1999). These different results were probably caused by the individual diversity of plantation management, spacing, stand density and the topography of the study sites.

As presenting in Table 9 and Figure 14, the parameter "L" expressed the upper asymptote of diameter at breast height, which calculated from logistic growth model. Native trees, *S. roxburghii* and *P. macrocarpus* seemed to be the lowest DBH with 7.38 and 7.47 cm, respectively. Meanwhile, "L" constants of other species were higher, and all species seemed to be more rapid growing than those couple species. The narrow spacing is one of the first reason which can explain the situation. The upper asymptote of diameter at breast height of *A. crassicarpa*, *A. indica*, *T. grandis* and *X. xylocarpa* were 16.36, 11.37, 11.26 and 10.18 cm, respectively. *A. crassicarpa* and *P. macrocarpus* showed the high relationship with r =1, while other species expressed between 0.98 and 0.99. Exotic species i.e. *A. indica* and *T. grandis* seemed to be the fastest growth species to reach the inflection point and the steady stage of growth in 2.16, 2.65 and 4.32, 5.30 years, respectively. DBH is the important parameter for decision the time of stand thinning; therefore the results from this present study indicated the suitable time for thinning by using the time to reach the steady stage. The results showed that the suitable time for thinning was from 4 to 8 years after planting.

**Table 8** Diameter at breast height (DBH) of each individual tree species (cm).

| Tree age | Ac | | Ai | | Pm | | Sr | | Tg | | Xx | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (years) | DBH | sd | DBH | sd | DBH | sd | DBH | sd | DBH | sd | DBH | sd |
| 1 | na. | na. | na. | na. | na. | na. | na. | na. | na. | na. | na. | na. |
| 2 | 5.44 | 1.33 | 5.16 | 1.29 | 2.35 | 1.01 | 1.42 | 0.55 | 3.90 | 1.76 | 1.68 | 1.05 |
| 3 | 7.82 | 1.63 | 7.64 | 1.33 | 2.85 | 1.58 | 2.75 | 1.08 | 7.12 | 1.97 | 3.89 | 1.81 |
| 4 | 9.02 | 2.06 | 8.29 | 1.57 | 3.25 | 1.73 | 3.57 | 1.59 | 7.55 | 2.19 | 5.49 | 2.36 |
| 14 | 16.21 | 5.58 | 11.19 | 4.21 | 6.91 | 4.08 | 6.56 | 3.79 | 10.84 | 3.17 | 9.54 | 5.47 |
| 15 | 16.28 | 4.88 | 11.57 | 4.61 | 7.97 | 4.35 | 8.18 | 3.50 | 11.73 | 2.67 | 10.84 | 5.02 |
| AGR | 1.09 | | 0.77 | | 0.53 | | 0.55 | | 0.78 | | 0.72 | |

**Remark**: Ac: *Acacia crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa*, na.: data not available and AGR: Absolute growth rate (cm year$^{-1}$)

**Table 9** Coefficient of logistic model of annual growth of diameter at breast height.

| species | L | a | b | r | infection point (years) | steady state (years) |
|---|---|---|---|---|---|---|
| *Acacia crassicarpa* | 16.36 | 4.61 | 0.45 | 1.00 | 3.40 | 6.79 |
| *Azadirachta indica* | 11.37 | 3.82 | 0.62 | 0.99 | 2.16 | 4.32 |
| *Pterocarpus macrocarpus* | 4.83 | 11.06 | 0.55 | 0.99 | 3.22 | 6.44 |
| *Shorea roxburghii* | 7.47 | 13.06 | 0.64 | 0.98 | 4.01 | 8.03 |
| *Tectona grandis* | 11.26 | 6.40 | 0.70 | 0.98 | 2.65 | 5.30 |
| *Xylia xylocarpa* | 10.18 | 22.83 | 0.84 | 0.99 | 3.72 | 7.45 |

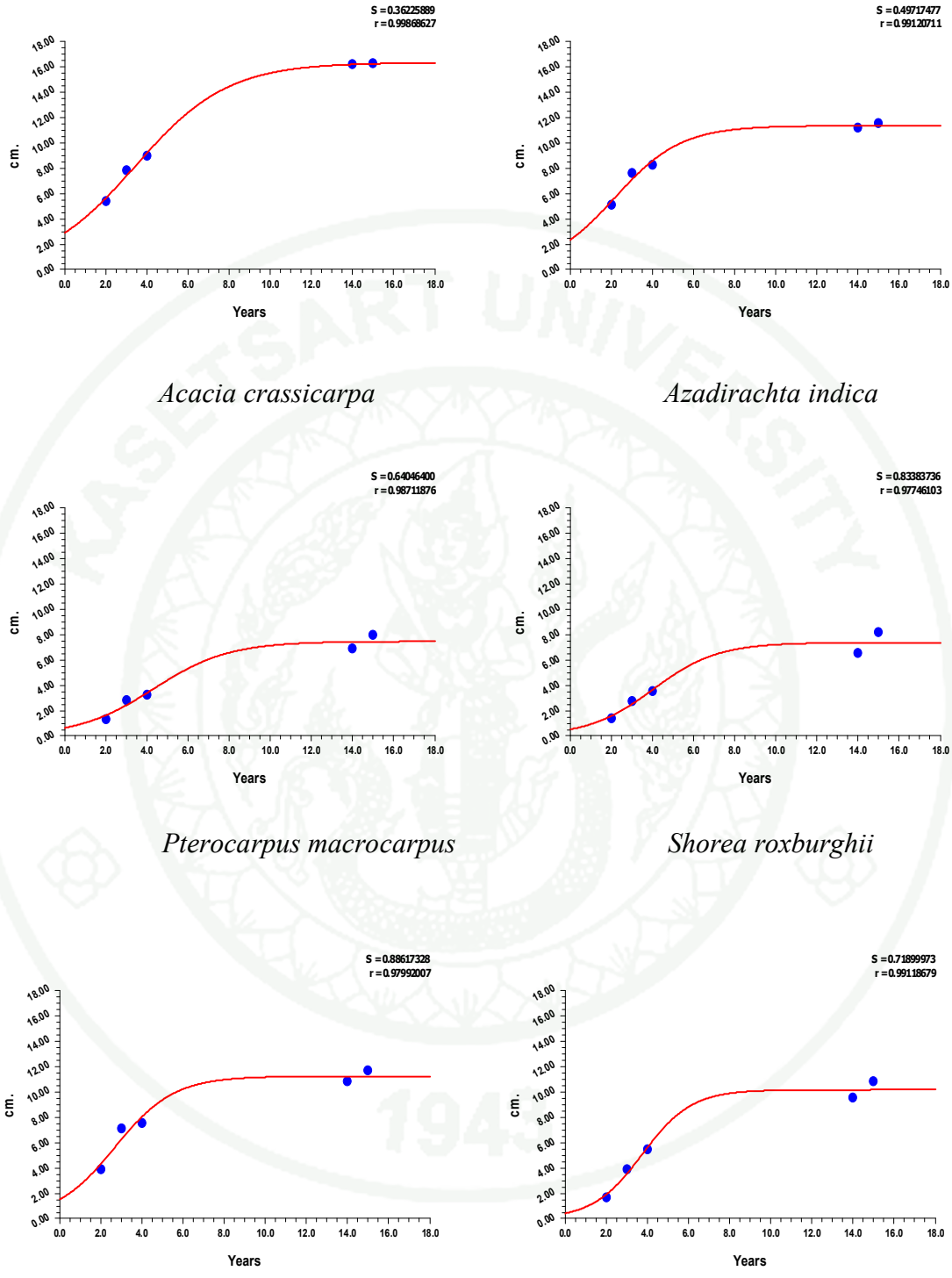



**Figure 14** Diameter at breast height (DBH) growth curve of each tree species.

2.3 Total height

*A. crassicarpa* showed the highest total height of all period. In the first year, total height of *A. crassicarpa* was 3.24 m., while other native tree species were ranged from 0.74 to 1.81 m. *A. crassicarpa* was 15.48 m height when the trees were 15 years-old, compared to height of *A. indica*, *P. macrocarpus*, *S. roxburghii*, *T. grandis* and *X. xylocarpa* were 10.11, 7.88, 9.33, 11.24 and 14.75 m, respectively. From results above, *A. crassicarpa* in the present study, showed higher than those reported from Africa region (Ngulube *et al*, 1993; Nyadzi *et al*., 2002). Nevertheless, height growth of *A. crassicarpa* was nearly the result reported by Roongrattanakul *et al*. (1999). They reported the average height of 5-year-old *A. crassicarpa* was ranged from 12.85 to 13.28 m. Rarivoson *et al*. (2007) revealed that 3-year-old height of *A. crassicarpa* planted in Madagascar was 4.86±0.79 m.

Native tree species, *X. xylocarpa* showed dramatically height growth after 15 years of planting. The results from this present study were higher than other reports e.g. height of 10-years-old plantation, northeastern Thailand was 6.18 m (Jongsuksuntigool and Lertnitiwong, 1999). Total height of *T. grandis* was lower than many studies that established in plantation e.g. Piananurak (1995), Sumantakul and Viriyabuncha (2007). Therefore, some reported that studied in poor site of the northern Thailand showed the similar results of the present study (Srisuksai, 1990; Piananurak, 1995). Total height of *T. grandis* in the present study (11.24 m) ought to be classified as the poor growth rate (Srisuksai, 1990; Anoop, 2005). The annual growth rate was highest with *A. crassicarpa*; 1.03 m year$^{-1}$. The second was *X. xylocarpa*; 0.98 m year$^{-1}$, followed by *T. grandis*, *A. indica*, *S. roxburghii* and *P. macrocarpus*; 0.75, 0.67, 0.62, and 0.53 m year$^{-1}$, respectively. *X. xylocarpa* was the native tree species that showed the fast annual height growth. Comparing by annual growth rates of *A. crassicarpa* and *X. xylocarpa* were quite similar, but they differed from others. Table 10 showed that total heights of trees were varied between species-to-species. Similar results were found in the first year until the trees were four-years-old. For that time, no differences of height growth rate were found among tree species. However, *A. crassicarpa* showed distinctly results in higher growth rate. Consequently, when the trees were 14- and 15-year-old, *X. xylocarpa* showed the rapid growth rate, and reach up to 13.67 and 14.7 m, respectively. Other species, including *A. indica*, *P. macrocarpus*, *S. roxburghii* and *T. grandis* showed the consistently growth rate throughout the period of study. Even total height at 15$^{th}$ year of *X. xylocarpa* was lower than that of *A. crassicarpa*, but it could grow up with more rapid rate and could reach up more in total height than *A. crassicarpa* in the near future. From Table 11 and Figure 15, the asymptote height was ranged from 7.75 to 15.20 m. *A. crassicarpa* expressed the highest result 15.20 m height followed by native tree species i.e. *X. xylocarpa* and *T. grandis*; 14.23 and 10.47 m height respectively. Other exotic, *A. indica* showed as similar height as *S. roxburghii*; 9.61 and 9.22 m. respectively. *P. macrocarpus* was the lowest feasible height, 7.75 m. High relationships between height growth and age of tree were found. *A. crassicarpa*, *A. indica* and *T. grandis* reached the maximum growth in less than three years (2.65,

2.57 and 2.50 years, respectively). In addition, other species took almost five years to reach the maximum growth rate. Therefore, *P. macrocarpus*, *S. roxburghii* and *X. xylocarpa* took 8.74, 9.90 and 10.01 years, respectively to reach the steady stage of height growth. Meanwhile, *A. crassicarpa*, *A. indica* and *T. grandis* should be thinned around 5 years after planting, and *P. macrocarpus*, *S. roxburghii* and *X. xylocarpa* should be thinned after 8 years of planting.

**Table 10** Total height of each individual tree species (m.) and standard deviation.

| Tree age | Ac | | Ai | | Pm | | Sr | | Tg | | Xx | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (years) | H | sd | H | sd | H | sd | H | sd | H | sd | H | sd |
| 1 | 3.24 | 0.41 | 2.03 | 0.37 | 1.03 | 0.64 | 1.12 | 0.30 | 1.81 | 1.13 | 0.74 | 0.39 |
| 2 | 5.62 | 1.11 | 3.94 | 0.58 | 1.61 | 0.85 | 1.60 | 0.53 | 3.32 | 1.46 | 1.59 | 0.75 |
| 3 | 9.10 | 1.22 | 5.43 | 0.79 | 2.69 | 1.18 | 2.67 | 1.01 | 7.23 | 1.95 | 3.08 | 1.35 |
| 4 | 11.04 | 1.62 | 7.37 | 1.04 | 3.40 | 1.28 | 3.48 | 1.49 | 8.54 | 2.14 | 4.72 | 2.18 |
| 14 | 14.97 | 3.70 | 9.10 | 6.84 | 7.55 | 0.54 | 8.95 | 3.46 | 9.80 | 4.53 | 13.67 | 2.87 |
| 15 | 15.48 | 4.23 | 10.11 | 4.94 | 7.88 | 0.65 | 9.33 | 3.21 | 11.24 | 3.88 | 14.75 | 2.21 |
| AGR | 1.03 | | 0.67 | | 0.53 | | 0.62 | | 0.75 | | 0.98 | |

**Remark**: Ac: *Acacia crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa* and AGR: Absolute growth rate (m. year$^{-1}$)

**Table 11** Coefficient of logistic model of annual growth of total height.

| species | L | a | b | r | infection point (years) | steady state (years) |
|---|---|---|---|---|---|---|
| *Acacia crassicarpa* | 15.20 | 7.88 | 0.78 | 1.00 | 2.65 | 5.29 |
| *Azadirachta indica* | 9.61 | 7.80 | 0.80 | 0.99 | 2.57 | 5.14 |
| *Pterocarpus macrocarpus* | 7.75 | 10.59 | 0.54 | 1.00 | 4.37 | 8.74 |
| *Shorea roxburghii* | 9.22 | 11.87 | 0.50 | 1.00 | 4.95 | 9.90 |
| *Tectona grandis* | 10.47 | 17.80 | 1.15 | 0.99 | 2.50 | 5.01 |
| *Xylia xylocarpa* | 14.23 | 30.04 | 0.68 | 1.00 | 5.00 | 10.01 |

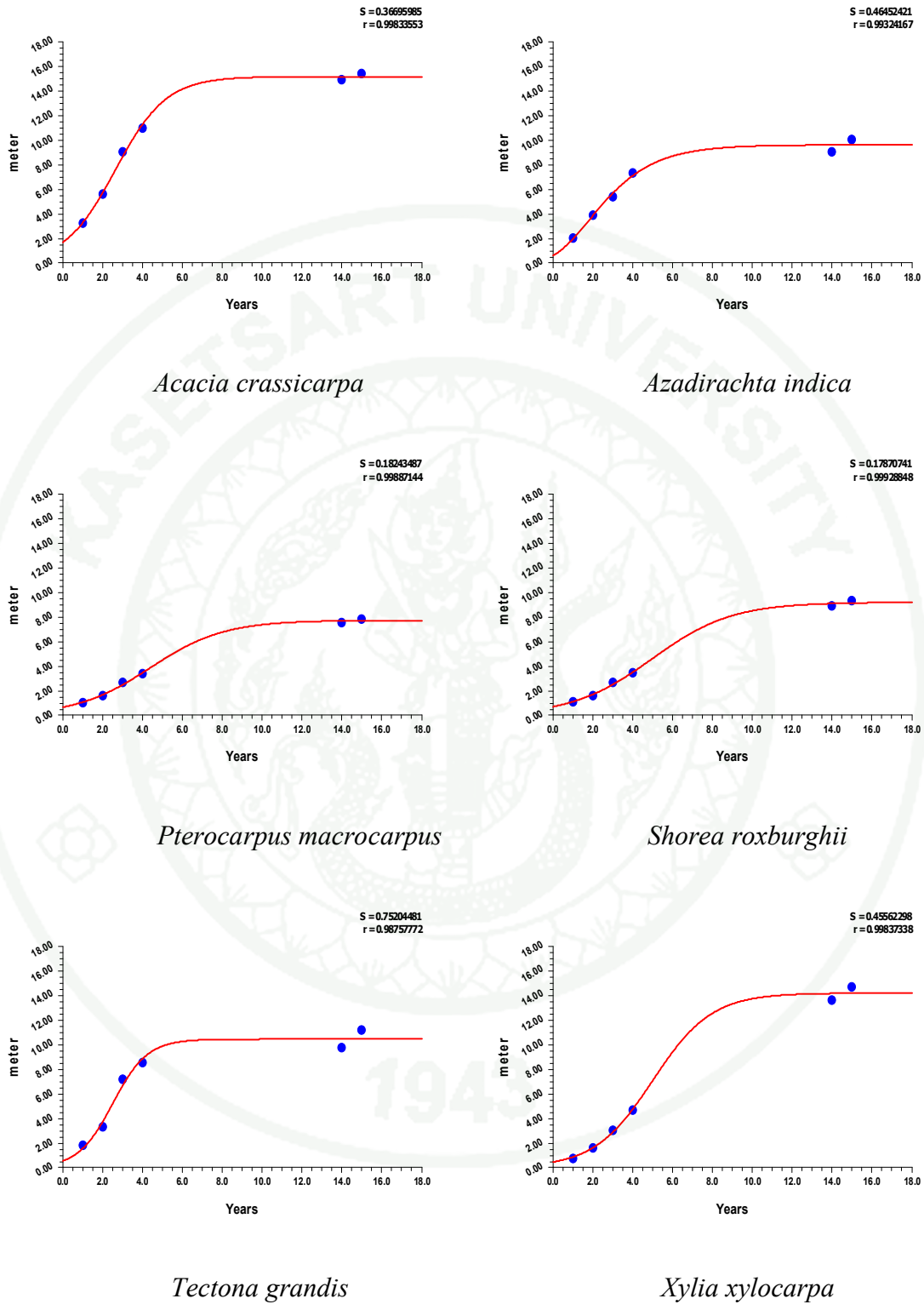



**Figure 15** Total height growth curve of each tree species.

## 3. Tree biomass

3.1 Allometrie equation for estimate tree biomass.

After finished tree census, five trees which covered all DBH classes were cutting down. Above- and belowground components obtained by using stratified clip technique. An allometric relationship of estimated component dry matter with DBH was developed from the harvested sample trees for each component separated using equation; $Y = aX^b$. All results were shown in Table 12.

**Table 12** Allometric equation ($Y = aX^b$) constants (a,b) and coefficients of determination ($R^2$) for estimating biomass components of individual tree species.

| Tree species | Tree component | a | b | $R^2$ |
|---|---|---|---|---|
| *Acacia crassicarpa* | stem | 0.27 | 2.10 | 0.98 |
| | branch | 0.10 | 1.70 | 0.73 |
| | leaf | 0.09 | 1.80 | 0.91 |
| *Azadirachta indica* | stem | 0.28 | 2.11 | 0.97 |
| | branch | 0.04 | 2.06 | 0.99 |
| | leaf | 0.04 | 1.66 | 0.98 |
| *Pterocarpus macrocarpus* | stem | 0.08 | 2.33 | 0.98 |
| | branch | 0.02 | 2.35 | 0.97 |
| | leaf | 0.00 | 2.43 | 0.98 |
| *Shorea roxburghii* | stem | 0.14 | 2.31 | 0.99 |
| | branch | 0.04 | 2.25 | 0.91 |
| | leaf | 0.05 | 1.70 | 0.92 |
| *Tectona grandis* | stem | 0.06 | 2.59 | 0.99 |
| | branch | 0.00 | 2.88 | 0.98 |
| | leaf | 0.01 | 2.24 | 0.83 |
| *Xylia xylocarpa* | stem | 0.11 | 2.47 | 0.98 |
| | branch | 0.02 | 2.43 | 0.93 |
| | leaf | 0.06 | 1.62 | 0.97 |

3.2 Aboveground biomass of each tree species.

Aboveground biomass of each tree species was calculated by using average DBH of each species. As shown in Table 13 and Figure 16, the above ground biomass distributed mainly into stem part, come after by branch and leaf, respectively. The results of *A. crassicarpa* showed that; stem, branch, leaf and total above ground biomass were 231.53, 26.84, 14.34 and 272.71 ton $ha^{-1}$, respectively. *A. indica* were 128.81, 17.15, 5.81 ton $ha^{-1}$, and total aboveground biomass was 151.77 ton $ha^{-1}$. *P. macrocarpus* was the lowest aboveground biomass species. The results expressed the stem, branch and leaf biomass was 27.76, 7.29 and 1.33 ton $ha^{-1}$, respectively. The total biomass of *P. macrocarpus* was 36.38 ton $ha^{-1}$. *S. roxburghii* were 42.83, 10.60, 3.63 ton $ha^{-1}$of stem, branch leaf biomass. The total biomass was 57.06 ton $ha^{-1}$. The total aboveground biomass of *T. grandis* was 92.85 ton $ha^{-1}$, divided into stem, branch and leaf; 76.83, 10.77 and 5.25 ton $ha^{-1}$, respectively. *X. xylocarpa*, showed remarkably higher result when compared to other native tree species. The total biomass was 114.22 ton $ha^{-1}$, divided into stem, branch and leaf with 93.50, 15.28 and 5.44 ton $ha^{-1}$, respectively.

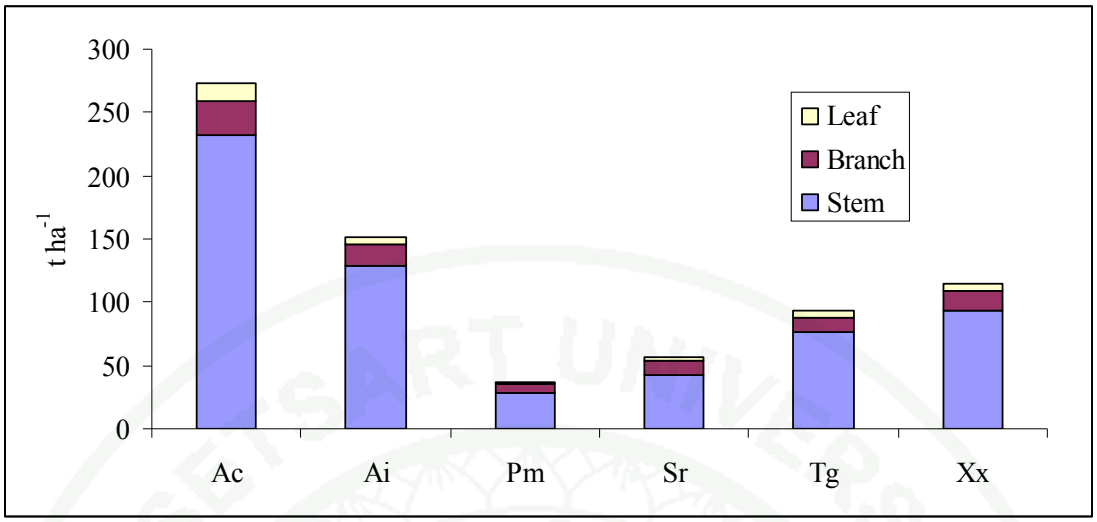
Duncan's multiple range test indicated the variation of tree biomass among tree species. For stem biomass, *A. crassicarpa* and *A. indica* showed distinctly different. However, those two species could classify as the same group as *X. xylocarpa*. Native tree, *P. macrocarpus* showed the distinctly lowest result of stem biomass. As stem part, branch biomass also varied species to species. Distinctly different results were found, the highest and the lowest results of branch biomass were *A. crassicarpa* and *P. macrocarpus*, respectively. For leaf biomass, *A. crassicarpa* showed the distinctly highest result. Furthermore, *A. indica*, *T. grandis* and *X. xylocarpa* were classified as the same group. In addition, *P. macrocarpus* and *S. roxburghii* were the lowest group of leaf biomass. Total biomasses of *A. crassicarpa*, *A. indica* and *X. xylocarpa* were distinctly different from the others. The aboveground biomasses of this study were varied when compared to other findings. The aboveground biomass of *A. crassicarpa* from this study was higher than the *A. crassicarpa* planted on acid sandy soil in Tanzania with 31.4 and 95.8 ton $ha^{-1}$ (Nyadzi, 2003) or 84.8 ton $ha^{-1}$ planted in southwestern Papua New Guinea where this species occurred naturally (Kiratiprayoon and Williams, 1991). Kiatwoottinan *et al*. (1997) researched in 4-year-old *A. crassicarpa* plantation and reported that aboveground biomass was 120.88 ton $ha^{-1}$. This result seemed to be higher when compared to the present.

Aboveground biomass values of the present study, with the exception of the *A. crassicarpa* plot, were lower than that reported by Nualngam (2002) who studied a 14-year-old plantation in northeastern Thailand. He reported that the above-ground biomass of *P. macrocarpus* and *X. xylocarpa* were 53.1 and 88.3 ton $ha^{-1}$, respectively. In contrast, he reported the above-ground biomass of *Acacia* spp. was ranged from 119.5 to 195.2 ton $ha^{-1}$, which was lower when compared to the results of *A .crassicarpa* from this study (272.71 ton $ha^{-1}$). The differences were due to

different tree density (2 m x 2 m spacing versus the spacing of 2 m x 3 m) and the higher survival rate of 89 % in the current study than the survival rates values of 69.5 and 52.6% that reported by Nualngam (2002). Total aboveground biomass of *T. grandis* of this present study was 2 times higher than the results reported by Petsri (2004). She revealed that the aboveground biomass of 15-year-old *T. grandis* plantation including stem, branch and leaf were 32.12, 7.72 and 0.41 ton $ha^{-1}$, respectively. These results were comparably lower than 76.83, 10.77 and 5.25 ton $ha^{-1}$, of the present study. More over, 40.26 ton $ha^{-1}$ total aboveground biomass reported by Petsri (2004) was lower than 92.85 ton $ha^{-1}$, that of the present study. Furthermore, Viriyabuncha *et al*. (1997) carried out the study on aboveground biomass of 21-years-old teak plantation and reported 70.09 ton $ha^{-1}$ total aboveground biomass, including stem, branch and leaf were 50.11, 16.42 and 3.56 ton $ha^{-1}$, respectively. This result from older stand was lower than this present study. Anyhow, many results reported on the adversely results i.e. Petmark and Sahunalu (1980) revealed that the aboveground biomass of 14-year-old *T. grandis* plantation planted 1,700 tree $ha^{-1}$ density was 110.88 ton $ha^{-1}$. In addition, resemble result was reported by Petmark (1980). He revealed that aboveground biomass of *T. grandis* in thinned and un-thinned stand were 78.97 and 81.79 ton $ha^{-1}$, respectively. These results were lower than *T. grandis* plot of this present study, that was probably due to the narrow spacing (2 m x 2 m) of present study occupied the high stand density (1,736 tree $ha^{-1}$). In addition, the highly survival rate (69.45 %) which was one of the important factor resulted higher aboveground of present study. According to the result reported by Dhammanonda (1981) revealed that 61.54 ton $ha^{-1}$, the largest aboveground biomass was found in 2 m x 2 m spacing of *T. grandis* plantation. On the other hand, the larger spacing, 3 m x 3 m, 4 m x 4 m and 6 m x 6 m spacing were 23.95, 13.73 and 2.53 ton $ha^{-1}$, respectively. He gave the results reason that because the 2 m x 2 m spacing stand occupied the highest stand density of 2,013 tree $ha^{-1}$, whereas, the stand densities of 3 m x 3 m, 4 m x 4 m and 6 m x 6 m spacing were 907, 457 and 201 tree $ha^{-1}$, respectively.

**Table 13** Aboveground biomass of each tree species (ton $ha^{-1}$).

| Year | Species | Above-ground biomass | | | Total above-ground biomass |
|---|---|---|---|---|---|
| | | Stem | Branch | Leaf | |
| 2007 | *A. crassicarpa* | 230.26 | 26.51 | 14.18 | 270.95 |
| | *A. indica* | 121.74 | 16.22 | 5.54 | 143.50 |
| | *P. macrocarpus* | 24.97 | 6.56 | 1.20 | 32.72 |
| | *S. roxburghii* | 34.31 | 8.54 | 3.09 | 45.94 |
| | *T. grandis* | 71.84 | 10.02 | 4.94 | 86.80 |
| | *X. xylocarpa* | 86.38 | 14.13 | 5.18 | 105.69 |
| 2008 | *A. crassicarpa* | $231.53^{a}$ | $26.84^{a}$ | $14.34^{a}$ | $272.71^{a}$ |
| | *A. indica* | $128.81^{b}$ | $17.15^{b}$ | $5.81^{b}$ | $151.77^{b}$ |
| | *P. macrocarpus* | $27.76^{e}$ | $7.29^{d}$ | $1.33^{e}$ | $36.38^{e}$ |
| | *S. roxburghii* | $42.83^{de}$ | $10.60^{cd}$ | $3.63^{d}$ | $57.06^{de}$ |
| | *T. grandis* | $76.83^{cd}$ | $10.77^{cd}$ | $5.25^{bc}$ | $92.85^{cd}$ |
| | *X. xylocarpa* | $93.50^{bc}$ | $15.28^{bc}$ | $5.44^{bc}$ | $114.22^{bc}$ |
| | F-value | 46.07 | 67.97 | 48.60 | 48.96 |
| | Significant | ** | ** | ** | ** |
| Absolute growth rate (AGR) | *A. crassicarpa* | 1.27 | 0.33 | 0.16 | 1.76 |
| | *A. indica* | 7.07 | 0.93 | 0.27 | 8.27 |
| | *P. macrocarpus* | 2.79 | 0.73 | 0.14 | 3.66 |
| | *S. roxburghii* | 8.52 | 2.06 | 0.55 | 11.12 |
| | *T. grandis* | 4.99 | 0.75 | 0.31 | 6.05 |
| | *X. xylocarpa* | 7.12 | 1.14 | 0.26 | 8.53 |




**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis*; Xx: *X. xylocarpa*

**Figure 16** Total above ground biomass of each tree species.

Table 13 indicated that, absolute growth rates of aboveground biomass gradually increased for *A. crassicarpa* and *P. macrocarpus* which were 1.76 and 3.66 ton ha$^{-1}$ year$^{-1}$, respectively. On the other hand, rapid growth of 14- to 15-year-old *S. roxburghii* was found (see Table 6, 8 and 10) that affecting absolute growth rate. This species increment was 11.12 ton ha$^{-1}$ year$^{-1}$. Absolute growth rates of *A. indica*, *T. grandis* and *X. xylocarpa* expressed comparable results ranged from 6.05 to 8.53 ton ha$^{-1}$ year$^{-1}$. Anthony *et al*. (2007) reported that absolute growth rate of *A. crassicarpa* was 10.2 ton ha$^{-1}$ year$^{-1}$. He also revealed that *A. crassicarpa* showed higher result of increment when compared to *A. mangium* and *A. polyacantha*. This contrary higher result of Anthony *et al*. (2007) was mainly due to the different of stand age. Anthony *et al*. (2007) achieved their results from 5-year-old stand. This early stage of stand development could be able to produce rapid growth rate. On the contrary, mean annual increment (1.76 ton ha$^{-1}$ year$^{-1}$) from present study may be resulted from dense stand and closed canopy. Generally, tree species which wide canopy and deep root system would be expected to produce high biomass under limited supply of growth resources (Anthony *et al*., 2007). Hence, *A. crassicarpa*, the species which eminently growth and present the wide canopy produce the largest aboveground biomass, 272.71 ton ha$^{-1}$. While, *P. macrocarpus* and *S. roxburghii* represented only 36.38 and 57.06 ton ha$^{-1}$, respectively. *A. indica* aboveground biomass was 151.77 ton ha$^{-1}$. This result may be related to the largest volume of root mass which functioning water and nutrient supply for tree growth mechanism.

**4. Total belowground biomass of each individual tree species.**

Root samples were categorized into fine root (<2 mm) and coarse root (>2 mm). Vertical distribution was studied 10 cm depth interval from soil surface. All data were showed in Table 14 and Figure 17. The results reveal that all species showed decreasing trend of root biomass with increasing soil depth. *A. indica*, *P. macrocarpus* and *T. grandis* expressed the highest total root biomass in top soil layer from 0 to 10 cm. While, *A. crassicarpa*, *S. roxburghii* and *X. xylocarpa* were the highest in the second layer from 10 to 20 cm. Most fine root biomass of *A. crassicarpa* was distributed in the second (5.34 ton $ha^{-1}$). While, the first, fourth and fifth were 3.95, 2.83, 2.22 and 1.14 ton $ha^{-1}$, respectively. Coarse root was distributed mostly in the first layer of 1.01 ton $ha^{-1}$. The second layer was 0.94 ton $ha^{-1}$, while the third, fourth and fifth layer were 0.27, 0.53 and 0.31 ton $ha^{-1}$, respectively. Total root biomass of *A. crassicarpa* was mostly distributed in the first and the second layer of 4.96 and 6.96 ton $ha^{-1}$, respectively. The third, fourth and fifth layers were 3.10, 2.75 and 1.44 ton $ha^{-1}$, respectively. Fine root of *A. indica* was distributed mostly in the first layer of 14.02 ton $ha^{-1}$, decreasing in the second layer to 5.76 ton $ha^{-1}$. The third, fourth and fifth layers were 3.15, 1.33 and 0.66 ton $ha^{-1}$, respectively. Coarse root was distributed mostly in the first layer of 15.43 ton $ha^{-1}$. While, the second, the third, fourth and fifth layers were 3.51, 3.59, 1.44 and 1.05 ton $ha^{-1}$, respectively. Total root mass of *A. indica* was mostly distributed in the first layer of 29.45 ton $ha^{-1}$. While, decreasing of root mass was found in the second layer of 6.66 ton $ha^{-1}$. Total root mass was increasing in the third layer of 9.35 ton $ha^{-1}$, and continuously decreasing in fourth and fifth layers of 2.77 and 1.71 ton $ha^{-1}$, respectively

Fine root of *P. macrocarpus* was mostly distributed in the first layer of 2.75 ton $ha^{-1}$, and then decreasingly in the second layer 2.21 ton $ha^{-1}$, the third layer 2.37 ton $ha^{-1}$, fourth layer 1.10 ton $ha^{-1}$ and fifth layer 0.60 ton $ha^{-1}$. The decreasing trend of fine root biomass with increasing depth also occurred with coarse root biomass. Coarse root biomass decreasing when soil depth was increasing from the first layer 2.49 ton $ha^{-1}$ and then root mass was decreasing from the second, the third, fourth and fifth layers of 2.11, 1.00, 0.02 and 0.01 ton $ha^{-1}$, respectively. Thus, total root mass also decreasing when soil depth was increasing, from the first layer of 5.24 ton $ha^{-1}$, and continuously decreased to the second layer of 4.32 ton $ha^{-1}$, the third layer of 3.37 ton $ha^{-1}$, fourth layer of 1.12 and the fifth layer of 0.61 ton $ha^{-1}$. Root mass distribution of *S. roxburghii*; fine root was found mostly in the second layer of 9.07 ton $ha^{-1}$. This was roughly 2 times higher result from top layer (4.80 ton $ha^{-1}$). At 30-50 cm depth, root biomass was a bit change that expressed between 0.91 and 1.11 ton $ha^{-1}$, respectively. Coarse root biomass of *S. roxburghii* was smaller amount than fine root and was decreased with increasing soil depth. The data was ranged between 0.05 and 0.47 ton $ha^{-1}$.

Root biomass of *T. grandis* distributed mostly in the first layer both fine root and coarse root were 6.79 and 5.41 ton $ha^{-1}$, respectively. While, the second layers, fine and coarse root mass were 2.97 and 4.24 ton $ha^{-1}$, respectively. The last three

layers, fine root were 2.79, 2.73 and 1.49 ton $ha^{-1}$, respectively. For coarse root, the last three layers contained of 1.62, 2.09 and 0.09 ton $ha^{-1}$, respectively. Total root mass of *T. grandis* from the upper most to the deepest layer were 12.20, 7.21, 4.41, 4.83 and 1.58 ton $ha^{-1}$, respectively. Fine root biomass of *X. xylocarpa* was distributed mostly in the first and second layers (1.36-1.39 ton $ha^{-1}$). After that, root masses continuously decreased from the third to fifth layers were 1.71, 1.08 and 0.68 ton $ha^{-1}$, respectively. Coarse root mass was mostly occurred in the second layer of 1.95 ton $ha^{-1}$, while the results from other layers were ranged between 0.21 and 0.34 ton $ha^{-1}$. From the results revealed above, mostly biomass of both coarse- and fine root were distributed in the second soil layer. Hence, total root mass of *X. xylocarpa* also appeared mostly in the 10-20 cm depth (3.34as ton $ha^{-1}$) while the top soil layer contained 1.73 ton $ha^{-1}$ of total root mass. After that, total root mass continued from the third layer to fifth layer and ranged between 0.90 and 2.02 ton $ha^{-1}$, respectively.

The below-ground biomass in the current study showed a similar trend to other exotic tree species plantations that had total below-ground biomass between 3.8 and 25.5 ton $ha^{-1}$ (Dutta and Madhoolika, 2003), and 26.54 ton $ha^{-1}$ reported by Singh (1994), who studied in *Eucalyptus* spp. hybrid plantations. Data in Table 14 and Figure 17 showed that all species mostly distributed root mass in upper surface soil layer, especially from 0-10 cm and 10-20 cm depths. According to Tongtapao (2008) , she revealed that 16-year-old *Acacia aulacocarpa* and *Eucalyptus urophylla*, fine root mass was mostly distributed in 0-20 cm soil depth (76.14 and 69.54 %, respectively). While, coarse root was mostly distributed in 0-30 cm soil (87.71 and 85.48 %, respectively). The differences of soil nutrient and moisture content between different soil depths were the major causes affecting to root distribution. Rytter and Hanson (1996) found the seasonal difference of root growth; fine root growth started in May and increased through summer and early autumn. After that, decreasing of growth occurred from September and continued during autumn. In addition, most fine roots were found in the upper 45 cm depth. The difference in the below-ground biomass among tree species might probably be due to genetic variation and adaptation to each natural habitat. *A. crassicarpa*, which was naturally distributed in moist regions, had a lower value for below-ground biomass than the species that were naturally distributed in dry regions, such as *P. macrocarpus* and *X. xylocarpa*. The greater below-ground biomass of *A. indica* and *T. grandis* signifies their suitability for forest restoration on dry land that were due to their greater moisture and nutrient absorption capacity. *X. xylocarpa*, the native tree species expressed the lowest survival rate of 69%, nevertheless, the total biomass of this species was greater than the species with greater survival rate e.g. *P. macrocarpus* (76%) and *S. roxburghi* (74%). The greater total biomass was due to the wider growing space and the height of *X. xylocarpa* was higher than other species. Srivastava *et al*. (1986) found that the spatial distribution of fine root of 19-year-old *T. grandis* plantation in dry tropical region was distributed of 10-30 cm depth with the total root mass of 5.46 ton $ha^{-1}$. This publishes revealed comparable higher result when compared to 2.72 ton $ha^{-1}$ fine root mass of this present study. However, there was the similar trend of root distribution in the upper most soil layer. Consistent to Parrotta *et al*. (1999) revealed that average fine-root mass in the plantation plots increased only slightly following rapid development during the first

year. He also found the decrease in fine root mass with soil depth. Pumijumnong (2007) who studied in 10-28-years-old plantation reported that range of lateral root distributed was 50 cm depth and 1.50 m wide. She also found that belowground biomass of *T. grandis* plantation was ranged from 0.54 to 5.72 ton $ha^{-1}$. This result seemed to be distinctly different from this present study that might be due to differences of stand density. The excavation method is very useful to assess root distribution and quality of belowground biomass. However, the method is time consuming. This method is very demonstrative and it has to be used when no information is available on a given species (Anegbe, 2006).

**Table 14** Vertical distribution of root biomass of each species (ton $ha^{-1}$).

| Root part | Depth (cm) | Ac | Ai | Pm | Sr | Tg | Xx |
|---|---|---|---|---|---|---|---|
| Fine root biomass | 0-10 | 3.95 | 14.02 | 2.75 | 4.80 | 6.79 | 1.36 |
| | 10-20 | 5.34 | 5.76 | 2.21 | 9.07 | 2.97 | 1.39 |
| | 20-30 | 2.83 | 3.15 | 2.37 | 1.11 | 2.79 | 1.71 |
| | 30-40 | 2.22 | 1.33 | 1.10 | 1.10 | 2.73 | 1.08 |
| | 40-50 | 1.14 | 0.66 | 0.60 | 0.91 | 1.49 | 0.68 |
| | total | 15.48 | 24.92 | 9.03 | 16.99 | 16.78 | 6.22 |
| Coarse root biomass | 0-10 | 1.01 | 15.43 | 2.49 | 0.29 | 5.41 | 0.37 |
| | 10-20 | 0.94 | 3.51 | 2.11 | 0.47 | 4.24 | 1.95 |
| | 20-30 | 0.27 | 3.59 | 1.00 | 0.21 | 1.62 | 0.31 |
| | 30-40 | 0.53 | 1.44 | 0.02 | 0.06 | 2.09 | 0.34 |
| | 40-50 | 0.31 | 1.05 | 0.01 | 0.05 | 0.09 | 0.21 |
| | total | 3.06 | 25.01 | 5.63 | 1.07 | 13.45 | 3.18 |
| Total root biomass | 0-10 | 4.96 | 29.45 | 5.24 | 5.08 | 12.20 | 1.73 |
| | 10-20 | 6.29 | 6.66 | 4.32 | 9.54 | 7.21 | 3.34 |
| | 20-30 | 3.10 | 9.35 | 3.37 | 1.32 | 4.41 | 2.02 |
| | 30-40 | 2.75 | 2.77 | 1.12 | 1.16 | 4.83 | 1.42 |
| | 40-50 | 1.41 | 1.71 | 0.62 | 0.96 | 1.58 | 0.90 |
| | total | 18.54 | 49.93 | 14.66 | 18.06 | 30.23 | 9.40 |

**Remark**: Ac: *A. crassicarpa*, Ai: *A. indica*, Pm: *P. macrocarpus*, Sr: *S. roxburghii*, Tg: *T. grandis* and Xx: *X. xylocarpa*

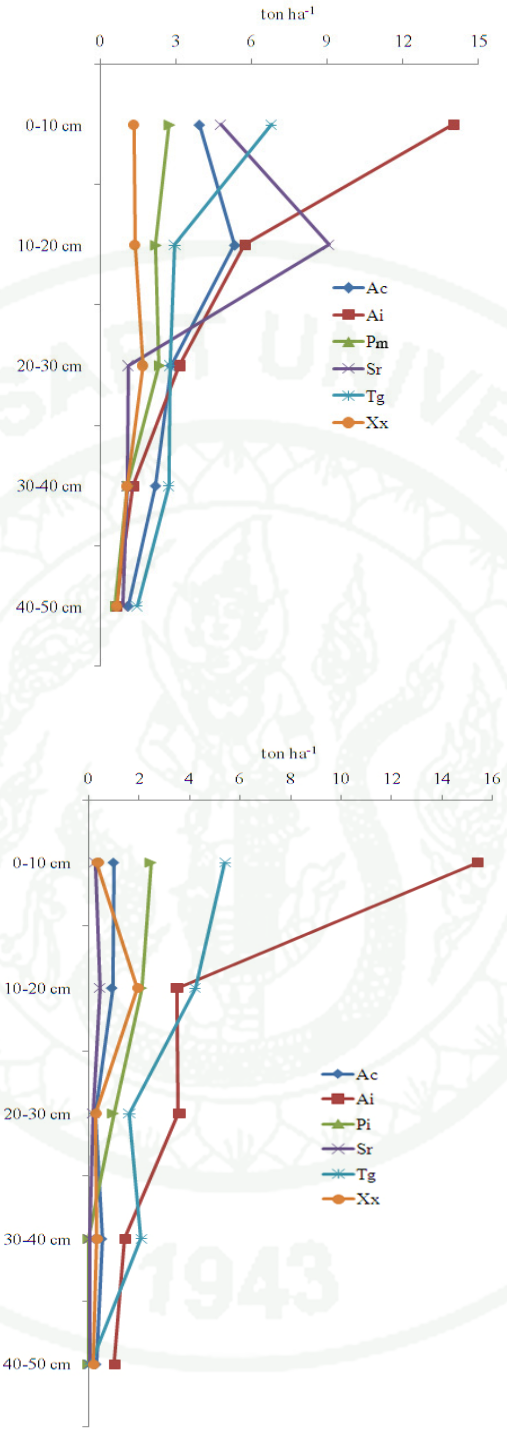



**Figure 17** Vertical distribution of fine root (above) and coarse root biomass (below) of each tree species.

Data of total belowground biomass in Table 14 (at 0-50 cm depth) were used to calculated the estimate total root mass in deeper soil layer. By generated the exponential equation of the relationships between soil depth and belowground biomass, the estimated data of root mass at 50-100 cm depth were showed in Table 15. The results were revealed that, no such increased of root mass both *S. roxburghii* and *T. grandis* plots. In the other hand, total root mass of *X. xylocarpa* was increased 2.97 ton $ha^{-1}$ that it changed from 9.40 into 12.37 ton $ha^{-1}$. Total root biomasses of *A. crassicarpa* and *P. macrocarpus* were 0.45 and 0.91 ton $ha^{-1}$. These results were lower than the increased of root mass derived from *A. indica* plot, 0.91 ton $ha^{-1}$. Data in Table 15 could be concluded that, when root mass at 50-100 cm was taken into account, a little changed in term of total belowground biomass was found. This situation could be described by the natural root distribution phenomena which was mostly occurred in the soil surface due to appropriate nutrients supply and moisture content. That was supported by many articles e.g. Schenk and Jackson (2002), they revealed that globally, at least 50% of all roots were found in the upper 0.3 m. Srivastava *et al*. (1986) reported that the bulk of the root mass of *T. grandis* was distributed at a depth of 10–30 cm. Toky and Bisht (1992) studied in 6-year-old trees of 9 indigenous and 3 exotic species growing in arid climate of north-western India , and found that top 30 cm soil contained up to 78% of the total biomass.

**Table 15** Total belowground biomass at 0-100 cm depth (ton $ha^{-1}$).

| Depth (cm) | Ac | Ai | Pm | Sr | Tg | Xx |
|---|---|---|---|---|---|---|
| 0-10 | 3.95 | 29.45 | 5.24 | 5.08 | 12.20 | 1.73 |
| 10-20 | 5.34 | 9.27 | 4.32 | 9.54 | 7.21 | 3.34 |
| 20-30 | 2.83 | 6.74 | 3.36 | 1.32 | 4.41 | 2.02 |
| 30-40 | 2.22 | 2.77 | 1.12 | 1.16 | 4.83 | 1.42 |
| 40-50 | 1.14 | 1.70 | 0.62 | 0.96 | 1.58 | 0.90 |
| 50-60 | 1.22 | 0.78 | 0.42 | 0.00 | 0.00 | 0.88 |
| 60-70 | 0.88 | 0.39 | 0.24 | 0.00 | 0.00 | 0.70 |
| 70-80 | 0.63 | 0.20 | 0.14 | 0.00 | 0.00 | 0.57 |
| 80-90 | 0.45 | 0.10 | 0.08 | 0.00 | 0.00 | 0.45 |
| 90-100 | 0.33 | 0.05 | 0.04 | 0.00 | 0.00 | 0.36 |
| Observed (0-50 cm) | 18.53 | 49.92 | 14.66 | 18.06 | 30.23 | 9.40 |
| Estimated (0-100 cm) | 18.98 | 51.43 | 15.57 | 18.06 | 30.23 | 12.37 |
| Estimated increase | 0.45 | 1.51 | 0.91 | 0 | 0 | 2.97 |

**Remark**: Ac: *A. crassicarpa*, Ai: *A. indica*, Pm: *P. macrocarpus*, Sr: *S. roxburghii*, Tg: *T. grandis* and Xx: *X. xylocarpa*

**5. Total tree biomass.**

Results of total tree biomass were shown in Table 16 and Figure 18. The results indicated that the total above-ground biomass of both exotic tree species i.e. *A. crassicarpa* and *A. indica* (272.71 and 157.77 ton $ha^{-1}$, respectively) were higher than that of all native tree species. In contrast, the two native species, *S. roxburghii* and *P. macrocarpus*, which were lowest values of total height and also presented the lowest above-ground biomass of only 57.06 and 36.38 ton $ha^{-1}$, respectively. Total above-ground biomass of *T. grandis* and *X. xylocarpa* were 92.85 and 114.22 ton $ha^{-1}$, respectively. Overall, differences of biomass among species plots were primarily due to the presence or absence of planted trees and also the growth performance of each tree species. *A. crassicarpa* showed the highest survival rate, 89%, with its biomass productivity 5-to-6 times greater than that of *S. roxburghi* and *P. macrocarpus*, which had lower survival rates of 74 and 76%, respectively. Above-ground biomass values from the current study, with the exception of the *A. crassicarpa* plot, were lower than reported by Nualngam (2002) who studied a 14-years-old plantation in northeastern Thailand. The above-ground biomasses of *P. macrocarpus*, *X. xylocarpa* and *Dalbergia cochinenesis* were 53.1, 88.3 and 84.2 ton $ha^{-1}$, respectively. In contrast, the above-ground biomass of *Acacia* spp. in the same plot ranged from 119.5 to 195.2 ton $ha^{-1}$, which were less than 272.71 ton $ha^{-1}$ for *A. crassicarpa* in the current study. The difference was due to the tree density of 2 m x 2 m spacing in the current study versus the spacing of 2 m x 3 m. In addition, the higher survival rate of 89 % in the current study compared to values of 69.5 and 52.6% reported by Nualngam (2002).

Total below-ground biomass to 50 cm soil depth ranged from 9.40 to 49.93 ton $ha^{-1}$, and the highest value was in the *A. indica* stand and the lowest value was in the *X. xylocarpa* stand. Fine- and coarse-root biomass ranged from 6.22 to 24.92 ton $ha^{-1}$, and ranged from 1.07 and 25.01 ton $ha^{-1}$, respectively. In contrast to the above-ground biomass, the total below-ground biomass of *A. crassicarpa* was only 18.54 ton $ha^{-1}$. Overall, the average fine root mass was greater than that of the coarse roots, irrespective of tree species. *S. roxburghii* had the smallest amount of coarse roots (1.07 ton $ha^{-1}$). The below-ground biomass from the current study showed a similar trend to that of other exotic tree species that had total below-ground biomass between 3.8 and 25.5 ton $ha^{-1}$ (Dutta and Madhoolika, 2003), and 26.54 ton $ha^{-1}$ reported by Singh (1994), who studied *Eucalyptus* spp. hybrid plantations. The differences in the below-ground biomass among tree species might probably be due to genetic variation and adaptation to each natural habitat. *A. crassicarpa*, which is naturally distributed in moist regions, has a lower value for below-ground biomass when compared to species that are naturally distributed in dry regions, such as *P. macrocarpus* and *X. xylocarpa*. The greater below-ground biomass of *A. indica* and *T. grandis* signifies their suitability for forest restoration on dry land due to their greater moisture and nutrient absorption capacity. *X. xylocarpa*, the native tree species expressed the lowest survival rate of 69%, nevertheless, the total biomass of this species was greater than the species with greater survival rate e.g. *P. macrocarpus* (76%) and *S. roxburghi* (74%).

The root-to-shoot ratio (R:S ratio) was lowest for *A. crassicarpa* (0.07) and *X. xylocarpa* (0.07), and was highest for *P. macrocarpus* (0.40). The low root-to-shoot ratios of *A. crassicarpa* could be explained the seriously situation that many trees in the study area have been damaged by wind snap and wind throw as a result of thunderstorms and strong winds. *A. crassicarpa* trees, which were taller and had a greater canopy surface area, were severely damaged. All native tree species, except *X. xylocarpa* had an R:S ratio between 0.32 and 0.40 which were higher than the value of 0.07 for the exotic tree species of *A. crassicarpa*. The R:S values of *T. grandis* found in the current study were greater than the range from 0.11 to 0.23, with a mean of 0.16 reported by Kraenzel (2003) in a 20-years-old teak plantation. However, that result was comparable to the report from Sheikh and Siddiqui. (2002). They reported that R:S ratio of 1-year-old *T. grandis* seedling was ranged between 0.1-0.4. In the same way, R:S ratio of *A. indica* from current studied showed the result (0.34) as in the same range of seedling stage of *A. indica* which were reported by Muthukuma *et al*. (2001) 0.15-0.34; and Puri and Swamy (2001) 0.25-0.48. Cairns *et al*. (1997) found the average R:S for tropical forests was 0.24. Only a few articles have reported on the below-ground biomass allocation of individual tree species. Nevertheless, there has been a reported progressive decrease in the values of the R:S ratio with increasing plantation age (Hase and Foelster, 1983; Kraenzel, 2003).

Although, the estimate of total belowground biomass through to 100 cm depth showed exceed data than observed belowground biomass (0-50 cm depth), R:S ratio derived between observed and estimated data seemed to be equal. The explanation was due to the increased of belowground biomass which estimated from 50-100 cm depth not affect neither total belowground biomass nor R:S ratio. The uprooting of many trees in the *A. crassicarpa* plot caused by wind throw made an interest point on the silvicultural method necessary to solve this problem. Intensive plantation management is necessary in *A. crassicarpa* plantations, involving suitable initial spacing and intermediate cutting for canopy structure improvement is required. An appropriate wider spacing, such as 4 m x 4 m or 2 m x 4 m, could favor tree diameter growth rate, which would allow trees to reach a satisfactory diameter size to resist the wind damage.

**Table 16** Average above-ground and below-ground biomass of each tree species (ton $ha^{-1}$).

| Species | Above-ground biomass | | | Below-ground biomass | | Total above-ground biomass | Total below-ground biomass (Obs.) | Total below-ground biomass (Est.) | Total biomass | R:S ratio (Obs.) | R:S ratio (Est.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Stem | Branch | Leaf | fine root | coarse root | | | | | | |
| *A. crassicarpa* | $231.53^{a}$ | $26.84^{a}$ | $14.34^{a}$ | $15.48^{b}$ | $3.06^{cde}$ | $272.71^{a}$ | $18.54^{cd}$ | 18.98 | $291.25^{a}$ | $0.07^{b}$ | 0.07 |
| *A. indica* | $128.81^{b}$ | $17.15^{b}$ | $5.81^{b}$ | $24.92^{a}$ | $25.01^{a}$ | $151.77^{b}$ | $49.93^{a}$ | 51.43 | $201.69^{b}$ | $0.33^{a}$ | 0.34 |
| *P. macrocarpus* | $27.76^{e}$ | $7.29^{de}$ | $1.33^{e}$ | $9.04^{c}$ | $5.62^{cd}$ | $36.38^{e}$ | $14.66^{cde}$ | 15.57 | $51.04^{d}$ | $0.40^{a}$ | 0.43 |
| *S. roxburghii* | $42.83^{de}$ | $10.60^{cde}$ | $3.63^{d}$ | $16.99^{b}$ | $1.07^{de}$ | $57.06^{de}$ | $18.06^{cd}$ | 18.06 | $75.12^{d}$ | $0.32^{a}$ | 0.32 |
| *T. grandis* | $76.83^{cd}$ | $10.77^{cd}$ | $5.25^{bc}$ | $16.78^{b}$ | $13.45^{b}$ | $92.85^{cd}$ | $30.23^{b}$ | 30.23 | $123.07^{c}$ | $0.33^{a}$ | 0.33 |
| *X. xylocarpa* | $93.5^{bc}$ | $15.28^{bc}$ | $5.44^{bc}$ | $6.22^{c}$ | $3.18^{cd}$ | $114.22^{bc}$ | $9.40^{de}$ | 12.37 | $123.62^{c}$ | $0.07^{b}$ | 0.11 |
| F-value | 46.07 | 67.97 | 48.60 | 21.80 | 104.58 | 48.96 | 48.04 | - | 40.95 | 17.65 | - |
| Significant | ** | ** | ** | ** | ** | ** | ** | - | ** | ** | - |

**Remark**: Obs. : Observed data from 0-50 cm soil depth, Est. : Estimated data from 0-100 cm soil depth.
ANOVA results; ns: treatment effect not significant; *: significant at $p<0.05$; **: significant at $p<0.01$.
The same letter in each column denotes groups that were not significantly different ($p>0.05$).

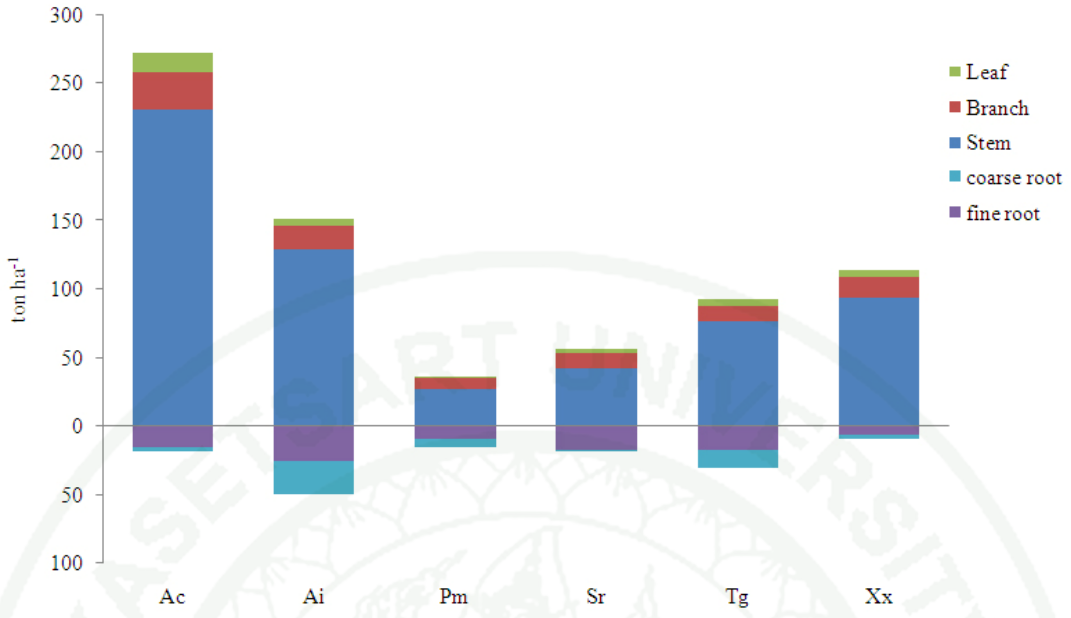



**Figure 18** Total biomass of 15-years-old forest plantation.

**6. Monthly litterfall**.

Litterfall collection was set in August 2007. For monthly litter collection, litter samples were sorted into 3 parts; leaf, branch and miscellaneous, after air dried. After that, each type of litter was weighted and calculated to dry weight. All results were showed in Table 17. *A. crassicarpa* showed the largest amount of litterfall in January 2008, 2.214 ton $ha^{-1}$ followed by 1.979 ton $ha^{-1}$ in December of the same year. Falling period occurred again in July 2008 with total litterfall of 1.979 ton $ha^{-1}$. In rainy season between August to October 2007, total litterfall was roughly estimated as 0.50 ton $ha^{-1}$. Litterfall of *A. crassicarpa* was dominated with leaf part that made up more than 90%. Miscellaneous and branch parts were the second and the third composed of *A. crassicarpa* litterfall. Annual litterfall of each part was 11.093, 0.808 and 0.538 ton $ha^{-1}$, respectively. Total yearly litterfall was 12.438 ton $ha^{-1}$. Litterfall of *A. indica* expressed the highest total litterfall in December 2007 with 1.025 ton $ha^{-1}$. Volume of litterfall, especially leaf part, was increased from August to December 2007. Total litterfall was increased from 0.350 to 1.025 ton $ha^{-1}$. From March to May 2008, litterfall of *A. indica* was dominated by miscellaneous part, which composed of fallen flower and seed. While, branch part of *A. indica* was fallen in the small amount though the year. Yearly litterfall of *A. indica* was composed of leaf, miscellaneous and branch with 1.951, 1.393 and 1.131 ton $ha^{-1}$, respectively. Total yearly litterfall was 4.475 ton $ha^{-1}$.

For native tree species, almost litterfall of *P. macrocarpus*, especially leaf part was fallen between December 2007 and January 2008. Only two months of falling period, leaf fall made up to 40% of total yearly litterfall. Miscellaneous part expressed the larger volume when compared to others from March to July 2008. There were the plant production organs e.g. flower and seed of *P. macrocarpus* that fall between this period. The annual litterfall was dominated by leaf, miscellaneous and branch part with 1.132, 1.062 and 0.768 ton $ha^{-1}$, respectively. Total litterfall of *P. macrocarpus* was 2.962 ton $ha^{-1}$. *S. roxburghii* leaf was fallen through a year, except in rainy season between August and November 2007. In January 2008, total litterfall was highest with the value of 0.436 ton $ha^{-1}$. Annual litterfall of *S. roxburghii* was dominated by leaf which was 1.193 ton $ha^{-1}$. In addition, branch and miscellaneous were 0.734 and 1.008 ton $ha^{-1}$, respectively. Total amount of yearly litterfall of *S. roxburghii* was 2.884 ton $ha^{-1}$.

*T. grandis* was the seasonal leaflet species. Leaf was the dominant compartment of *T. grandis* litterfall. Especially in dry season between November 2007 and January 2008, amount of leaf fall was ranged between 0.219 and 0.459 ton $ha^{-1}$. Short period of extremely litterfall occur in dry season followed by the rainy season that small amount of litter were fallen. Yearly litterfall of *T. grandis* was 2.424 ton $ha^{-1}$. *X. xylocarpa* also expressed the seasonal leaflet trend. Most leaf of trees was fallen in dry season from December 2007 to February 2008. Leaf litter of *X. xylocarpa* was extremely fallen in 2 month between December 2007 and January 2008 with 0.852 and 1.512 ton $ha^{-1}$, respectively. Annual amount of *X. xylocarpa*

litter fall was highest in leaf part followed by branch and miscellaneous, which were 3.110, 1.429 and 0.624 ton $ha^{-1}$, respectively. Total amount of litterfall was 5.163 ton $ha^{-1}$. Monthly details of litterfall and change trend related to seasonal change were shown in Figure 19.

**Table 17** Total amount of monthly litterfall of each tree species (ton $ha^{-1}$).

| month | *Acacia crassicarpa* | | | | *Azadirachta indica* | | | | *Pterocarpus macrocarpus* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | leaf | Branch | miscellaneous | **total** | Leaf | Branch | miscellaneous | **total** | Leaf | Branch | miscellaneous | **total** |
| Aug.07 | 0.635 | 0.130 | 0.051 | **0.815** | 0.153 | 0.143 | 0.054 | **0.350** | 0.027 | 0.089 | 0.086 | **0.202** |
| Sep.07 | 1.046 | 0.023 | 0.064 | **1.133** | 0.216 | 0.074 | 0.067 | **0.357** | 0.042 | 0.069 | 0.078 | **0.189** |
| Oct.07 | 0.378 | 0.005 | 0.071 | **0.454** | 0.239 | 0.062 | 0.039 | **0.341** | 0.019 | 0.021 | 0.076 | **0.116** |
| Nov.07 | 0.932 | 0.005 | 0.016 | **0.954** | 0.280 | 0.090 | 0.037 | **0.406** | 0.031 | 0.012 | 0.028 | **0.071** |
| Dec.07 | 1.839 | 0.040 | 0.101 | **1.979** | 0.730 | 0.216 | 0.079 | **1.025** | 0.477 | 0.089 | 0.041 | **0.607** |
| Jan.08 | 2.155 | 0.014 | 0.045 | **2.214** | 0.111 | 0.123 | 0.102 | **0.337** | 0.363 | 0.111 | 0.054 | **0.528** |
| Feb.08 | 0.452 | 0.017 | 0.031 | **0.500** | 0.026 | 0.035 | 0.072 | **0.132** | 0.071 | 0.048 | 0.064 | **0.183** |
| Mar.08 | 0.554 | 0.093 | 0.057 | **0.704** | 0.021 | 0.020 | 0.151 | **0.192** | 0.022 | 0.042 | 0.113 | **0.176** |
| Apr.08 | 0.324 | 0.032 | 0.114 | **0.470** | 0.035 | 0.083 | 0.330 | **0.449** | 0.016 | 0.055 | 0.182 | **0.253** |
| May 08 | 0.328 | 0.021 | 0.112 | **0.461** | 0.035 | 0.083 | 0.329 | **0.447** | 0.016 | 0.058 | 0.182 | **0.256** |
| Jun.08 | 0.614 | 0.102 | 0.059 | **0.775** | 0.056 | 0.064 | 0.081 | **0.202** | 0.012 | 0.073 | 0.041 | **0.126** |
| Jul.08 | 1.836 | 0.055 | 0.088 | **1.979** | 0.049 | 0.137 | 0.051 | **0.237** | 0.035 | 0.103 | 0.117 | **0.254** |
| total | 11.093 | 0.538 | 0.808 | **12.438** | 1.951 | 1.131 | 1.393 | **4.475** | 1.132 | 0.768 | 1.062 | **2.962** |

**Table 17** (Continued)

| month | *Shorea roxburghii* | | | | *Tectona grandis* | | | | *Xylia xylocarpa* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | leaf | Branch | miscellaneous | **total** | Leaf | Branch | miscellaneous | **total** | Leaf | Branch | miscellaneous | **total** |
| Aug.07 | 0.010 | 0.102 | 0.035 | **0.147** | 0.051 | 0.073 | 0.039 | **0.163** | 0.078 | 0.100 | 0.032 | **0.210** |
| Sep.07 | 0.029 | 0.036 | 0.066 | **0.132** | 0.177 | 0.022 | 0.059 | **0.257** | 0.086 | 0.063 | 0.046 | **0.195** |
| Oct.07 | 0.004 | 0.035 | 0.043 | **0.082** | 0.034 | 0.008 | 0.033 | **0.075** | 0.028 | 0.063 | 0.040 | **0.132** |
| Nov.07 | 0.024 | 0.035 | 0.025 | **0.084** | 0.219 | 0.007 | 0.038 | **0.265** | 0.019 | 0.002 | 0.018 | **0.040** |
| Dec.07 | 0.127 | 0.066 | 0.030 | **0.224** | 0.459 | 0.023 | 0.049 | **0.531** | 0.852 | 0.234 | 0.081 | **1.166** |
| Jan.08 | 0.335 | 0.016 | 0.085 | **0.436** | 0.349 | 0.083 | 0.080 | **0.512** | 1.512 | 0.366 | 0.072 | **1.950** |
| Feb.08 | 0.108 | 0.029 | 0.094 | **0.231** | 0.030 | 0.024 | 0.054 | **0.108** | 0.257 | 0.224 | 0.056 | **0.537** |
| Mar.08 | 0.165 | 0.028 | 0.123 | **0.316** | 0.006 | 0.008 | 0.045 | **0.059** | 0.079 | 0.055 | 0.046 | **0.179** |
| Apr.08 | 0.157 | 0.085 | 0.205 | **0.447** | 0.032 | 0.077 | 0.058 | **0.168** | 0.029 | 0.057 | 0.078 | **0.164** |
| May 08 | 0.158 | 0.067 | 0.170 | **0.394** | 0.032 | 0.044 | 0.036 | **0.112** | 0.028 | 0.057 | 0.078 | **0.163** |
| Jun.08 | 0.015 | 0.151 | 0.071 | **0.237** | 0.026 | 0.028 | 0.022 | **0.077** | 0.022 | 0.122 | 0.038 | **0.182** |
| Jul.08 | 0.061 | 0.084 | 0.061 | **0.153** | 0.076 | 0.011 | 0.013 | **0.101** | 0.119 | 0.085 | 0.040 | **0.244** |
| total | 1.193 | 0.734 | 1.008 | **2.884** | 1.469 | 0.424 | 0.970 | **2.428** | 3.110 | 1.429 | 0.624 | **5.163** |

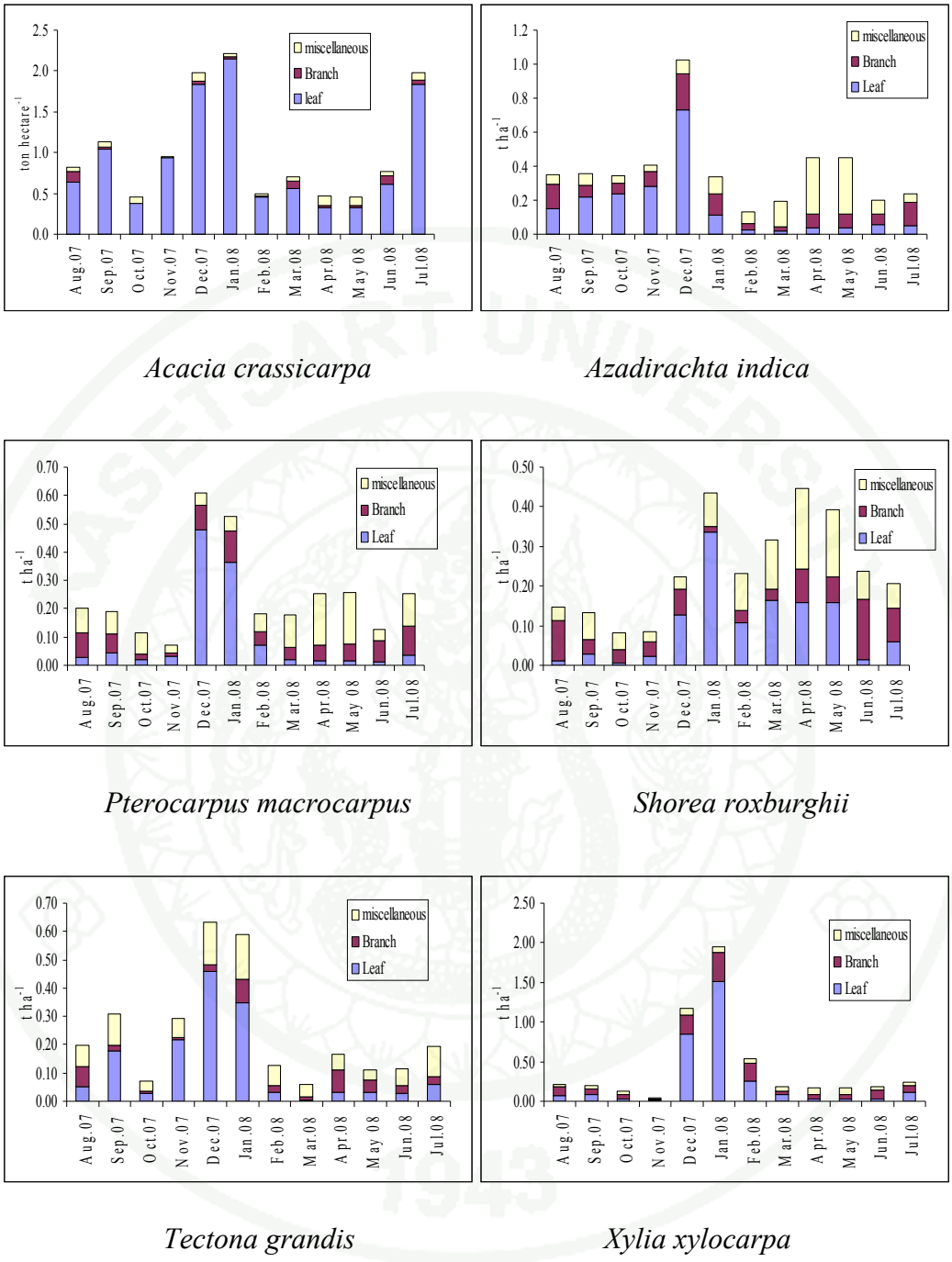



**Figure 19** Monthly litterfall of each tree species.

The total litterfall throughout the year showed a marked seasonal distribution (Figure 19-20). Total litterfall was lowest during the rainy season (August – October 2007 and February – June 2008) and highest during dry season (November 2007 – February 2008). It could suggest that the litterfall might be related to the water shortage in dry season. Highest amount of monthly litterfall of *A. indica*, *T.grandis* and *P. macrocarpus* were occurred in December 2007, in addition, *A. crassicarpa*, *S. roxburghii* and *X. xylocarpa* were occurred in January 2008. In rainy season, only a few amount of litterfall were found of all species. These results indicated that the dispersion pattern of litterfall were negative correlation with rainfall. Factors which affected the rate of litter fall in each forest were ages, species of plants (Thaiutsa *et al*., 1978), stand density, crown cover, silvicultural systems (Bray and Gorham, 1964), climatic condition such as annual rainfall, maximum temperature, dry season (Comforth, 1970), storm and water deficit in plants physiology (Heald, 1971), topography such as the differences of latitude and longitude, aspect, elevation and climatic region (Bray and Gorham, 1964), site fertility (Jorgensen *et al*., 1975). evapotranspiration (Meentemeyer *et al*., 1982). The amount and the duration of litterfall in the present study were significantly affected by the total amount of rainfall during the dry period and the peak of litterfall occurred in the dry season for most species. Many related publication were supported results from this present study e.g. Ghosh *et al*. (1982); Kikuzawa *et al*. (1984); Jordan (1988); Lonsdale (1988); Kimu and Deepu, (1992); Bernhard-Reversat and Loumeto (2002). The proportion of litterfall component was varied between tree species. Nevertheless, leaf part accounted for over 90 % of all species. Many publishes confirmed these results e.g. Parrotta (1999), Ruhende *et al.* (2004), Bo *et al*. (2006). Litter production of 15 year-old exotic and native tree species ranged from 2.86 to 5.16 ton $ha^{-1}$ $y^{-1}$. Differences in the litter production observed in this study could be attributed to differences in the species and canopy type of the tree. *A. indica and X. xylocarpa* were characterized by a large branch and dense spreading crown. While, *P. macrocarpus* and *S. roxburghii* were smaller trees with narrow and light spreading crown. Many results from this study showed the lower results of litterfall when compared to other i.e. 5-years-old of *A. crassicarpa* planted in dry land of Western Tanzania, the total litterfall was 4.86 ton $ha^{-1}$ $y^{-1}$ (Raphael *et al*., 2004) vs. 3.92 ton $ha^{-1}$ y $ear^{-1}$ ; *A. indica* raised on coal mine spoil in India, the total litterfall was 36.2 ton $ha^{-1}$ $year^{-1}$ (Singh *et al*., 1999) vs. 3.92 ton $ha^{-1}$ $ear^{-1}$ , 6 to 27 year-old of *T. grandis* planted in Western Thailand were ranged from 4.5 to 6.7 ton $ha^{-1}$ $year^{-1}$ (Sumantakul and Viriyabuncha, 2007) vs. 2.86 ton $ha^{-1}$ $year^{-1}$ of the present study.

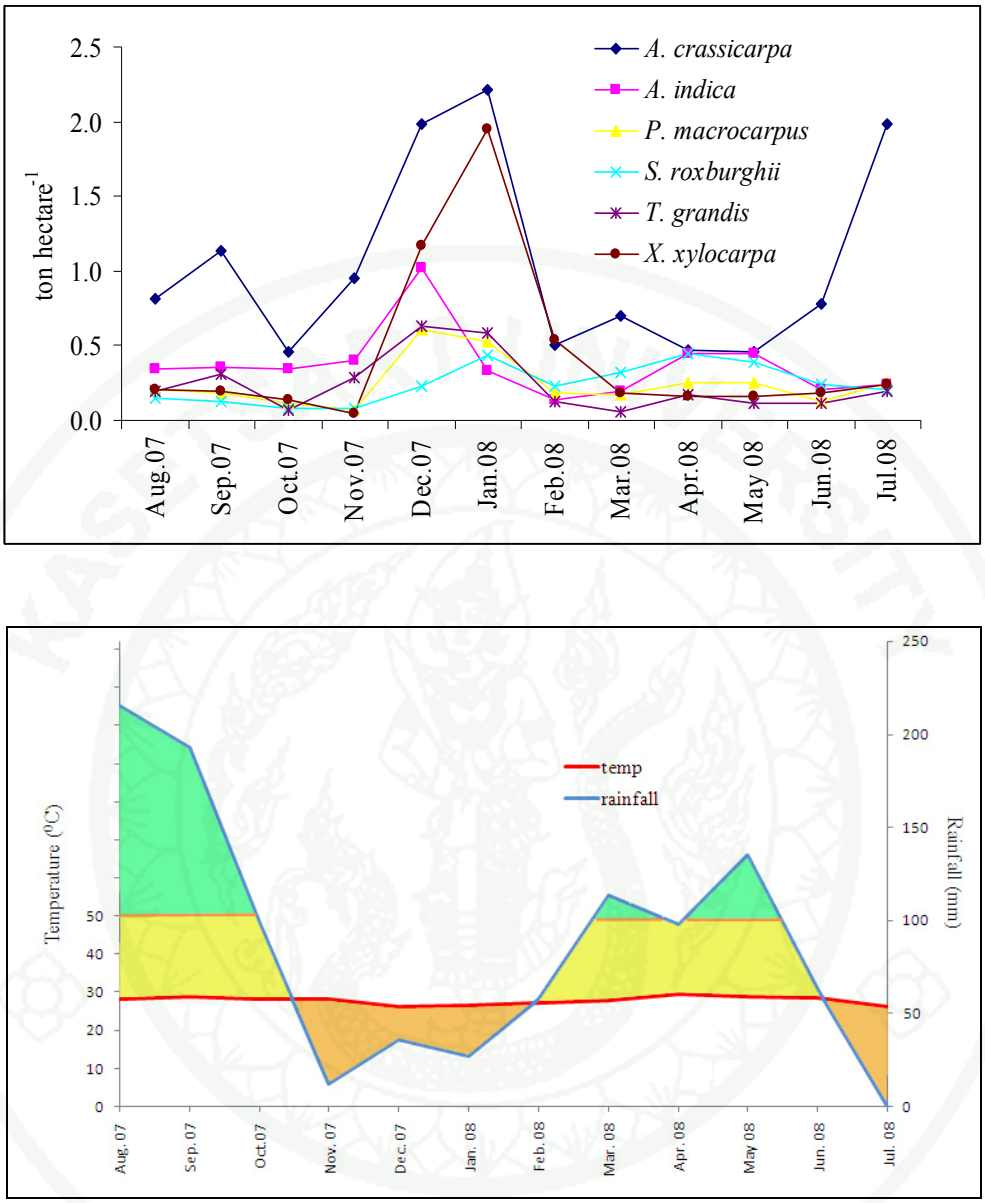



**Figure 20** Variation of total litterfall of each tree species with climatic condition.

**7. Leaf litter decomposition and constant of decomposition rate (k)**.

Litter decomposition was studied by following the changes in weight of the litter samples of each species. The results revealed that changes in dry weight of the litter samples over the study period were different (Table 18 and Figure 21). All species were shown the rapid decomposition in the first four months, weight loss of *A. crassicarpa, A. indica, S. roxburghii, T. grandis* and *X. xylocarpa* were 37.25, 63, 14.25, 39.48 and 18.00 g, respectively. Weight loss of *P. macrocarpus* was 49.12 g and found only in the first month. All species expressed a slow decomposition rate or stop decomposition process in the dry season between November 2007 and April 2008. Anyhow, it was clearly that litters of different species did not decompose at the same rate even under similar environment conditions. This was due to differences in the structure and composition of their leaf parts. The mass remaining was characterized by an initial faster rate of disappearance followed by a subsequent slower rate. High rate of decomposition recorded at the early stage and around July and August might be attributed to less moisture content in the soil, leading to high aeration, causing the aerobic organism to be active. Berg and Staaf (1980); McClaugherty and Berg (1987) revealed that in the initial stages (0-3 months) of leaf breakdown, small soluble carbon molecules i.e. starches and amino acids, were lost first leaving behind the more recalcitrant molecules i.e. lignin.

Decomposition during the first phase is rapid because these molecules are easy to break down and rich energy. The second stage of decomposition or the breakdown of lignin is much slower because lignin consists of very large and complex molecules. This rapid initial breakdown followed by a longer period of slow decomposition results in a mass loss curve that resembles an exponential decay curve. During the wet season, the rate of litter decomposition is increase due to increasing in microbial activity, the penetration of fine root and the increasing in the biological activity of macro arthropods, especially termite (Luizao and Sehubart, 1987). Frioretto *et al.* (1998) suggested that microbial activity could be limited by litter moisture content. This supported the hypothesis that climate set the general limits of the litter decomposition process through physiological constraints on the activity of organisms. The general conclusion was that physical climate determined rate of decay (Courteaux *et al*., 1995; Temel, 2003). The result showed a small percentage of original weight remaining; this might suggest that there was always litter remaining before new litter fall, a situation that favors erosion control in plantations. Slow decomposition rate recorded after the first raining period might indicate period of low humidity. Padley *et al*. (2007) advocated that mass loss of litterfall was significantly correlated with percent relative humidity. On the contrary, temperature, population of fungi and actinomycetes were weak negative correlations. However, decomposition still occurred in dry season from September 2007 to April 2008. High temperatures tended to increase microbial activity, which, in turn, led to increased decomposition. Moreover, decomposition of leaf litter showed a clear seasonal change and was high in rainy season while in dry season decomposition rate was rather low comparing with those in rainy. Slow rate of decomposition recorded between September 2007 and July 2008 was associated with period of low rainfall.

**Table 18** Remaining weight of litter (g).

| | *A. crassicarpa* | | *A. indica* | | *P. macrocarpus* | | *S. roxburghii* | | *T. grandis* | | *X. xylocarpa* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| month | weight | sd | weight | sd | weight | sd | weight | sd | weight | sd | weight | sd |
| Jul-07 | 100.00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00 |
| Aug-07 | 82.55 | 0.21 | 63.00 | 0.83 | 50.88 | 0.72 | 87.05 | 0.22 | 80.08 | 0.78 | 90.98 | 0.64 |
| Sep-07 | 82.03 | 0.71 | 49.85 | 0.36 | 41.13 | 1.42 | 83.13 | 0.47 | 61.08 | 1.49 | 88.90 | 0.35 |
| Oct-07 | 62.75 | 2.17 | 37.00 | 0.58 | 42.50 | 3.86 | 85.75 | 0.66 | 60.53 | 0.61 | 82.50 | 1.05 |
| Nov-07 | 63.75 | 1.24 | 35.10 | 0.41 | 41.45 | 2.22 | 83.03 | 0.64 | 52.33 | 1.32 | 78.83 | 0.46 |
| Dec-07 | 66.30 | 2.18 | 26.10 | 0.76 | 32.98 | 1.42 | 76.68 | 1.29 | 50.55 | 1.04 | 72.28 | 2.54 |
| Jan-08 | 60.43 | 1.93 | 25.75 | 0.74 | 33.90 | 1.58 | 67.78 | 3.02 | 44.45 | 1.24 | 75.05 | 0.72 |
| Feb-08 | 63.65 | 1.06 | 25.75 | 0.68 | 36.58 | 1.28 | 62.35 | 1.50 | 46.65 | 0.31 | 78.93 | 0.72 |
| Mar-08 | 62.15 | 2.15 | 29.60 | 0.69 | 27.70 | 2.05 | 47.95 | 1.52 | 38.28 | 0.63 | 74.63 | 0.80 |
| Apr-08 | 61.11 | 1.86 | 32.97 | 0.90 | 24.13 | 1.25 | 47.70 | 1.08 | 34.76 | 0.86 | 73.96 | 0.91 |
| May-08 | 48.30 | 1.38 | 31.70 | 1.02 | 23.88 | 1.60 | 41.63 | 1.08 | 22.78 | 1.44 | 69.33 | 0.83 |
| Jun-08 | 43.90 | 1.40 | 31.65 | 0.38 | 20.28 | 2.20 | 29.20 | 1.86 | 9.85 | 0.40 | 38.58 | 2.33 |
| Jul-08 | 35.10 | 1.34 | 18.75 | 0.48 | 18.87 | 1.93 | 17.75 | 0.62 | 6.25 | 0.40 | 30.50 | 1.83 |

Changes in weight of leaf litter samples over the study period were fitted by negative exponential function that proposed by Olson (1963). Data in Table 18 showed the decreasing trend of leaf litter in each sample plot. The results found that decomposition rate constant (k) of leaf litter were varied. The decomposition rates estimated of this study were summarized in Table 19 and Figure 21. Decomposition rate of *T. grandis* was highest with 2.025 month$^{-1}$, followed by *P. macrocarpus* (1.894 month$^{-1}$) and *S. roxburghii* (1.187 month$^{-1}$). While *A. indica* and *A. crassicarpa a* k constant were 1.797 and 0.908 month$^{-1}$, respectively. The slowest decomposing species was *X. xylocarpa* with 0.744 month$^{-1}$. All species expressed a slow decomposition rate or stop decomposition process in the dry season between November 2007 and April 2008.

**Table 19** Decomposition rate of leaf litter (k) in each species plot.

| Species | Decomposition rate (k) | Weight remaining (g) | |
|---|---|---|---|
| | | 6 month | 12 month |
| *A. crassicarpa* | 0.908 | 66.30 | 35.01 |
| *A. indica* | 1.797 | 26.10 | 18.75 |
| *P. macrocarpus* | 1.894 | 32.98 | 18.87 |
| *S. roxburghii* | 1.187 | 76.68 | 17.75 |
| *T. grandis* | 2.025 | 50.55 | 6.25 |
| *X. xylocarpa* | 0.744 | 72.28 | 30.50 |

All K constant of this studied shown the higher results value compared to many results i.e. in temperate forest, in Korea, k constant ranged from 0.33 to 0.82 month$^{-1}$ (Yang and Shim, 2003). Tateno *et al.* (2007) found that k constant of exotic black locust plantation and indigenous oak forest in China ranged from 0.15 to 0.48 month$^{-1}$. Bubb *et al.* (1998) found the k value of hoop pine (*Araucaria cunninghamii*) planted in Queensland; Australia was 1.7 month$^{-1}$. In radiate pine plantation forest, after 13 years, log-wood, log-bark and side branches lost 59, 55 and 24 % of their initial mass, respectively (Ganjegunte *et al*., 2004). Multipurpose tree species plantation in Central Himalaya, India, k constant ranged from 0.63 to 1.16 month$^{-1}$ (Semwal *et al*., 2003). However, all k results were distributed in the same range or a little bit lower than many studies in the tropical region such as, 2.01 and 3.09 month$^{-1}$ of k constants were found in 7 and 3 years-old forest plantation, and 2.28 month$^{-1}$ k constant in hill evergreen forest at Huay Kogma watershed research station in northern Thailand (Gawinchan *et al*., 2004). In West Africa, Attignon *et al*. (2004) found that, k value range from 1.3 month$^{-1}$ in *T. grandis* plantation to 4.7 month$^{-1}$ in *Afzelia africana* in natural forest. Deborah *et al*., (2000) found that k constant of agro-forestry system in Amazonian ranged from 0.4 to 2.1 month$^{-1}$. The k values of tropical tree plantation in Brazil ranged from 0.39 month$^{-1}$ (*Pinus caribaea*) to 1.13 month$^{-1}$ (Leguminosae) (Smith *et al*., 1998). In addition, 0.24 to 1.96 month$^{-1}$ k constants were found in fast growing tree plantation in Congo (France and Schwartz, 1997). The decomposition rate estimated of this study was higher than that of exotic tree plantations at Doi Ang Khang, Chiang Mai province, northern Thailand. Sang-on

(2007) found that the decomposition constants of 6 exotic tree species were ranged from 0.2744 to 1.2886 month$^{-1}$. *A. crassicarpa* was 0.908 month$^{-1}$ that close to the results of k constant derived from some *Acacia* species such as, in African forest-tree plantations; Bernhard-Reversat (1993) found that k constant of Eucalyptus spp. were ranged from 0.35 and 0.49 month$^{-1}$, k constant of *Acacia mangium* and *Acacia auriculiformis* were 0.69 month$^{-1}$. *T. grandis* resulted (2.025 month$^{-1}$) was equal to the report from Egunjobi (1974) found that k constant of *Tectona grandis* was 2.02 month$^{-1}$. Egunjobi *et al*. (1979) found that k constants of *Pinus caribea* was 0.34 month$^{-1}$. Decomposition constant of *Pinus caribaea* were ranged from 0.29 to 0.33 (Kadeba *et al*., 1998). Harmand (1997) had studied decomposition rate of *Acacia polycantha* and *Eucalyptus camaldulensis* that were 0.92 and 0.39 month$^{-1}$, respectively. Kumer and Deepu (1992) were studied in moist deciduous forest, Western Ghats, India. They found that decomposition constant of *Tectona* sp. and *Xylia* sp. were 0.32 and 0.35 month$^{-1}$, respectively. Ladpala and Phanuthai revealed that constant of *X. xylocarpa* in natural mixed deciduous forest was 1.83 month$^{-1}$. Kumer and Deepu reported that monthly k constant of *X. xylocarpa* was range between 0.31 and 0.39, with 0.32 in mean. They also categorized *X. xylocarpa* into fast decomposition species. There were slightly lower when compared to *T. grandis* and *X. xylocarpa* from this present study (2.025 and 0.744 month$^{-1}$, respectively). Yamasita and Takeda reported that k constant of *Shorea lepurosula* mixed with *Heritiera javanica* was 0.063 month$^{-1}$. That was slightly lower result than *S. roxburghii* k constant of this present study (0.187 month$^{-1}$).

At a regional scale with similar climatic condition, litter decomposition rates were primarily controlled by the substrate quality of litter (Berg, 2000). The enhance litter decomposition rates in rainy season of all species showed a combined effect of rainfall and relative humidity. Changes in temperature and moisture availability had been related to decomposition rates (Agbim, 1987). Differences of temperature and moisture supply interactions and higher activity of the decomposers or organisms could explain the large variation in litter decomposition rate altered the external environmental factors. In dry season, deceased rainfall and relative humidity were responsible for a slow rate of litter decomposition. Pandey *et al*. (2007) suggested that relative humidity, maximum temperature, population of fungi and actinomycetes were the best predictor variables for litter mass loss rate. Numerous studies in tropical tree plantations showed a large accumulation of litter standing crop, especially when the planted species was exotic (Kadeba and Aduayi, 1985; Lugo, 1992; Bernhard-Reversat, 1993; Singh *et al*., 1993; Bernhard-Reversat and Loumeto, 2002). They were suggested that local decomposers were poorly adapted to the biochemical composition of the litter. When the planted species were not exotic, as *S. roxburghii* or *T. grandis* in the present study or Mahogany in the study by Lugo (1992), the litter standing crop was comparable to that of the natural forest. The occurrences of the adapted soil biota, and the higher nutrient content of native species compared to *Acacia* spp., might be involved.

Furthermore, the quality of the leaves is another important factor. Substrate quality has been defined in many different ways i.e. the nitrogen concentration as the lignin content, the C:N ration (Kumer and Deepu, 1992; Moorhead *et al*. 1999). Taylor and Jones (1990) reported that decomposition of leaf litter could be predicted by the C:N ratio. More over, lignin content or lignin: nitrogen ratio could be used for predict the composition rate (Meentemeyer, 1978; Melillo *et al*., 1982). Semwall *et al*. (2003) initiated that the species with the three-phase decomposition pattern (initial slow phase, intermediate first phase and terminal slow phase of decomposition) incubated before rainy season and species with two-phase pattern (initial fast followed by a slow phase) incubated in the beginning of rainy season. Litter decomposition, all k constants of this study showed lower value than those of temperate forest (Yang and Shim, 2003; Tateno *et al*., 2007; Bubb *et al*., 1998; Ganjegunte *et al*., 2004 and Semwal *et al*., 2003). In the other hand, k constant in the tropical region was distributed in ranged of results reported by many researchers (Attignon *et al*., 2004; Deborah *et al*., 2000; Smith *et al*., 1998 and France and Schwartz, 1997). Olson k constant ranged from slightly more than 1 to slightly more than 4 in any given stand (Thaiutsa and Granger, 1979). Bernhard and Loumeto (2002) suggested that the ranges of k were very wide from 0.2 $month^{-1}$ in eucalypt plantations to 5 $month^{-1}$ in rubber plantation. Therefore, the k values found here were comparable in this range. All results indicated that almost of leaf litter of all species nearly extinct in 1 year period. Furthermore, in tropical forest plantation, there were very little or no accumulation of litter, implying a fast turnover of organic matter in the soil.

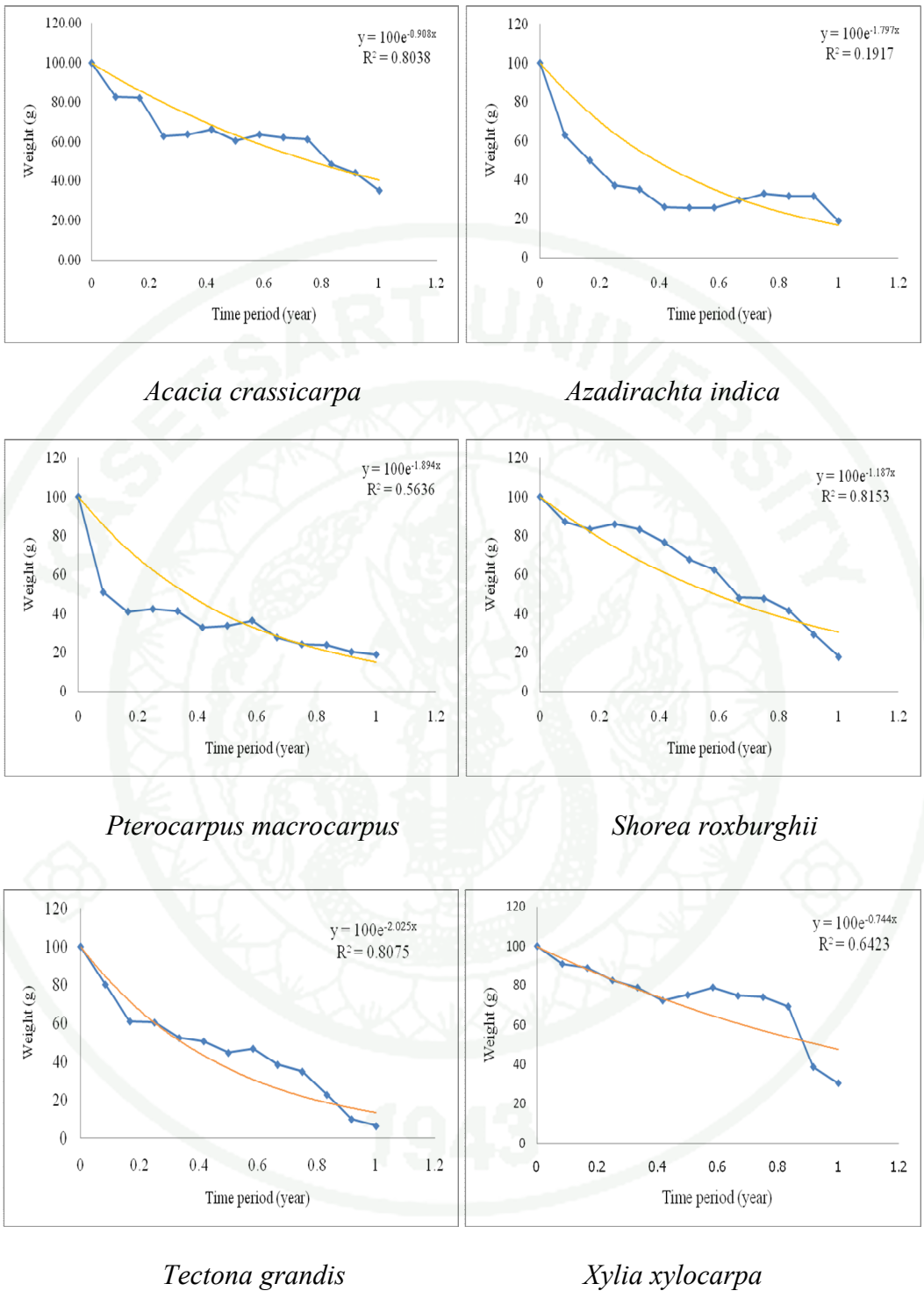



**Figure 21** Relationships of remaining weights of litter and time period between August 2007 and June 2008.

**8. Nutrient concentration in soils.**

Nutrient concentrations of litter on soil surface were shown in Table 20. *T. grandis* represented 0.46 % of N concentration of litter on soil. This result was lower than other species which ranged between 0.72 and 0.84 %. P concentration was resemble results, and ranged between 0.11 and 0.15 %. *P. macrocarpus* expressed the highest of K concentration which the result of 0.34%. On the other hand, *S. roxburghii*, *A. crassicarpa* and *T. grandis* were ranged between 0.11 and 0.15%. Ca concentration was comparatively higher than other elements. The results of Ca concentration were ranged between 0.41 and 1.15 % of *A. crassicarpa* and *A. indica*, respectively. *S. roxburghii* showed the highest result of Mg concentration (0.29%), which was comparable 2 times higher than 0.14%, the lowest result from *A. crassicarpa*. Na concentration expressed the lowest result when compared to other elements, and ranged between 0.01 and 0.03%.

After root sampling by excavation method, soil sampling was conducted in each soil pit. Soil samples were taken from 5 depth intervals, 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm. In each horizon, disturbed and undisturbed soil sample were collected for 1 kg each. Undisturbed sample was conducted by using 100 cc soil samples. Soil samples were collected for analysis of physical and chemical properties. The physical and chemical properties of soil in each species plot were shown in Table 21 and Figure 22. Soil nutrient concentration beneath *A. crassicarpa* plot was slightly different via soil depth. Highly significant differences were found with N and P. In addition, significant difference was found with Na. On the contrary, no significant differences were found with other elements. N concentration was highest in the top soil layer from 0-10 cm with 0.11 %. Slightly decreased of N concentration was found with increasing soil depth and ranged from 0.07 to 0.08%. P was greatest in the top soil layer with 11.00 mg $kg^{-1}$. Uncertainly decreasing trend of P concentration was found accordance with soil depth. The results showed between 2.68 and 9.27 mg $kg^{-1}$. No significant difference was found with soil K concentration. The data ranged from 0.26 to 0.32 cmol $kg^{-1}$. Resemble highest results were found in 0-10 and 40-50 cm depths. Ca concentration was no significant difference result. The data showed similarly results of all depth and ranged from 0.79 to 1.08 cmol $kg^{-1}$. Mg concentration of *A. crassicarpa* plot was increased with increasing soil depth. Anyhow, no significant difference was found. The data in Table 21 were ranged from 0.19 to 0.29 cmol $kg^{-1}$. Na concentration was significant difference. The data were slightly differences and varied from 0.10 to 0.15 cmol $kg^{-1}$.

Soil nutrient concentrations beneath *A. indica* plot were different according to elements and depth. Highly significant differences were found with N and P. In addition, significant differences were found with Mg and Na. Anyhow, no significant differences were found with K and Ca. N concentration of soil in *A. indica* plot was ranged from 0.05 to 0.09 %. P concentration of 0-10 and 10-20 cm depths were grouped (8.00 and 9.22 mg $kg^{-1}$). On the contrary, there were no significant

differences of the data at 20-50 cm depth which ranged from 1.29 to 1.43 mg $kg^{-1}$. For K and Ca, no significant differences were found. Nevertheless, the highest results was found in the top soil layer, and decreased through soil depth. Soil Mg concentration was highest in the top soil (0.21 cmol $kg^{-1}$), and decreased through soil depth (0.16 – 0.20 cmol $kg^{-1}$). On the contrary to other elements, soil Na concentration was lowest in the top soil layer at 0-10 cm depth (0.08 cmol $kg^{-1}$). While, the highest result was occurred in the second layer at 10-20 cm depth with 0.15 cmol $kg^{-1}$, and decreased through soil depth (0.09-0.13 cmol $kg^{-1}$). Soil N and P concentration of *P. macrocarpus* plots were highly significant differences. The results revealed that the highest results occurred in 0-10 and 10-20 cm depth of both elements. N concentration was ranged from 0.05 to 0.09 %, while P was ranged 1.29 to 8.00 mg $kg^{-1}$. On the contrary, K, Ca, Mg and Na concentration showed no significant differences results. K was ranged from 0.23 to 0.45 cmol $kg^{-1}$. Ca was ranged from 0.16 to 0.44 cmol $kg^{-1}$. Mg was ranged from 0.13 to 0.21 cmol $kg^{-1}$. In addition, Na was ranged from 0.09 to 0.15 cmol $kg^{-1}$.

Soil nutrient of *S. roxburghii* plot showed no significant differences, except P. Most elements showed the highest results in the top soil layer (0-10 cm), and were decreasing through soil depth. N concentration was ranged from 0.04 to 0.10 %. P was highest in surface soil (10.74 mg $kg^{-1}$) and decreased through soil depth in the same time (1.35-5.88 mg $kg^{-1}$). K concentration was ranged from 0.23 to 0.32 cmol $kg^{-1}$. Ca, Mg and Na expressed the highest in the third layer (20-30 cm depth). Ca was ranged from 0.44 to 0.77 cmol $kg^{-1}$. While, Mg was ranged from 0.14 to 0.18 cmol $kg^{-1}$. In addition, Na concentration was ranged from 0.09 to 0.18 cmol $kg^{-1}$. Soil N concentration of *T. grandis* was highly significant difference through depth. The data expressed the highest results at 0-10 and 10-20 cm depth with 0.09 %. While, N concentration was decreasing through soil depth. P concentration was significant difference. The upper layers showed the highest results of P concentration with 8.60 and 8.03 mg $kg^{-1}$. The other deeper layers were ranged from 1.34 to 1.70 mg $kg^{-1}$. For other element, no significant differences were found. Data from Table 21 showed that, K concentration was ranged from 0.22 to 0.28 cmol $kg^{-1}$. Soil Ca concentration was ranged from 0.32 to 0.53 mg $kg^{-1}$. Mg concentration was ranged from 0.58 to 0.77. Na concentration was ranged from 0.12 and 0.16 cmol $kg^{-1}$. In *X. xylocarpa* plot, only N and P that expressed the significant difference results. As same as other plots, N showed the highest results in the top layer with 0.09 %. While, N concentrations from other layers were ranged from 0.05 to 0.08 %, which decreased through soil depth. P concentration was ranged from 1.17 to 7.16 mg $kg^{-1}$. For other elements, no significant differences were found. The data from Table 21 showed that, K concentration was ranged from 0.17 to 0.22 cmol $kg^{-1}$. Soil Ca concentration was ranged from 0.20 to 0.32 cmol $kg^{-1}$. Mg concentration was ranged from 0.07 to 0.19 cmol $kg^{-1}$. Na concentration was ranged from 0.05 to 0.12 cmol $kg^{-1}$. Control plot showed the similar results of nutrient concentration of other plots. The results revealed that the highest results still occurred in the two upper layers of most elements.

N was the only one element which showed the significant difference results. The data was ranged from 0.05 to 0.08 %. The other elements showed no significant differences between different soil depths. P concentration was ranged from 2.47 to 7.85 mg $kg^{-1}$. K concentration was ranged from 0.59 to 0.93 cmol $kg^{-1}$. Soil Ca concentration was ranged from 0.87 to 1.41 cmol $kg^{-1}$. Mg concentration was ranged from 0.14 to 0.20 cmol $kg^{-1}$. Na concentration was ranged from 0.09 to 0.128 cmol $kg^{-1}$. Despite differences of biomass and litter productivity, there were very few differences in soil nutrient concentration (to 50 cm depth) among species plots. N concentration slightly decreased with increasing soil depth. In the top soil layer, N concentration was greatest in *S. roxburghii* plot (0.10 %) and was higher than control plot (0.080 %). Data of available elements (P, K, Ca, Mg and Na) indicated few different in soil of plantation and control plots. Several apparent differences in soil properties, especially for the top most layer (0 to 20 cm) were probably due to pre-plantation site variability. One very obvious difference between plantation and control plot was the higher results of exchangeable K and Ca in the abandon crop field (control plot) and plantation. That was probably due to translocation and was absorbed by plant tissues that K and Ca showed highly concentration comparing to other elements. This result advocated with the report of Nualngam (2002). He reported that in abandoned fields replaced with *Imperata cylindrical*, soil exchangeable K and Ca were distinctly higher than those soils from plantation plot. He also concluded that it was probably due to low rate of nutrients uptake from plants with lower results of biomass ( 3.88 ton $ha^{-1}$) comparing to other plantations (53.11 -195.22 ton $ha^{-1}$).

The results in this present study revealed that, most tree species had the highest concentration of N followed by Ca, K, Mg, P and Na, respectively. Glumphabutr (2004) reported the highest soil nutrient concentration in evergreen forest was Ca>N>Mg>K>P, and it was similar to the report of Punsatha (2002) that studied in *A. indica* plantation. Concentration of nutrients declines according to soil depth, which was similar trend to Glumphabutr (2004), Suksawang (1998) and Jutikidecha (1996). Soil properties were distinctly different according to soil depth. Especially N and P, the results from all plots (except *S. roxburghii*) showed that at 0 to 20 cm depth, these elements were significantly different from the deeper soil layers. Morisada *et al*. (2005) advocated that available nutrient especially P and K seemed to be added in the top soil layer at 0-20 cm depth. For other elements, either no significant or only weak significant different were found between difference soil depths. That might be due to the highly return of N and P from leaf litter, consistently with the report from Watt *et al*. (2005). Murray *et al*. (2007) determined impacts of forest plantation on soil nutrients and revealed that significant positive relationships between foliar nutrients and 0-10 cm layer properties were evident for N and P. Relative to control treatment, N and P concentration in plantation plot seemed to be exceeding result. Furthermore, slightly different results were found with Ca, Mg and Na between plantation and control plots.

**Table 20** Nutrient concentration of litter on soil surface.

| Spp | Litter ($kg\ ha^{-1}$) | Nutrient concentration (% by dry weight) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | sd | P | sd | K | sd | Ca | sd | Mg | sd | Na | sd |
| Ac | 3,483.23 | 0.72 | 0.071 | 0.12 | 0.016 | 0.14 | 0.040 | 0.41 | 0.336 | 0.14 | 0.020 | 0.02 | 0.008 |
| Ai | 670.56 | 0.84 | 0.222 | 0.12 | 0.044 | 0.27 | 0.141 | 1.15 | 0.399 | 0.26 | 0.123 | 0.02 | 0.012 |
| Pm | 355.21 | 0.80 | 0.294 | 0.15 | 0.066 | 0.34 | 0.177 | 0.72 | 0.485 | 0.20 | 0.102 | 0.01 | 0.006 |
| Sr | 403.27 | 0.81 | 0.047 | 0.13 | 0.027 | 0.11 | 0.094 | 0.76 | 0.175 | 0.29 | 0.026 | 0.03 | 0.011 |
| Tg | 72.94 | 0.46 | 0.036 | 0.13 | 0.037 | 0.15 | 0.060 | 1.10 | 0.506 | 0.23 | 0.049 | 0.02 | 0.003 |
| Xx | 1,032.01 | 0.74 | 0.118 | 0.11 | 0.014 | 0.25 | 0.056 | 0.69 | 0.038 | 0.19 | 0.021 | 0.03 | 0.006 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

**Table 21** Nutrient concentration of soils from each species plot.

| Spp. | depth (cm) | N | | Avail. P | | Exch. K | | Exch. Ca | | Exch. Mg | | Exch. Na | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | sd | mg $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd |
| Ac | 0-10 | $0.11^{a}$ | 0.02 | $11.00^{a}$ | 3.21 | 0.31 | 0.06 | 0.79 | 0.43 | 0.21 | 0.08 | $0.13^{abc}$ | 0.02 |
| | 10-20 | $0.09^{b}$ | 0.01 | $6.47^{b}$ | 0.11 | 0.26 | 0.07 | 0.79 | 0.52 | 0.19 | 0.08 | $0.15^{a}$ | 0.01 |
| | 20-30 | $0.07^{b}$ | 0.01 | $9.27^{ab}$ | 1.72 | 0.23 | 0.03 | 1.08 | 0.18 | 0.24 | 0.04 | $0.11^{bc}$ | 0.02 |
| | 30-40 | $0.08^{b}$ | 0.01 | $2.68^{c}$ | 2.02 | 0.26 | 0.06 | 0.94 | 0.45 | 0.24 | 0.06 | $0.14^{ab}$ | 0.01 |
| | 40-50 | $0.08^{b}$ | 0.00 | $6.11^{bc}$ | 1.09 | 0.32 | 0.08 | 0.97 | 0.24 | 0.29 | 0.06 | $0.10^{c}$ | 0.02 |
| | significant | ** | | ** | | ns | | ns | | ns | | * | |
| Ai | 0-10 | $0.09^{a}$ | 0.01 | $8.00^{a}$ | 2.29 | 0.38 | 0.03 | 0.72 | 0.26 | $0.21^{a}$ | 0.03 | $0.08^{c}$ | 0.00 |
| | 10-20 | $0.08^{ab}$ | 0.01 | $9.22^{a}$ | 4.74 | 0.34 | 0.06 | 0.58 | 0.19 | $0.19^{ab}$ | 0.02 | $0.15^{a}$ | 0.02 |
| | 20-30 | $0.06^{c}$ | 0.01 | $1.43^{b}$ | 0.49 | 0.35 | 0.13 | 0.51 | 0.23 | $0.20^{a}$ | 0.01 | $0.13^{ab}$ | 0.01 |
| | 30-40 | $0.06^{bc}$ | 0.00 | $1.31^{b}$ | 0.08 | 0.29 | 0.14 | 0.39 | 0.18 | $0.16^{b}$ | 0.02 | $0.10^{bc}$ | 0.01 |
| | 40-50 | $0.05^{c}$ | 0.01 | $1.29^{b}$ | 0.16 | 0.31 | 0.17 | 0.33 | 0.16 | $0.16^{b}$ | 0.03 | $0.09^{bc}$ | 0.04 |
| | significant | ** | | ** | | ns | | ns | | * | | * | |
| Pm | 0-10 | $0.09^{a}$ | 0.02 | $10.74^{a}$ | 1.65 | 0.32 | 0.04 | 0.44 | 0.31 | 0.14 | 0.07 | 0.13 | 0.03 |
| | 10-20 | $0.08^{a}$ | 0.01 | $6.71^{b}$ | 1.98 | 0.27 | 0.07 | 0.31 | 0.15 | 0.14 | 0.04 | 0.12 | 0.04 |
| | 20-30 | $0.05^{b}$ | 0.00 | $1.37^{c}$ | 0.33 | 0.31 | 0.12 | 0.26 | 0.17 | 0.17 | 0.08 | 0.15 | 0.03 |
| | 30-40 | $0.06^{b}$ | 0.00 | $1.44^{c}$ | 0.45 | 0.23 | 0.11 | 0.16 | 0.08 | 0.13 | 0.08 | 0.09 | 0.02 |
| | 40-50 | $0.06^{b}$ | 0.00 | $3.24^{c}$ | 1.92 | 0.45 | 0.36 | 0.23 | 0.10 | 0.21 | 0.11 | 0.14 | 0.05 |
| | significant | ** | | ** | | ns | | ns | | ns | | ns | |

**Table 21** (Continued)

| Spp. | depth (cm) | N | | Avail. P | | Exch. K | | Exch. Ca | | Exch. Mg | | Exch. Na | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | sd | mg $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd |
| Sr | 0-10 | 0.10 | 0.01 | 11.93 [a] | 0.53 | 0.32 | 0.03 | 0.47 | 0.47 | 0.18 | 0.04 | 0.11 | 0.03 |
| | 10-20 | 0.09 | 0.02 | 5.88 [b] | 1.34 | 0.25 | 0.02 | 0.61 | 0.09 | 0.14 | 0.01 | 0.12 | 0.01 |
| | 20-30 | 0.06 | 0.01 | 1.35 [c] | 0.47 | 0.27 | 0.02 | 0.77 | 0.38 | 0.17 | 0.07 | 0.18 | 0.09 |
| | 30-40 | 0.06 | 0.00 | 1.51 [c] | 0.48 | 0.29 | 0.06 | 0.64 | 0.36 | 0.14 | 0.04 | 0.13 | 0.06 |
| | 40-50 | 0.04 | 0.00 | 1.36 [c] | 0.45 | 0.23 | 0.03 | 0.44 | 0.22 | 0.15 | 0.05 | 0.09 | 0.02 |
| | significant | ns | | * | | ns | | ns | | ns | | ns | |
| Tg | 0-10 | 0.09 [a] | 0.00 | 8.60 [a] | 3.20 | 0.28 | 0.07 | 0.40 | 0.04 | 0.14 | 0.04 | 0.15 | 0.11 |
| | 10-20 | 0.09 [a] | 0.01 | 8.03 [a] | 5.04 | 0.26 | 0.04 | 0.53 | 0.36 | 0.16 | 0.02 | 0.16 | 0.07 |
| | 20-30 | 0.06 [b] | 0.01 | 1.63 [b] | 1.10 | 0.24 | 0.07 | 0.50 | 0.42 | 0.15 | 0.04 | 0.11 | 0.03 |
| | 30-40 | 0.07 [b] | 0.01 | 1.34 [b] | 0.59 | 0.24 | 0.06 | 0.41 | 0.27 | 0.12 | 0.04 | 0.13 | 0.04 |
| | 40-50 | 0.05 [c] | 0.00 | 1.70 [b] | 0.73 | 0.22 | 0.02 | 0.32 | 0.14 | 0.16 | 0.07 | 0.11 | 0.08 |
| | significant | ** | | * | | ns | | ns | | ns | | ns | |
| Xx | 0-10 | 0.09 [a] | 0.00 | 7.16 [a] | 1.11 | 0.18 | 0.01 | 0.20 | 0.03 | 0.07 | 0.01 | 0.05 | 0.01 |
| | 10-20 | 0.08 [b] | 0.01 | 6.44 [a] | 1.65 | 0.22 | 0.04 | 0.33 | 0.07 | 0.15 | 0.02 | 0.08 | 0.01 |
| | 20-30 | 0.05 [b] | 0.01 | 1.80 [b] | 0.71 | 0.19 | 0.05 | 0.32 | 0.12 | 0.16 | 0.02 | 0.09 | 0.03 |
| | 30-40 | 0.07 [b] | 0.00 | 2.16 [b] | 0.50 | 0.17 | 0.03 | 0.32 | 0.07 | 0.16 | 0.02 | 0.09 | 0.01 |
| | 40-50 | 0.05 [b] | 0.01 | 1.17 [b] | 0.11 | 0.17 | 0.04 | 0.29 | 0.13 | 0.19 | 0.09 | 0.12 | 0.05 |
| | significant | * | | ** | | ns | | ns | | ns | | ns | |

**Table 21** (Continued)

| Spp. | depth (cm) | N | | Avail. P | | Exch. K | | Exch. Ca | | Exch. Mg | | Exch. Na | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % | sd | mg $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd | cmol $kg^{-1}$ | sd |
| Cf | 0-10 | 0.08 [a] | 0.00 | 7.85 | 1.51 | 0.65 | 0.28 | 0.87 | 0.06 | 0.15 | 0.06 | 0.09 | 0.04 |
| | 10-20 | 0.08 [a] | 0.01 | 7.78 | 3.52 | 0.77 | 0.18 | 1.33 | 0.65 | 0.15 | 0.01 | 0.09 | 0.03 |
| | 20-30 | 0.06 [b] | 0.00 | 6.54 | 4.25 | 0.93 | 0.20 | 1.41 | 0.42 | 0.20 | 0.06 | 0.12 | 0.04 |
| | 30-40 | 0.07 [b] | 0.00 | 2.47 | 2.32 | 0.59 | 0.34 | 1.14 | 0.46 | 0.14 | 0.03 | 0.09 | 0.04 |
| | 40-50 | 0.05 [b] | 0.01 | 2.82 | 1.60 | 0.64 | 0.23 | 1.07 | 0.11 | 0.16 | 0.02 | 0.09 | 0.01 |
| | significant | ** | | ns | | ns | | ns | | ns | | ns | |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis*; Xx: *X. xylocarpa* and Cf: Abandoned crop field (control plot)

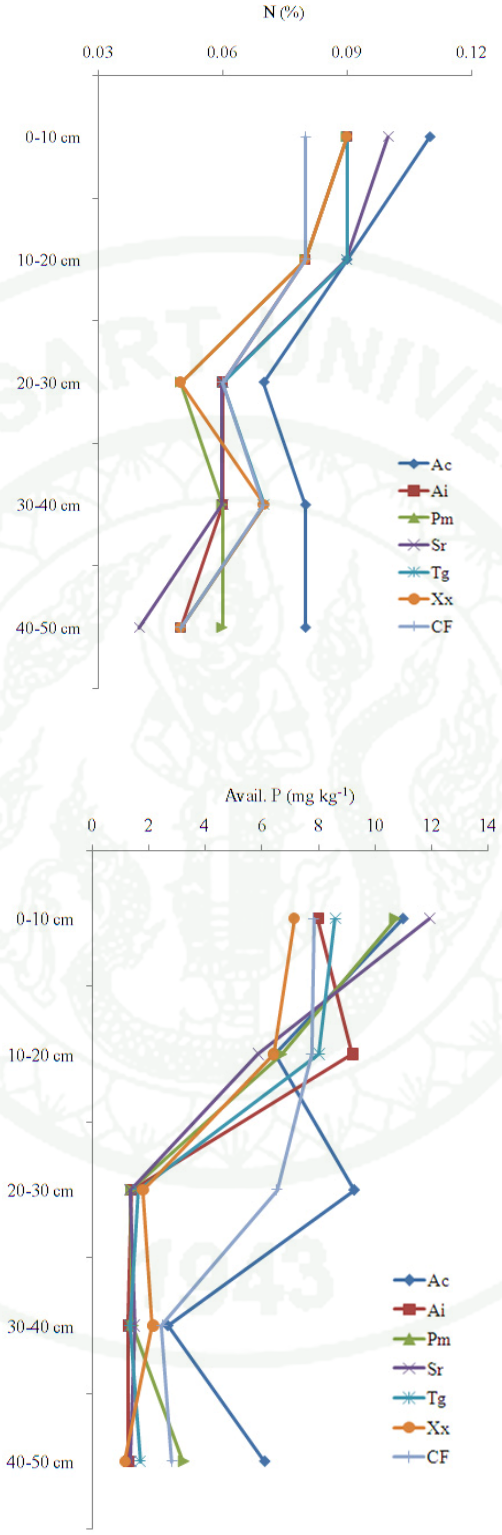



**Figure 22** Nutrient concentration of soils from each species plot.

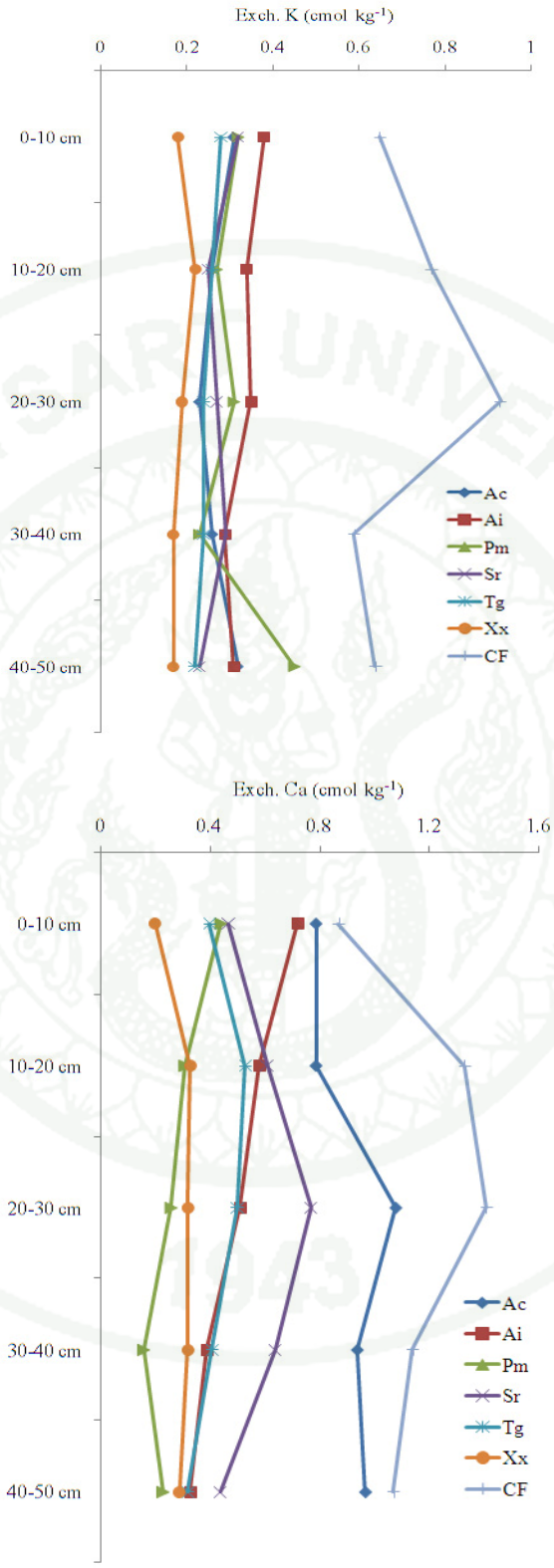



**Figure 22** (Continued)

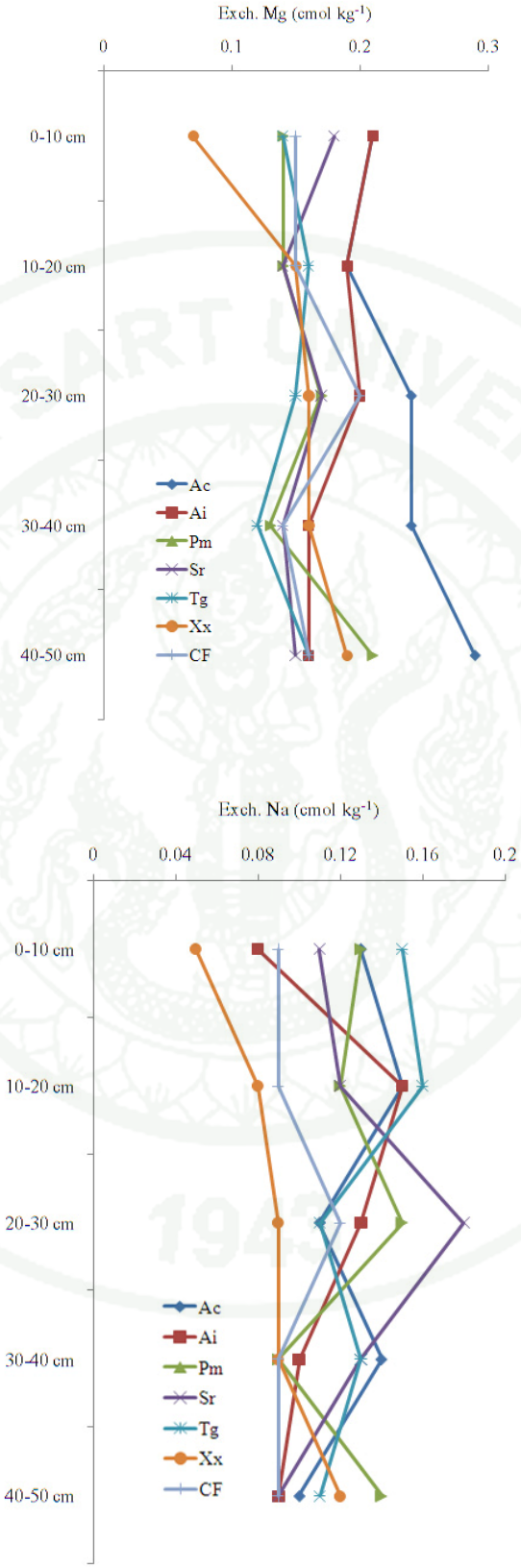



**Figure 22** (Continued)

**9. Plant nutrient concentrations**

Plant nutrient concentrations of each tree species were studied in 2 different categories as living tree part e.g. leaf, branch, stem, fine- and coarse root part. Another was the study in senescence tree part e.g. falling litter. All results were as follows;

9.1 Living tree part nutrient concentration;

Tree species differed greatly in the relative amount of nutrients absorbed from soil. Consequently, the chemical composition of trees fraction (leaf, branch, stem and root) of various species was different even when the trees were growing in the same habitat (Thaiutsa *et al*., 1978). Parrotta (1999) advocated that differences in biomass production and nutrient return, that was due to differ in soil properties. In the present study, nutrients concentration in each part of tree was obtained from 5 trees of each species which cover all sized classes. Tree samples divided into leaf, branch, stem, fine and coarse root. All samples were oven dried and were ground with 20 mesh sieve. Ground materials were analyzed for N, P, K, Ca, Mg and Na in the laboratory. Nutrient concentrations varied greatly among tree component for each of the planted tree species.

N concentration of *A. crassicarpa* was varied on consequently leaf>fine root>branch>coarse root>stem with value of 2.09, 1.49, 0.98, 0.61 and 0.24%, respectively. While no significant differences were found with concentration that ranged from 0.09 % of stem part to 0.15 % of leaf part. K concentration was highest in leaf part (1.06%). Branch and fine root were classified as the same group (0.59 % and 0.54 %, respectively). Stem and coarse root were also classified as the same group as well (0.22 % and 0.16 %, respectively). Concentration of Ca was varied from part to part of *A. crassicarpa*. Branch and fine root were 1.12 and 1.26 % which categories the same highest group. Leaf, stem and coarse root were 0.83, 0.30 and 0.23 %, respectively. Mg concentration was greatest in leaf part (0.33%). Mg concentration of *A. crassicarpa* was varied. Branch and fine root were 0.13 and 0.16 %, respectively. While stem and coarse root were classified into the same group (similarly result 0.20%). Na concentration was greatest result in fine root (0.10 %). The other parts were varied from 0.20 to 0.08 %. All nutrient concentration (except P) of *A. crassicarpa* was highly significant differences. Leaf part of *A. crassicarpa* showed the greatest results of concentration for all elements except Ca and Na. Stem and coarse root showed the lowest result of most elements.

*A. indica* expressed the varied results of nutrient concentration. N concentration was highly significant differences between tree parts. The result was highest in leaf part (2.55 %). Other elements were classified as the same group. N concentration of branch, stem, fine- and coarse root were 1.23, 0.80, 1.60 and 1.22 %, respectively. No significant differences were found with P and K. P concentration of *A. indica* was ranged from 0.17 % in stem to 0.32 % in fine root part. K concentration

was ranged from 0.87 % in stem part to 1.35 % in leaf part. Ca concentration in leaf, fine root and branch were little difference and ranged from 2.41, 2.23 and 1.57 %, respectively. Ca concentration in stem and coarse root were 0.88 and 0.96 %, respectively. Significant difference was found with Ca concentration. As the same trend of Ca, Mg concentration was highest in leaf part, followed by fine root and branch with 0.70, 0.46 and 0.45 %, respectively. While the lowest results were coarse root and stem part (0.19 and 0.15 %). Highly significant difference of Mg concentration was found between different tree parts. There was no significant difference of Na concentration between tree parts. The results were varied from 0.02 % in leaf and coarse root to 0.04 % in branch and fine root. Most of all elements showed the highest concentration values in leaf part. Except P and Na that were highest in branch and fine root. Anyhow, no significant difference was found.

For *P. macrocarpus*, N concentration in leaf part was 3.01 % which greater than those in other parts. N concentration of fine- and coarse root were 1.92 % and 1.37 %, respectively. N concentration of branch and stem parts were the lowest with 0.99 and 0.72 %, respectively. P concentration of *P. macrocarpus* was classified in two groups. The higher results appeared in leaf and fine root with 0.29 and 0.25 %, respectively. The other groups were branch, stem and coarse root with 0.10, 0.09 and 0.14 %, respectively. K concentration of *P. macrocarpus* showed similarly consequence results. Leaf part still showed the greatest results with 1.37 %. The other parts were varied from 0.90 % in coarse root to 1.22 % in fine root. As same as K, Ca concentration showed similarly trend varied. Leaf part expressed the greatest result with 1.70 %. While other parts were ranged from 0.54 % in stem part and 1.05 % in branch part. Mg concentration was greatest in leaf part (0.70 %) and was lowest in stem part (0.12 %). On the contrary to other elements, Na concentration was highest in fine root with 0.13 %. While other parts were categories in the same group. There was ranged from 0.02 to 0.07 %. Concentration of all elements showed the significant difference. Leaf part always showed the highest concentration of all elements, except Na.

*S. roxburghii* expressed the greatest N concentration in leaf part with 2.28 %, followed by fine root, branch and coarse root with 0.95, 0.77 and 0.70 %, respectively. Stem part expressed the lowest N concentration with 0.43 %. For P, leaf part expressed the highest result with 0.41 %. Branch and fine root were categories as the same level (0.16 and 0.19 %, respectively). Stem and coarse root parts were classified in the same level as well. As same as P, K concentration still highest in leaf part (1.23 %), followed by branch and fine root (0.77 and 0.72 %, respectively). K concentration of stem and coarse root were the lowest group with 0.40 and 0.37 %, respectively. Ca concentration of Sr was greatest in fine root (1.98 %). Nearby, Ca concentration in leaf and branch were 1.14 and 0.98 %, respectively. Stem part showed the lowest result with 0.36 %. Mg concentrations of all part except leaf resembled results. The highest result was 0.48 % in leaf part. While, Mg concentration in branch, stem, fine- and coarse root parts were 0.23, 0.07, 0.30 and 0.06 %, respectively. As same as Ca, Na concentration of *S. roxburghii* were resembled except fine root (0.08 %). Leaf, branch, stem and coarse root were

classified as the same group. The results were 0.04, 0.03, 0.03 and 0.06 %, respectively. Remarkable for *S. roxburghii*, N, P, K and Mg showed the highest results in leaf part. While Ca and Na were highest results in fine root part. On the contrary, stem and coarse root expressed the lowest results of all most elements. Highly significant differences of all elements concentration were found.

*T. grandis* showed the highest of N concentration in leaf part (2.11 %). While the other parts expressed similarly results. The results showed that N concentration of branch, stem, fine- and coarse root were 0.76, 0.43, 0.16 and 1.00 %, respectively. P concentration was highest in leaf part with 0.35 %. The other parts were categorized as the same group. P concentration of branch, stem, fine- and coarse root were 0.08, 0.06, 0.16 and 0.17 %, respectively. K concentration was highest in leaf part (1.27 %). K concentration of branch and fine root were classified as the same group with 1.01 and 1.05 %, respectively. The lowest K concentration was shown in stem and coarse root with 0.56 and 0.62 %, respectively. Ca concentration was highest in branch and fine root with 1.43 and 1.53 %, respectively. Coarse root contained the lowest Ca concentration with 0.65 %. Mg was highest in leaf part followed by fine root part with 0.57 and 0.30 %, respectively. Branch, stem and coarse root were categorized as the same group. Their Mg concentration was 0.16, 0.08 and 0.11 %, respectively. No significant difference of Na concentration was found. The Na results were ranged from 0.02 to 0.08 %. On the contrary, highly significant differences were found for all other elements. Most of all elements except Ca were highest in leaf part. Stem and coarse root always showed the lowest results as well.

On similar way as other species, N, P and K of *X. xylocarpa* were highest in leaf part. On the contrary, stem and coarse root parts were shown the lowest results. N concentration of *X. xylocarpa* was highest in leaf part, followed by in fine root and branch with 2.62, 1.29 and 1.01 %, respectively. The N concentration of stem and coarse root parts were 0.97 and 0.51 %, respectively. P concentration of *X. xylocarpa* was highest in leaf part with 0.22 %. The other parts were classified into the same group. The results were ranged from 0.03 to 0.11 %. As same as P, K concentration was highest in leaf part with 1.23 %. Branch, stem, fine- and coarse root were classified as the same group. The values ranged from 0.65 to 0.83 %. Ca concentration was highest in branch part with 1.85 %. The other parts expressed similarly results with no significant differences. In addition, no significant difference was found for Na. Na concentration of *X. xylocarpa* was ranged from 0.03 to 0.06 %. The overall results from this present study showed that the percentage of nutrient concentration differed among parts of tree and found that concentration of N, P, K, Ca, Mg and Na in various parts of trees of most tree species were similar trend in sequence of leaf>branch>stem for aboveground biomass. According to the studies of Glumphabutr (2004) in evergreen forest in eastern region, and Punsatha (2001) in *A. indica* plantation, their publications also reported on the same sequence. The results of *A. crassicarpa* plot of present study were supported by Qin *et al*. (2007). They were studied in *A. crassicarpa* plantation in China, the results revealed that concentration of N was highest followed by Ca, K, Mg and P, respectively. All details were shown in Table 22 and Figure 23.

**Table 22** Plant nutrient concentrations of each tree part (via part).

| Spp. | part | Nutrient concentration (% dry weight) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | sd | P | sd | K | sd | Ca | sd | Mg | sd | Na | sd |
| Ac | Leaf | $2.09^{a}$ | 0.30 | 0.15 | 0.05 | $1.06^{a}$ | 0.19 | $0.83^{ab}$ | 0.21 | $0.33^{a}$ | 0.08 | $0.08^{ab}$ | 0.02 |
| | Branch | $0.98^{c}$ | 0.14 | 0.13 | 0.06 | $0.59^{b}$ | 0.22 | $1.12^{a}$ | 0.35 | $0.13^{bc}$ | 0.06 | $0.05^{bc}$ | 0.04 |
| | Stem | $0.42^{d}$ | 0.06 | 0.09 | 0.07 | $0.22^{c}$ | 0.05 | $0.30^{b}$ | 0.14 | $0.02^{c}$ | 0.01 | $0.03^{c}$ | 0.01 |
| | Fine root | $1.49^{b}$ | 0.29 | 0.12 | 0.12 | $0.54^{b}$ | 0.13 | $1.26^{a}$ | 0.12 | $0.16^{b}$ | 0.12 | $0.10^{a}$ | 0.05 |
| | Coarse root | $0.61^{d}$ | 0.06 | 0.02 | 0.01 | $0.16^{c}$ | 0.06 | $0.23^{b}$ | 0.05 | $0.02^{c}$ | 0.01 | $0.03^{c}$ | 0.01 |
| | significant | ** | | ns | | ** | | ** | | ** | | ** | |
| Ai | Leaf | $2.55^{a}$ | 0.46 | 0.33 | 0.05 | 1.35 | 0.10 | $2.41^{a}$ | 1.03 | $0.70^{a}$ | 0.00 | 0.02 | 0.01 |
| | Branch | $1.23^{b}$ | 0.05 | 0.27 | 0.12 | 1.28 | 0.26 | $1.57^{ab}$ | 0.05 | $0.45^{a}$ | 0.07 | 0.04 | 0.01 |
| | Stem | $0.80^{b}$ | 0.44 | 0.17 | 0.17 | 0.87 | 0.40 | $0.88^{b}$ | 0.33 | $0.15^{b}$ | 0.15 | 0.03 | 0.01 |
| | Fine root | $1.60^{b}$ | 0.55 | 0.32 | 0.05 | 1.19 | 0.02 | $2.23^{a}$ | 0.22 | $0.46^{a}$ | 0.24 | 0.04 | 0.43 |
| | Coarse root | $1.22^{b}$ | 0.40 | 0.19 | 0.06 | 0.91 | 0.36 | $0.96^{b}$ | 0.27 | $0.19^{b}$ | 0.10 | 0.02 | 0.28 |
| | significant | ** | | ns | | ns | | * | | ** | | ns | |
| Pm | Leaf | $3.01^{a}$ | 0.31 | $0.29^{a}$ | 0.02 | $1.37^{a}$ | 0.07 | $1.70^{a}$ | 0.50 | $0.70^{a}$ | 0.00 | $0.03^{b}$ | 0 |
| | Branch | $0.99^{cd}$ | 0.12 | $0.10^{b}$ | 0.01 | $1.05^{ab}$ | 0.02 | $1.05^{ab}$ | 0.48 | $0.23^{c}$ | 0.08 | $0.03^{b}$ | 0.01 |
| | Stem | $0.72^{d}$ | 0.17 | $0.09^{b}$ | 0.03 | $0.93^{b}$ | 0.09 | $0.54^{b}$ | 0.07 | $0.12^{d}$ | 0.02 | $0.02^{b}$ | 0.01 |
| | Fine root | $1.92^{b}$ | 0.36 | $0.25^{a}$ | 0.06 | $1.22^{ab}$ | 0.08 | $1.50^{a}$ | 0.57 | $0.36^{b}$ | 0.09 | $0.13^{a}$ | 0.04 |
| | Coarse root | $1.37^{c}$ | 0.20 | $0.14^{b}$ | 0.07 | $0.90^{b}$ | 0.32 | $0.88^{ab}$ | 0.37 | $0.19^{cd}$ | 0.03 | $0.07^{b}$ | 0.02 |
| | significant | ** | | ** | | * | | * | | ** | | ** | |

**Table 22** (Continued)

| Spp. | part | Nutrient concentration (% dry weight) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | sd | P | sd | K | sd | Ca | sd | Mg | sd | Na | sd |
| Sr | Leaf | $2.28^{a}$ | 0.17 | $0.41^{a}$ | 0.05 | $1.23^{a}$ | 0.10 | $1.14^{b}$ | 0.20 | $0.48^{a}$ | 0.01 | $0.04^{b}$ | 0.02 |
| | Branch | $0.77^{c}$ | 0.05 | $0.16^{b}$ | 0.03 | $0.77^{b}$ | 0.12 | $0.98^{b}$ | 0.17 | $0.23^{bc}$ | 0.02 | $0.03^{b}$ | 0.01 |
| | Stem | $0.43^{d}$ | 0.02 | $0.07^{c}$ | 0.01 | $0.40^{c}$ | 0.03 | $0.36^{c}$ | 0.07 | $0.07^{c}$ | 0.02 | $0.03^{b}$ | 0.01 |
| | Fine root | $0.95^{b}$ | 0.08 | $0.19^{b}$ | 0.05 | $0.72^{b}$ | 0.19 | $1.98^{a}$ | 0.45 | $0.30^{ab}$ | 0.24 | $0.08^{a}$ | 0.09 |
| | Coarse root | $0.70^{c}$ | 0.05 | $0.07^{c}$ | 0.02 | $0.37^{c}$ | 0.08 | $0.75^{bc}$ | 0.23 | $0.06^{c}$ | 0.02 | $0.06^{b}$ | 0.04 |
| | significant | ** | | ** | | ** | | ** | | ** | | ** | |
| Tg | Leaf | $2.11^{a}$ | 0.15 | $0.35^{a}$ | 0.02 | $1.27^{a}$ | 0.03 | $1.26^{ab}$ | 0.01 | $0.57^{a}$ | 0.12 | 0.03 | 0.01 |
| | Branch | $0.76^{bc}$ | 0.07 | $0.08^{b}$ | 0.03 | $1.01^{b}$ | 0.07 | $1.43^{a}$ | 0.26 | $0.16^{c}$ | 0.05 | 0.03 | 0.01 |
| | Stem | $0.43^{c}$ | 0.02 | $0.06^{b}$ | 0.02 | $0.56^{c}$ | 0.13 | $0.79^{bc}$ | 0.09 | $0.08^{c}$ | 0.02 | 0.02 | 0 |
| | Fine root | $1.16^{b}$ | 0.34 | $0.16^{b}$ | 0.10 | $1.05^{b}$ | 0.18 | $1.53^{a}$ | 0.53 | $0.30^{b}$ | 0.07 | 0.08 | 0.07 |
| | Coarse root | $1.00^{b}$ | 0.29 | $0.07^{b}$ | 0.01 | $0.62^{c}$ | 0.10 | $0.65^{c}$ | 0.01 | $0.11^{c}$ | 0.04 | 0.03 | 0.01 |
| | significant | ** | | ** | | ** | | ** | | ** | | ns | |
| Xx | Leaf | $2.62^{a}$ | 0.12 | $0.22^{a}$ | 0.06 | $1.23^{a}$ | 0.07 | $1.09^{b}$ | 0.36 | $0.35^{a}$ | 0.01 | 0.03 | 0 |
| | Branch | $1.01^{bc}$ | 0.17 | $0.07^{b}$ | 0.04 | $0.80^{b}$ | 0.26 | $1.85^{a}$ | 0.43 | $0.19^{b}$ | 0.07 | 0.03 | 0.01 |
| | Stem | $0.51^{d}$ | 0.02 | $0.03^{b}$ | 0.02 | $0.65^{b}$ | 0.08 | $0.44^{b}$ | 0.06 | $0.10^{c}$ | 0.01 | 0.03 | 0.01 |
| | Fine root | $1.29^{b}$ | 0.06 | $0.11^{b}$ | 0.01 | $0.83^{b}$ | 0.17 | $0.87^{b}$ | 0.28 | $0.26^{c}$ | 0.07 | 0.06 | 0.02 |
| | Coarse root | $0.97^{c}$ | 0.31 | $0.06^{b}$ | 0.02 | $0.71^{b}$ | 0.27 | $0.76^{b}$ | 0.63 | $0.20^{c}$ | 0.14 | 0.03 | 0.01 |
| | significant | ** | | ** | | * | | ** | | ** | | ns | |

**Remark**: Ac: *A. crassicarpa*, Ai: *A. indica*, Pm: *P. macrocarpus*, Sr: *S. roxburghii*, Tg: *T. grandis* and Xx: *X. xylocarpa*

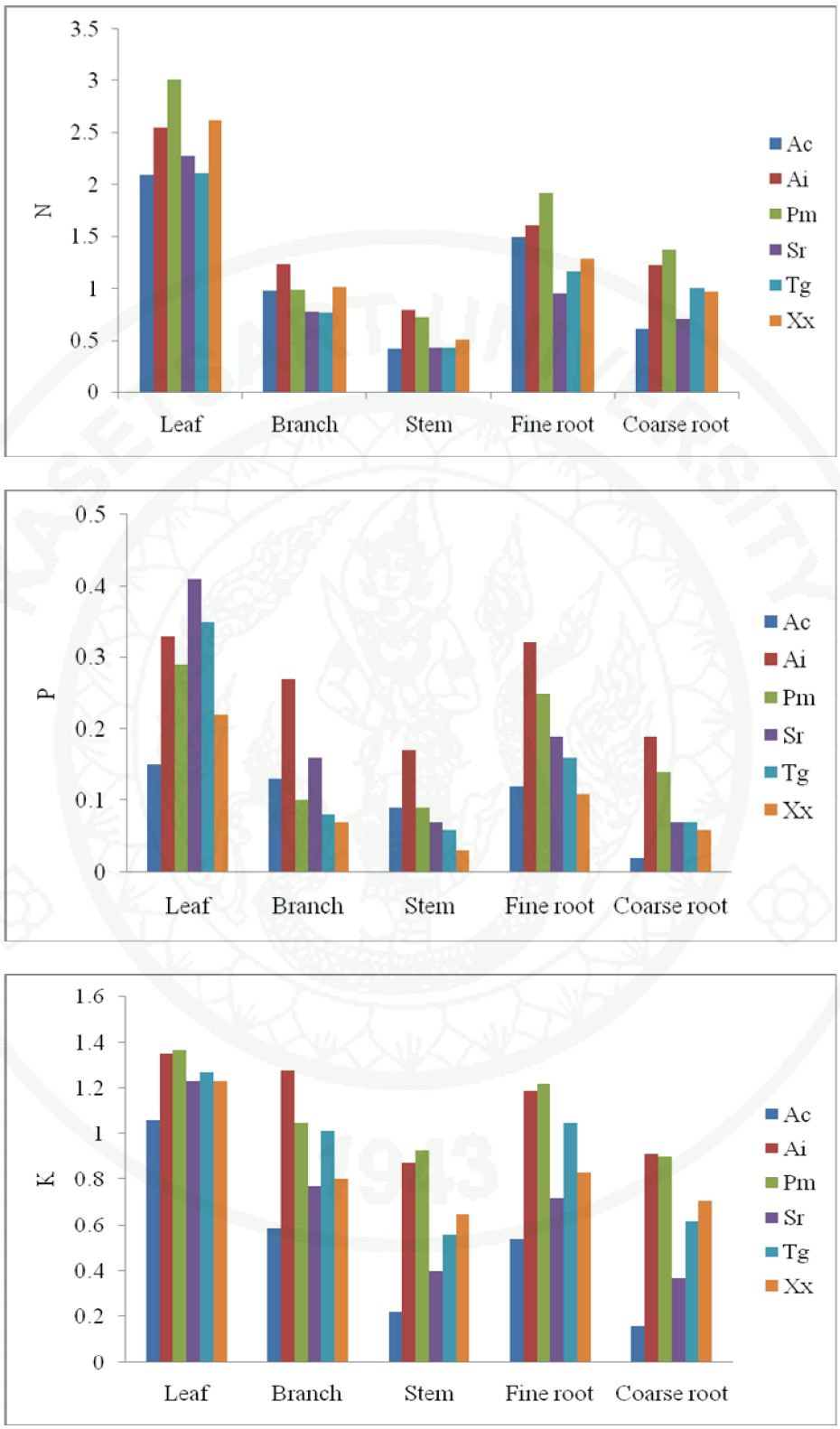



**Figure 23** Nutrient concentration in various tree part (% by dry weight).

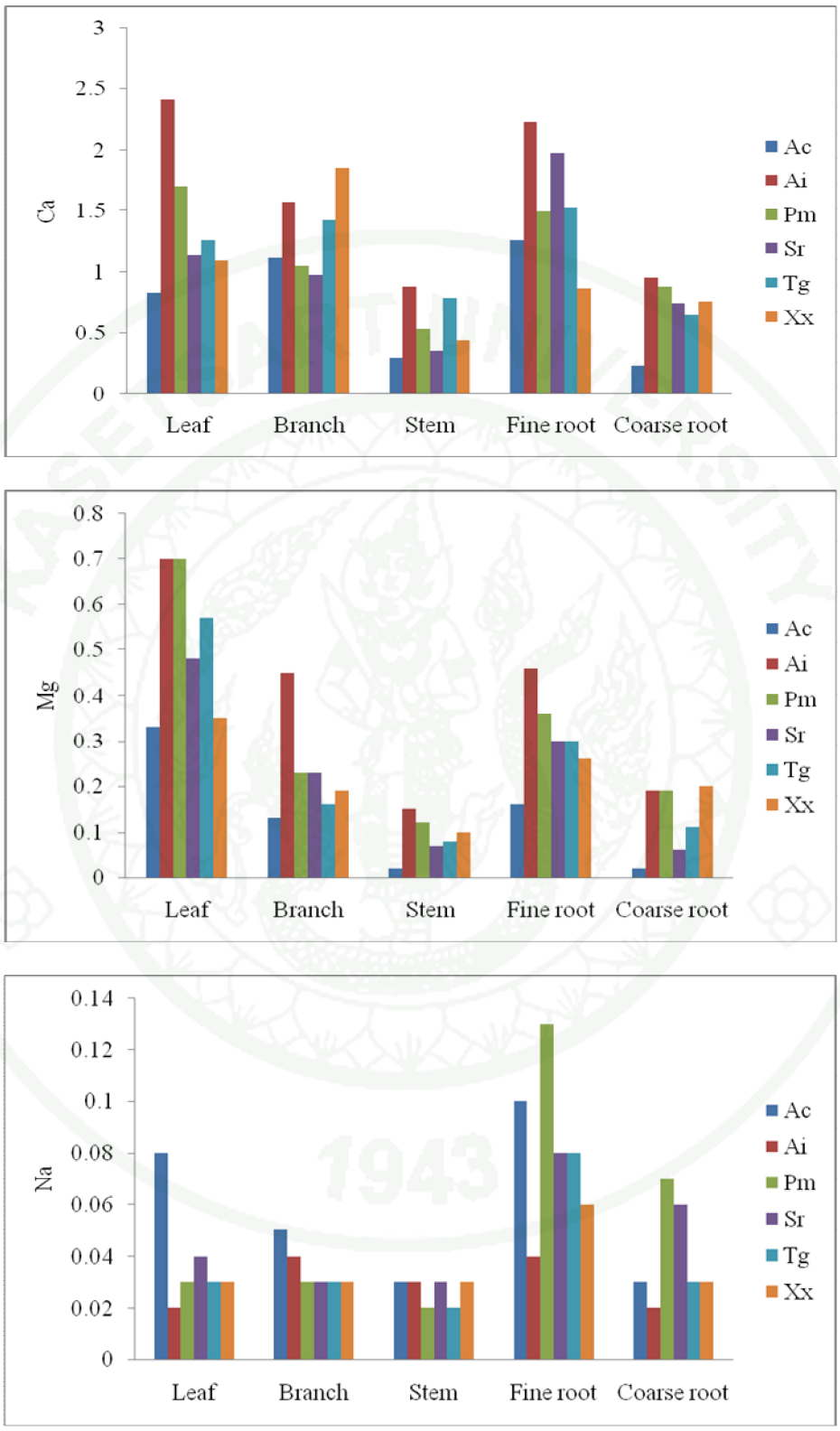



**Figure 23** (Continued)

The cluster analysis classified the plated tree species into 2 principal difference groups via nutrient concentration of tree parts as shown in Figure 24. Parameters of plant nutrient concentration i.e. N, P, K, Ca, Mg and Na from leaf, stem, fine- and coarse root parts showed the similarly cluster results when using 50% of remaining information. The results indicated that *A. indica* and *P. macrocarpus* was classified as the same group. Furthermore, *A. crassicarpa*, *S. roxburghii*, *T. grandis* and *X. xylocarpa* were classified as the same another group. Anyhow, cluster result from branch nutrient properties indicated the differences result. The results revealed above probably due to highly nutrient concentration of *A. indica* and *P. macrocarpus*, which seemed to be higher than other species that classified into another group.

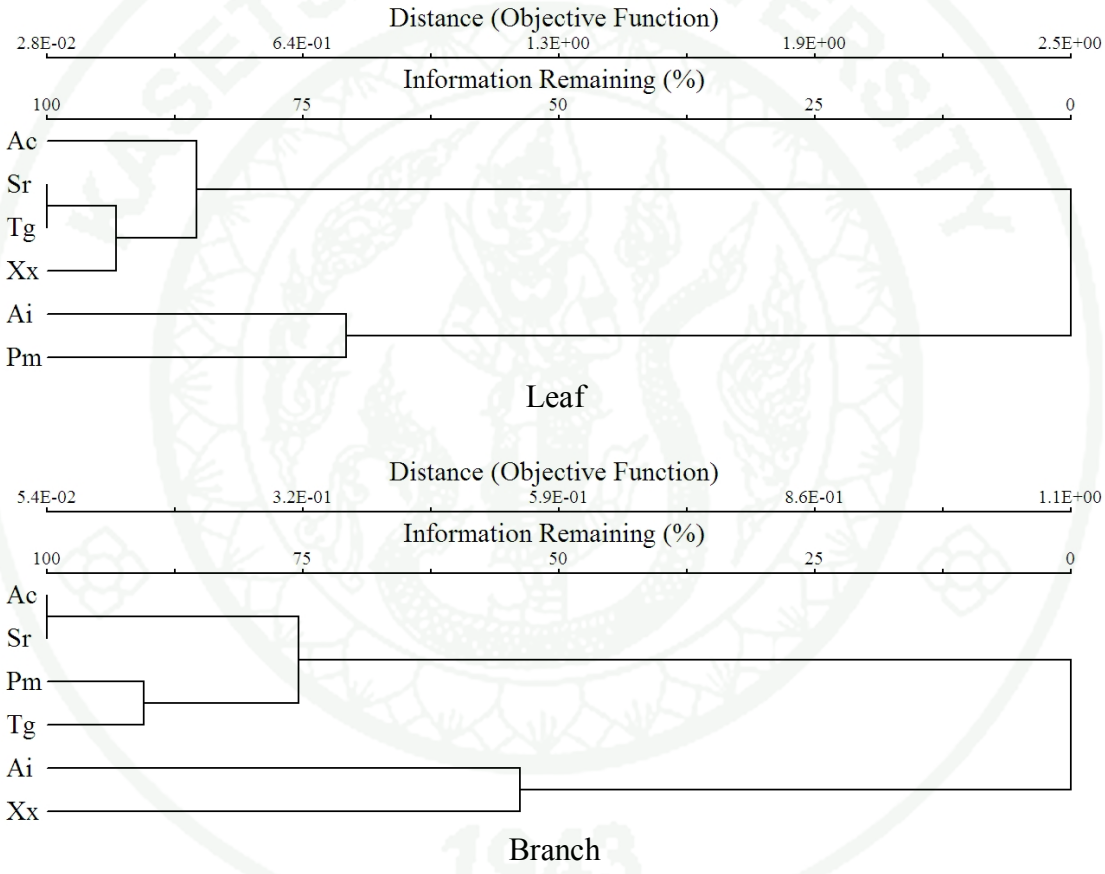
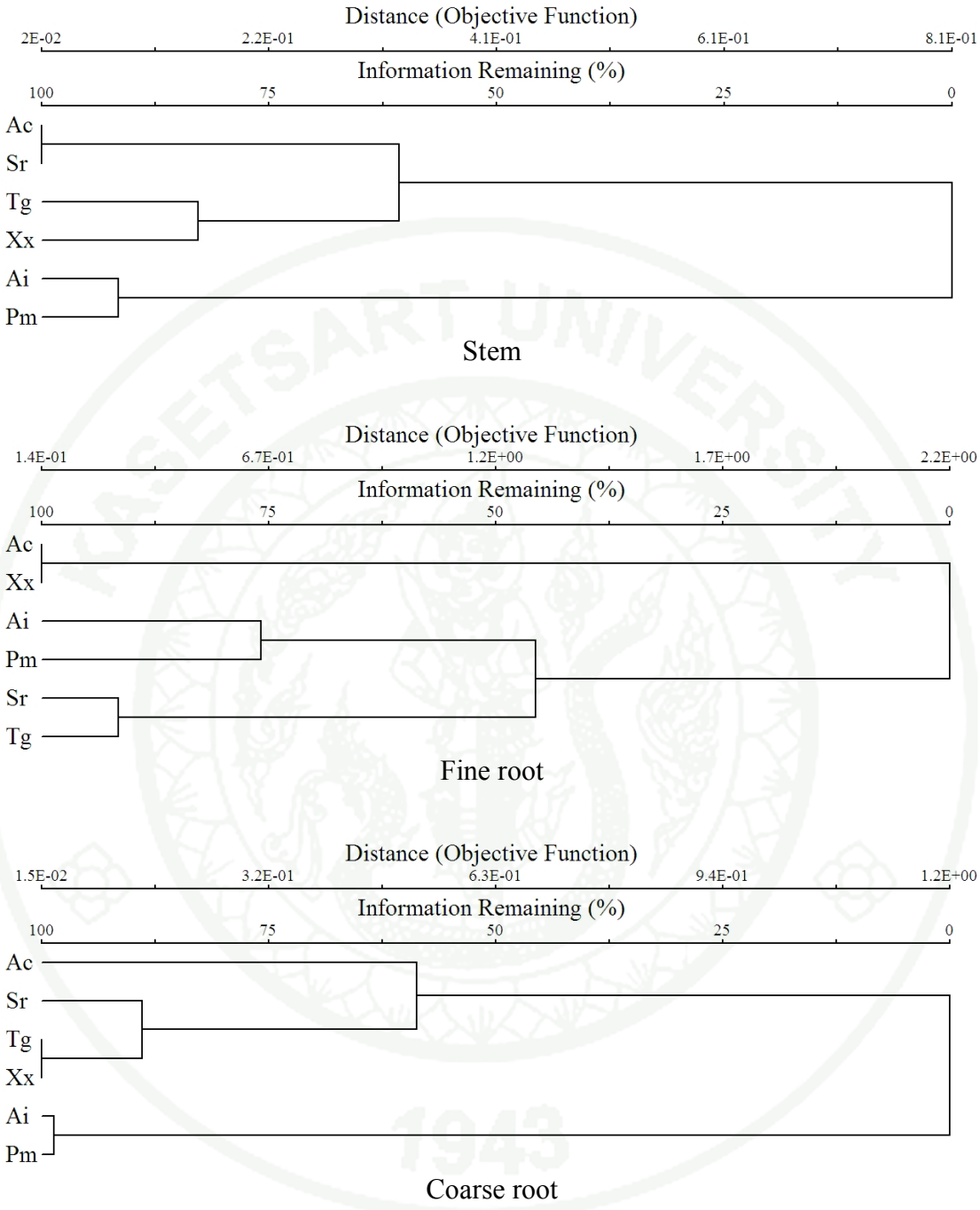



**Figure 24** Dendrogram obtained by the cluster analysis of nutrient concentration in different tree parts.




**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

**Figure 24** (Continued)

9.2 Senescence tree part nutrient concentration;

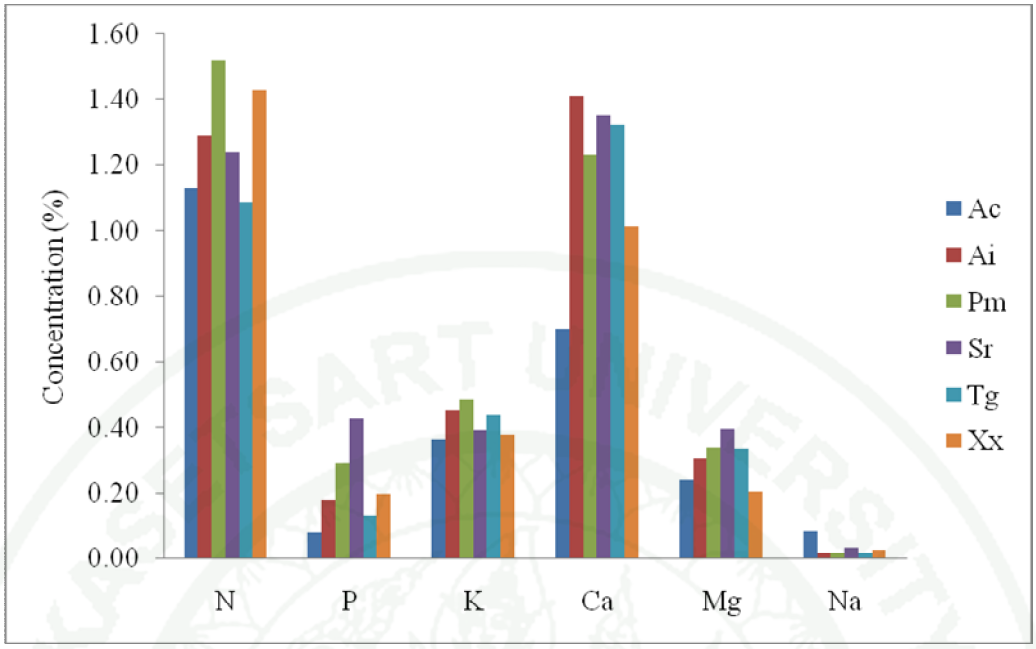
Senescence tree part or litterfall was varied in element content because of the varied properties of leaf. Table 23 and Figure 25 showed concentration of N, P, K, Ca, Mg and Na in leaf litterfall of each plot. N and Ca seemed to be the highest concentrations of nutrients remain in leaf litter. *A. crassicarpa, P. macrocarpus* and *X. xylocarpa* showed the highest concentration of N. While, *A. indicus*, *S. roxburghii* and *T. grandis* showed the highest concentration of Ca. Anyhow, both elements expressed comparable results of nutrient concentration for all tree species. The orders of abundance of nutrients in leaf litter were in sequence of N>Ca>K>Mg>p>Na for *A. crassicarpa*, Ca>N>K>Mg>P>Na for *A. indicus* and *X. xylocarpa*, N>Ca>K>Mg>P>Na for *P. macrocarpus* and *T. grandis*, and Ca>N>P>Mg>K>Na for *S. roxburghii*. K and P concentrations were the third and the fifth for most species, respectively except *S. roxburghii*. While, Mg concentration was the fourth for all tree species. Na was the lowest nutrient concentration in leaf litter for all tree species as well. The resemble results of nutrient concentration consequence in forest litter were reported from many researchers e.g. Semwall *et al*. (2003), Glumphabutr (2004), Joseph and Bernhard-Reversat (2006) and Ma *et al*. (2007). Ngoran *et al.* (2006) revealed that leaf litter of *Acacia mangium* and *A. auriculiformis* planted on sandy soil in Ivory Coast represented the N, P, K and Mg concentration of 1.97-2.03, 0.09-1.15, 1.07-1.19 and 0.19-0.22%, respectively. These results were comparably higher than the results derived from *Acacia* spp. in present study. Figure 26 revealed that *A. crassicarpa* was classified in distinctly group when using 50% of remaining information which was probably due to lower nutrient concentration than other species. This result could be indicated the highly re-translocation rate of nutrient from senescence leaves of *A. crassicarpa* (see Table 22 and 23).

Data in Table 22 and 23 indicated that nutrient concentration in living leaf was higher than that leaf litter. The translocation processes of nutrient from old- to younger parts were the one of the reasonable reasons. Furthermore, comparing to living leaf nutrient concentration, nutrient conservation mechanisms like strong nutrient re-translocation efficiency and immobilization of nutrients are operated. All species, especially *P. macrocarpus* and *X. xylocarpa* adapted a strong nutrient conservation mechanism, as evident from higher nutrients re-translocation from senescing leaves to permanent plant tissue. This mechanism could be help these species to competition with other species in nutrient deficiently soil. This result was supported by many publication e.g. Tripathi and Singh (1995); Rapp *et al*. (1999); Xu *et al*. (2003); Pandey *et al*. (2007). Their researched indicated that nutrient concentration in leaf litter was lower than that in green leaf. With regard to nutrient analysis of senescent leaves and fresh leaves, obviously different result was observed, possibly because they are the most mobile elements. However, lower mobility elements such as Ca and Mg were less fluctuating. This result revealed above

was advocated with the publication of Xu *et al*. (2003). Nutrient re-translocation is one of the important nutrient dynamic processes. Rapp *et al*. (1999) revealed that translocation of N and P in tree, from leaves to woody tissue, was a more important process than return to the soil by litter fall and recycling through the ecosystem.

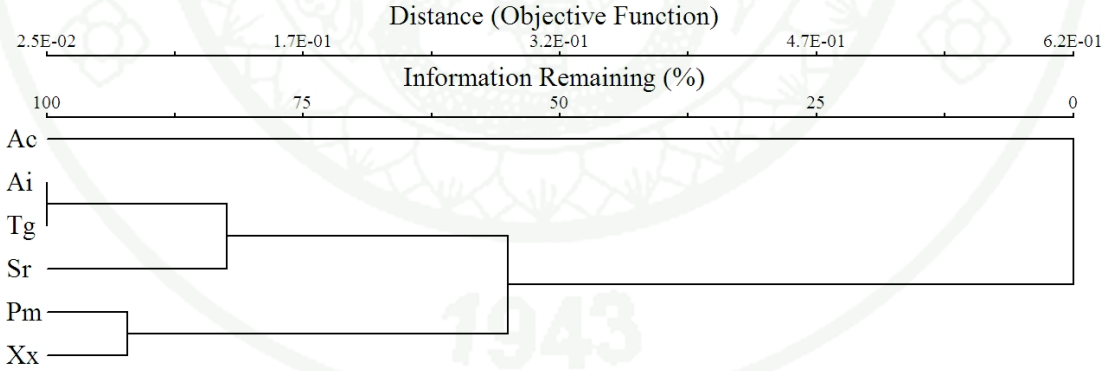
**Table 23** Nutrient concentration in litterfall.

| Spp. | Nutrient concentration (% dry weight) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | sd | P | sd | K | sd | Ca | sd | Mg | sd | Na | sd |
| *A. crassicarpa* | $1.13^{de}$ | 0.02 | $0.08^{d}$ | 0.01 | $0.36^{c}$ | 0.33 | $0.70^{c}$ | 0.83 | $0.24^{cd}$ | 0.26 | $0.08^{a}$ | 0.01 |
| *A. indica* | $1.29^{bc}$ | 0.15 | $0.18^{c}$ | 0.06 | $0.45^{a}$ | 0.36 | $1.41^{a}$ | 2.81 | $0.31^{bc}$ | 0.57 | $0.02^{b}$ | 0.00 |
| *P. macrocarpus* | $1.52^{a}$ | 0.13 | $0.29^{b}$ | 0.04 | $0.49^{a}$ | 0.55 | $1.23^{ab}$ | 0.89 | $0.34^{ab}$ | 0.29 | $0.02^{b}$ | 0.00 |
| *S. roxburghii* | $1.24^{cd}$ | 0.06 | $0.43^{a}$ | 0.03 | $0.39^{bc}$ | 0.22 | $1.35^{a}$ | 0.78 | $0.40^{a}$ | 0.45 | $0.03^{b}$ | 0.00 |
| *T. grandis* | $1.09^{e}$ | 0.06 | $0.13^{d}$ | 0.02 | $0.44^{ab}$ | 0.24 | $1.33^{a}$ | 1.70 | $0.34^{ab}$ | 0.69 | $0.02^{b}$ | 0.00 |
| *X. xylocarpa* | $1.43^{ab}$ | 0.07 | $0.20^{c}$ | 0.03 | $0.38^{c}$ | 0.30 | $1.01^{b}$ | 1.32 | $0.21^{d}$ | 0.36 | $0.03^{b}$ | 0.00 |
| Significant | ** | | ** | | ** | | ** | | ** | | ** | |




**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

**Figure 25** Concentration of nutrients in leaf litterfall of each tree species.




**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

**Figure 26** Dendrogram obtained by the cluster analysis of nutrient concentration in litterfall.

**10. Soil nutrient content.**

Soil nutrient accumulation was divided into 2 portions as follows;

10.1 Nutrient content in litter on soil surface.

Table 24 showed nutrient content that accumulated on soil surface, the results were found that the amounts of litter that accumulated on soil surface were highest in *A. crassicarpa* plot (3,438.23 kg $ha^{-1}$) while *A. indica*, *P. macrocarpus*, *S. roxburghii*, *T. grandis* and *X. xylocarpa* were 670.56, 355.21, 403.27, 729.43 and 1,032.01 kg $ha^{-1}$, respectively. The highest amount of remaining litter on soil surface in *A. crassicarpa* plot was mainly due to the highest results of all nutrient accumulation in litter on soil surface. On the other hand, results derived from *P. macrocarpus* and *S. roxburghii* plot showed the absolutely different results which were due to small amount of remaining litter on soil surface. N content of litter on soil surface was varied from 2.86 kg $ha^{-1}$ in *P. macrocarpus* to 24.91 kg $ha^{-1}$ of *A. crassicarpa* plots. While P content in litter on soil was ranged from 0.52 to 4.16 kg $ha^{-1}$. *S. roxburghii* and *P. macrocarpus* expressed the equivalently results of P content. Anyhow, *P. macrocarpus* expressed slightly higher results than *S. roxburghii* for P and K content. Ca seemed to be the lager amount of nutrient content than others except N. The high concentrations in living and dead tree parts were mainly due to the higher Ca content of litter on soil surface. The data revealed that Ca content of litter on soil surface was ranged between 2.56 and 14.26 kg $ha^{-1}$. Mg content was ranged between 0.73 and 4.75 kg $ha^{-1}$. While, Na showed the lowest results when compared to other elements. The results from Table 24 indicated that Na content was ranged between 0.05 and 0.76 kg $ha^{-1}$, of *P. macrocarpus* and *A. crassicarpa* plots, respectively. Comparing to the results from other studies, nutrient content in litter on soil surface was distinctly lower than other results e.g. Jutikidecha (1996) and Punsatha (2002) who was studied In *Eucalyptus camaldulensis* and *A. indica* plantation, or the results from natural forest e.g. Chinsukjaiprasert (1984), Suksawang (1988) and Glumphabutr (2004). That lower results in this present study because of lower amount of remaining litter on soil surface. Moreover, the lower nutrient concentration of the remaining litter was another important factor on the accumulation of nutrients. These results indicated that nutrient accumulation on soil surface were varied with the amount of litter fall and nutrient concentration of litter that accumulated on soil surface.

**Table 24** Nutrient content of litter on soil surface**.**

| Spp. | Litter (kg ha$^{-1}$) | Nutrient content (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Ac | 3,483.23 | 24.91 | 4.16 | 4.86 | 14.26 | 4.75 | 0.76 |
| Ai | 670.56 | 5.66 | 0.79 | 1.82 | 7.74 | 1.73 | 0.11 |
| Pm | 355.21 | 2.86 | 0.53 | 1.20 | 2.56 | 0.73 | 0.05 |
| Sr | 403.27 | 3.25 | 0.52 | 0.44 | 3.07 | 1.16 | 0.11 |
| Tg | 729.43 | 3.35 | 0.98 | 1.16 | 8.13 | 1.75 | 0.19 |
| Xx | 1,032.01 | 7.61 | 1.10 | 2.62 | 7.12 | 1.99 | 0.30 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

10.2 Nutrient content in mineral soil.

Soil was sampled to the depth of 50 cm, in 10 cm intervals in all treatments and grass land. Despite differences in biomass productivity and litter production, there were differences in soil nutrient content among experimental treatments. All results showed variable of the soil properties through soil dept (to 50 cm). Definitely, only upper soil layer (0 to 10 cm) expressed the highest value of all elements of most treatments. In the other hand, uncertainly results were found in the lower soil layers. All results were shown in Table 25.

*A. crassicarpa* showed the greatest amount of soil N content especially in the top soil layer (1,644.14 kg ha$^{-1}$). The result from 10-20 cm and 40-50 cm depths were similar (1,235.25 and 1,224.73 kg ha$^{-1}$). While, 910.36 and 949.56 kg ha$^{-1}$ of N were found in 20-30 and 30-40 cm depth. respectively. P was ranged from 3.89 to 17.23 kg ha$^{-1}$, in 30-40 and 0-10 cm depth, respectively. Different results of N and P, K contents were highest in the deepest layer at 40-50 cm depth, with 40.39 kg ha$^{-1}$. Anyhow, from the top layer to 40 cm depths, P content was decreased with increasing soil depth. Ca and Mg contents were highest at 40-50 cm depth, with amount of 250.74 and 44.54 kg ha$^{-1}$, respectively. Whereas, Na content at 10-20 cm was the highest (11.28 kg ha$^{-1}$). Moreover, unclear of change trend on nutrient content were exist in the latest 3 elements. *A. indica* showed the N content between 851.95 and 1,486.30 kg ha$^{-1}$. The highest result was appeared in the top soil layer. In addition, N content was decreased with soil depth. P expressed 14.35 kg ha$^{-1}$, the highest results at 10-20 depth. Except the top layer (12.80 kg ha$^{-1}$), P content was decreased with increasing soil depth. As same as other elements, K content in soil of *A. indica* plot was decreased with depth. The results ranged from 32.78 to 46.98 kg ha$^{-1}$. Ca was ranged from 89.21 to 183.39 kg ha$^{-1}$. The results showed decreasing trend from top to the deepest soil layer. Mg was ranged from 21.85 to 32.09 kg ha$^{-1}$. Na was ranged from 6.68 to 10.40 kg ha$^{-1}$. N content in soil of *P. macrocarpus* plot expressed clearly decreasing trend from top soil layer to the deepest soil layers. The result was ranged from 773.05 to 1,526.88 kg ha$^{-1}$. In case of P, the top soil layer

expressed the content more than ten times when compared to the deeper layers such as 20-30 cm and 30-40 cm depths (28.34 vs. 2.04 and 2.31 kg $ha^{-1}$, respectively). While, K content from each layer seemed to be the same, and ranged from 32.59 to 51.47 kg $ha^{-1}$. Ca content of top soil layer was the highest (115.05 kg $ha^{-1}$). This result was nearly two times over those other layers (56.46-78.11 kg $ha^{-1}$). Moreover, the decreasing trend of content was also found with Ca. Na and Mg elements showed the highest results of nutrient content in 30-40 cm depth. Anyhow, the data of both elements were closely i.e. 21.28-33.10 kg $ha^{-1}$ for Mg, and 8.48-11.78 kg $ha^{-1}$ for Na. Greatest result of N content of *S. roxburghii* plot was distributed to the top soil layer (1,497.13 kg $ha^{-1}$). In the same way, P content was highest in the top soil layer (18.25 kg $ha^{-1}$) and was decreasing through soil depth. The results revealed that P content from the top soil layer was nearly or more than ten times greater than the deeper soil layers (1.44-2.37 kg $ha^{-1}$). K content was similarly results, and ranged from 28.49 to 36.94 kg $ha^{-1}$. Change of Ca content through soil depth was oscillation. The data reveal that 20-30 cm and 0-10 cm depth were the greatest amount of Ca content with 180.22 and 171.41 kg $ha^{-1}$, respectively. Mg content was ranged from 20.70 to 25.18 kg $ha^{-1}$. While, Na content was ranged from 6.74 to 12.20 kg $ha^{-1}$.

N, P and K content in soil of *T. grandis* plot were decreased with increasing soil depth. All results revealed that the greatest amounts of nutrient were occurred in top soil layer. Nutrient contents of N, P and K were ranged from 789.30-1,554.87, 2.22-14.97 and 28.76-38.43 kg $ha^{-1}$, respectively. Ca content showed the greatest result in the middle layer at 20-30 cm depth (131.11 kg $ha^{-1}$). The results of other layers were varied between 87.80 and 128.19 kg $ha^{-1}$. Mg content was ranged from 19.46 to 26.60 kg $ha^{-1}$. While, Na content was ranged from 8.12 to 12.37 kg $ha^{-1}$. N content of *X. xylocarpa* plot was greatest in top soil layer (1,589.54 kg $ha^{-1}$), and was decreasing via depth. Anyhow, at 30-40 cm depth, N content was increasing to 1,213.77 kg $ha^{-1}$. Majority of P content was occurred in the upper layer from 0-10 and 10-20 cm depths (12.34 and 11.29 kg $ha^{-1}$, respectively). In other layers, the results were ranged from 1.95 to 4.26 kg $ha^{-1}$. K and Ca contents were greatest in the top soil layer (48.87 and 111.42 kg $ha^{-1}$, respectively). K content of other layers was ranged from 21.21 to 29.27 kg $ha^{-1}$. While Ca content in other layers was ranged from 75.50 to 102.86 kg $ha^{-1}$. Mg content showed the increasing trend in deeper soil depth. The data was ranged from 24.40 to 30.19 kg $ha^{-1}$, which the greatest content of Mg was in the deepest layer of 40-50 cm depth. The result of Na content was varied, and ranged from 6.59 to 9.37 kg $ha^{-1}$. The greatest result also appeared in the deepest layer. In grass land, N content in soil layer was ranged from 867.55 to 1,291.84 kg $ha^{-1}$. The normally decreasing trend of nutrient content was occurred. Anyway, at 30-40 cm depth the result was increased (1,006.93 kg $ha^{-1}$). P content was ranged from 4.81 to 12.77 kg $ha^{-1}$. The decreasing trend of nutrient content was almost the same as other elements. K was ranged from 84.67 to 115.35 kg $ha^{-1}$. Most of content of K was occurred at 20-30 and 30-40 cm depths with values of 115.35 and 112.97 kg $ha^{-1}$, respectively. Ca content of grass land was greater than that of other plantation plot. The data was ranged from 287.03 to 529.62 kg $ha^{-1}$. Mg and Na contents were varied through soil depth. The results of both elements revealed the greatest results at 30-40 cm depth with values of 37.31 and 12.22 kg $ha^{-1}$, respectively.

**Table 25** Soil nutrient content in 10 cm interval.

| Species | soil depth (cm) | Bulk density ($g\ cm^3$) | nutrient content ($kg\ ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | Ca | Mg | Na |
| *A. crassicarpa* | 0-10 | 1.55 | 1,666.14 | 17.03 | 37.50 | 195.24 | 30.45 | 8.89 |
| | 10-20 | 1.59 | 1,235.25 | 10.26 | 32.85 | 201.34 | 28.68 | 11.28 |
| | 20-30 | 1.52 | 910.36 | 14.23 | 26.53 | 259.37 | 35.28 | 7.75 |
| | 30-40 | 1.48 | 949.56 | 3.89 | 29.76 | 221.38 | 33.72 | 9.40 |
| | 40-50 | 1.61 | 1,224.73 | 10.52 | 40.39 | 250.74 | 44.54 | 7.60 |
| | total | - | 5,986.04 | 55.93 | 167.03 | 1,128.06 | 172.67 | 44.92 |
| *A. indica* | 0-10 | 1.59 | 1,486.30 | 12.80 | 46.98 | 183.39 | 32.09 | 5.68 |
| | 10-20 | 1.52 | 1,228.18 | 14.35 | 41.08 | 137.68 | 28.34 | 10.40 |
| | 20-30 | 1.52 | 826.08 | 10.95 | 42.95 | 120.92 | 29.60 | 9.20 |
| | 30-40 | 1.45 | 884.45 | 9.30 | 32.78 | 92.05 | 21.85 | 6.68 |
| | 40-50 | 1.69 | 851.95 | 5.03 | 40.73 | 89.21 | 25.40 | 7.04 |
| | total | - | 5,276.95 | 52.42 | 204.53 | 623.24 | 137.28 | 38.99 |
| *P. macrocarpus* | 0-10 | 1.59 | 1,526.88 | 28.34 | 40.24 | 115.05 | 21.28 | 9.28 |
| | 10-20 | 1.51 | 1,199.33 | 9.75 | 32.59 | 78.11 | 21.62 | 8.48 |
| | 20-30 | 1.51 | 806.21 | 2.04 | 37.07 | 65.05 | 24.80 | 10.23 |
| | 30-40 | 1.62 | 994.35 | 2.31 | 48.96 | 67.96 | 33.10 | 11.78 |
| | 40-50 | 1.53 | 773.05 | 4.97 | 51.47 | 56.46 | 29.90 | 9.77 |
| | total | - | 5,299.82 | 47.42 | 210.33 | 382.63 | 130.71 | 49.53 |

**Table 25** (Continued)

| Species | soil depth (cm) | Bulk density ($g\ cm^3$) | nutrient content ($kg\ ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | Ca | Mg | Na |
| *S. roxburghii* | 0-10 | 1.50 | 1,497.13 | 18.25 | 36.94 | 171.41 | 25.18 | 7.32 |
| | 10-20 | 1.51 | 1,383.72 | 1.96 | 29.60 | 148.31 | 20.70 | 8.42 |
| | 20-30 | 1.48 | 1,062.22 | 2.02 | 31.13 | 180.22 | 24.01 | 12.20 |
| | 30-40 | 1.47 | 1,118.75 | 2.37 | 34.52 | 156.00 | 20.93 | 9.13 |
| | 40-50 | 1.60 | 1,134.09 | 1.44 | 28.49 | 111.16 | 23.32 | 6.74 |
| | total | - | 6,195.90 | 26.04 | 160.68 | 767.09 | 114.13 | 43.80 |
| *T. grandis* | 0-10 | 1.73 | 1,554.87 | 14.91 | 38.43 | 110.39 | 23.37 | 12.37 |
| | 10-20 | 1.59 | 1,440.10 | 12.87 | 32.49 | 128.19 | 24.43 | 11.25 |
| | 20-30 | 1.65 | 1,012.26 | 2.70 | 30.82 | 131.11 | 23.40 | 8.12 |
| | 30-40 | 1.65 | 1,165.76 | 2.22 | 30.49 | 109.66 | 19.46 | 10.03 |
| | 40-50 | 1.69 | 789.30 | 2.84 | 28.76 | 87.80 | 26.60 | 8.63 |
| | total | - | 5,962.29 | 35.54 | 160.98 | 567.16 | 117.25 | 50.40 |
| *X. xylocarpa* | 0-10 | 1.72 | 1,589.54 | 12.34 | 48.87 | 111.42 | 24.44 | 8.40 |
| | 10-20 | 1.74 | 983.28 | 11.29 | 29.27 | 92.52 | 24.40 | 6.59 |
| | 20-30 | 1.56 | 924.15 | 2.76 | 22.76 | 78.92 | 24.45 | 6.75 |
| | 30-40 | 1.92 | 1,213.77 | 4.26 | 24.87 | 102.86 | 29.56 | 8.15 |
| | 40-50 | 1.65 | 801.97 | 1.95 | 21.21 | 75.50 | 30.19 | 9.37 |
| | total | - | 5,512.72 | 32.60 | 146.98 | 461.22 | 133.04 | 39.25 |

**Table 25** (Continued)

| Species | soil depth (cm) | Bulk density ($g\ cm^3$) | nutrient content ($kg\ ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | Ca | Mg | Na |
| Abandoned crop field (control plot) | 0-10 | 1.61 | 1,291.84 | 12.77 | 96.91 | 287.81 | 26.69 | 8.13 |
| | 10-20 | 1.56 | 1,171.14 | 11.83 | 94.76 | 323.32 | 22.85 | 6.50 |
| | 20-30 | 1.60 | 970.07 | 16.01 | 115.35 | 363.42 | 30.58 | 9.05 |
| | 30-40 | 1.66 | 1,006.93 | 9.16 | 112.97 | 520.62 | 37.31 | 12.22 |
| | 40-50 | 1.67 | 867.55 | 4.81 | 84.67 | 287.03 | 26.13 | 6.68 |
| | total | - | 5,307.52 | 54.58 | 504.66 | 1,782.21 | 143.55 | 42.58 |

Data in Table 26 and Figure 27 showed that total N content at 0-50 cm depth was varied. The results revealed that the comparable of N content of all species were; *S. roxburghii*>*A. crassicarpa*>*T. grandis*>*X. xylocarpa*>abandoned crop field>*P. macrocarpus*>*A. indica* with 6,195.90, 5,986.04, 5,962.29, 5,512.72, 5,307.52, 5,299.82 and 5,276.95 kg $ha^{-1}$, respectively. Anyhow, no significant difference was found. The effect of tree species on total N stock in the soil was inconsistent (Augusto *et al*., 2002; Rouhi-Moghaddam *et al*., 2008). Many results revealed that soil N content between different forest types or species were similar (e.g. Binkley, 1997; Montagnini, 2000; Parrotta, 1999; Rouhi-Moghaddam *et al*.; 2008). More over, the results form present study revealed that soil N content in Leguminosae *A. crassicarpa* plot was quite higher than that of other species. That would be described by many results which indicated that *Leguminicae* spp. can fix and stored N from the atmosphere (Garcia-Mantiel and Binkley, 1998; Hansen and Dawson, 1982; DeBell *et al*., 1989; Tokky and Singh, 1993; Parrotta, 1999). No significant difference was found with P content. Comparable values of P content of the studied species; *A. crassicarpa* >grass land> *A. indica*> *P. macrocarpus*> *T. grandis*> *X. xylocarpa*> *S. roxburghii* were 55.93, 54.58, 52.42, 47.42, 35.54, 32.60 and 26.04 kg $ha^{-1}$, respectively. K content was highly significant differences from species to species. All data could be comparable as follow; grass land > *P. macrocarpus* > *A. indica*> *A. crassicarpa* > *T. grandis* > *S. roxburghii* > *X. xylocarpa*. The results of K content through 50 cm depth were 504.66, 210.33, 204.53, 167.03, 160.98, 146.98 kg $ha^{-1}$, respectively. Ca content also expresses the highly significant differences by species. The results could be arranged as follow; grass land > *A. crassicarpa* > *S. roxburghii* > *A. indica* > *T. grandis* > *X. xylocarpa* > *P. macrocarpus*. The results were 1,782.21, 1,128.06, 767.09, 623.24, 567.16, 461.22 and 382.63 kg $ha^{-1}$, respectively. Highly significant difference was found with Mg content from plot to plot. All results could be comparable as follow; *A. crassicarpa* > grass land > *A. indica* > *X. xylocarpa* > *P. macrocarpus* > *T. grandis* >*S. roxburghii* with 172.67, 143.55, 137.28, 133.04, 130.71, 117.25 and 114.14 kg $ha^{-1}$, respectively. Yamashita *et al*. (2008) found that the total stock for entire soil profile (0-30 cm) were 248.7 kg $ha^{-1}$ for Ex.-Ca and 110.9 kg $ha^{-1}$ for Ex. Mg in Acacia plantation, and were 755.9 kg $ha^{-1}$ for Ex.-Ca and 199.6 kg $ha^{-1}$ for Ex. Mg in Imperata grasslands. Anyway, no significant differences among vegetation type were found for C, N, P, K and P at 0-30 cm depth. The stocks of Ca and Mg in the soil were higher in grass land (grass land) than other plantation plots (except *A. crassicarpa* plot). This result may be related to the different plant biomass. The differences of soil Ca and Mg among the vegetation types resulted from the translocation from soils into tree biomass. In case of *A. crassicarpa* plot, Ca and Mg were clearly higher than other species. That was probably due to amount of litterfall with impact on soil nutrients characteristics. Lugo *et al*. (1990) suggested that amounts of nutrient return to the forest floor had a measurable impact on soil nutrient characteristics, especially in the surface soil. Therefore, *A. crassicarpa* plot was higher amount of litterfall than other plots that would be the cause of larger volume of nutrient in soil. The last element, Na content revealed no significant difference via plots.

**Table 26** Total soil nutrient content through 50 cm depth (kg $ha^{-1}$).

| Species | nutrient content (kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | Na |
| *A. crassicarpa* | 5,986.04 | 55.93 | 167.03 $^{bc}$ | 1,128.06 $^{b}$ | 172.67 $^{a}$ | 44.92 |
| *A. indica* | 5,276.95 | 52.42 | 204.53 $^{b}$ | 623.24$^{cd}$ | 137.28 $^{b}$ | 38.99 |
| *P. macrocarpus* | 5,299.82 | 47.42 | 210.33 $^{b}$ | 382.63$^{d}$ | 130.71 $^{b}$ | 49.53 |
| *S. roxburghii* | 6,195.90 | 26.04 | 160.68 $^{bc}$ | 767.09$^{c}$ | 114.13 $^{b}$ | 43.80 |
| *T. grandis* | 5,962.29 | 35.54 | 160.98 $^{bc}$ | 567.16$^{cd}$ | 117.25 $^{b}$ | 50.40 |
| *X. xylocarpa* | 5,512.72 | 32.60 | 146.98 $^{c}$ | 461.22 $^{cd}$ | 133.04 $^{b}$ | 39.25 |
| Abandoned crop field | 5,307.52 | 54.58 | 504.66$^{a}$ | 1,782.21 $^{a}$ | 143.55 $^{b}$ | 42.58 |
| f-value | 0.40 | 0.69 | 50.73 | 21.06 | 4.04 | 1.29 |
| significant | $^{ns}$ | $^{ns}$ | ** | ** | ** | $^{ns}$ |

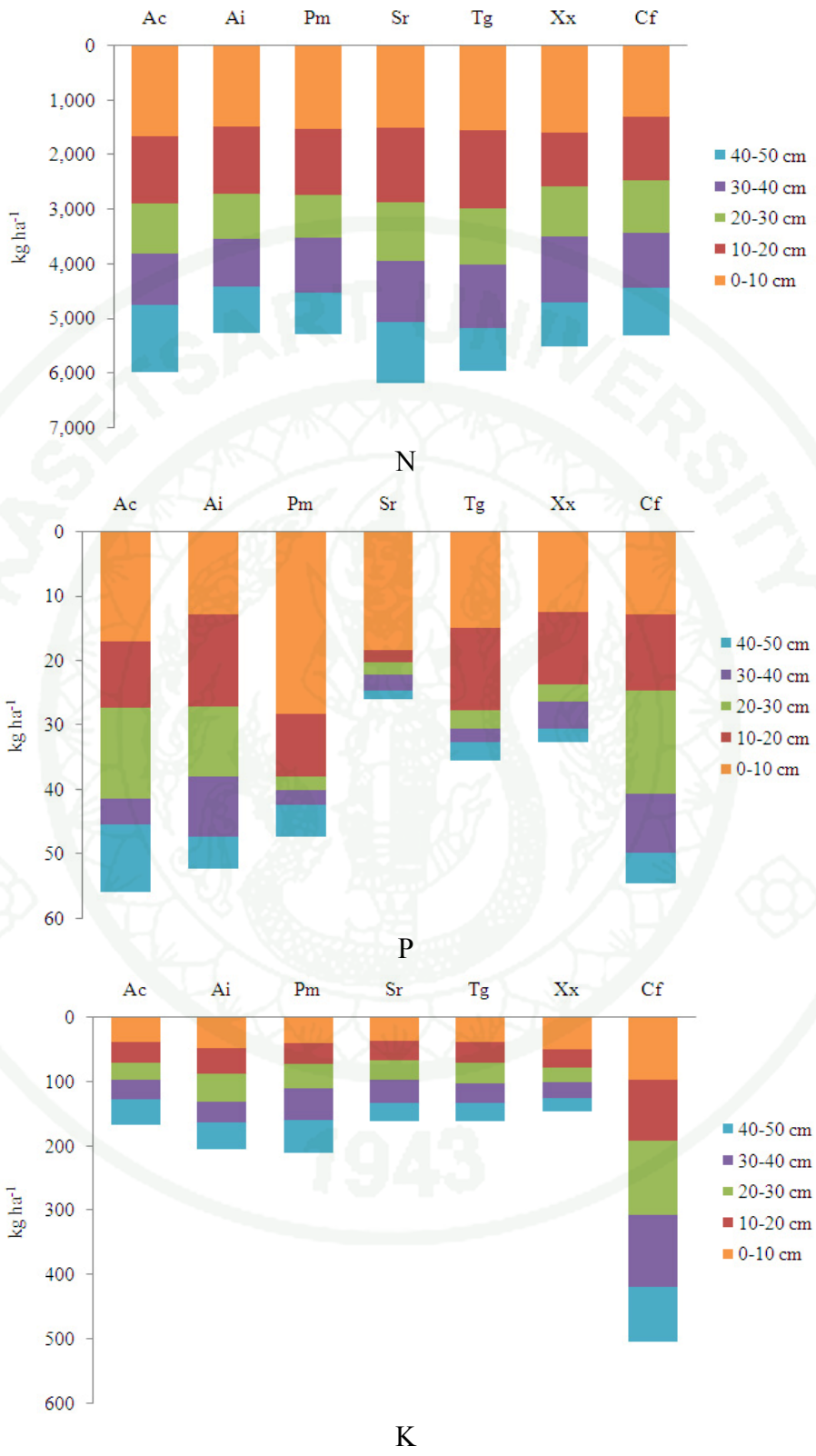



**Figure 27** Total soil nutrient content through 50 cm depth (kg $ha^{-1}$).

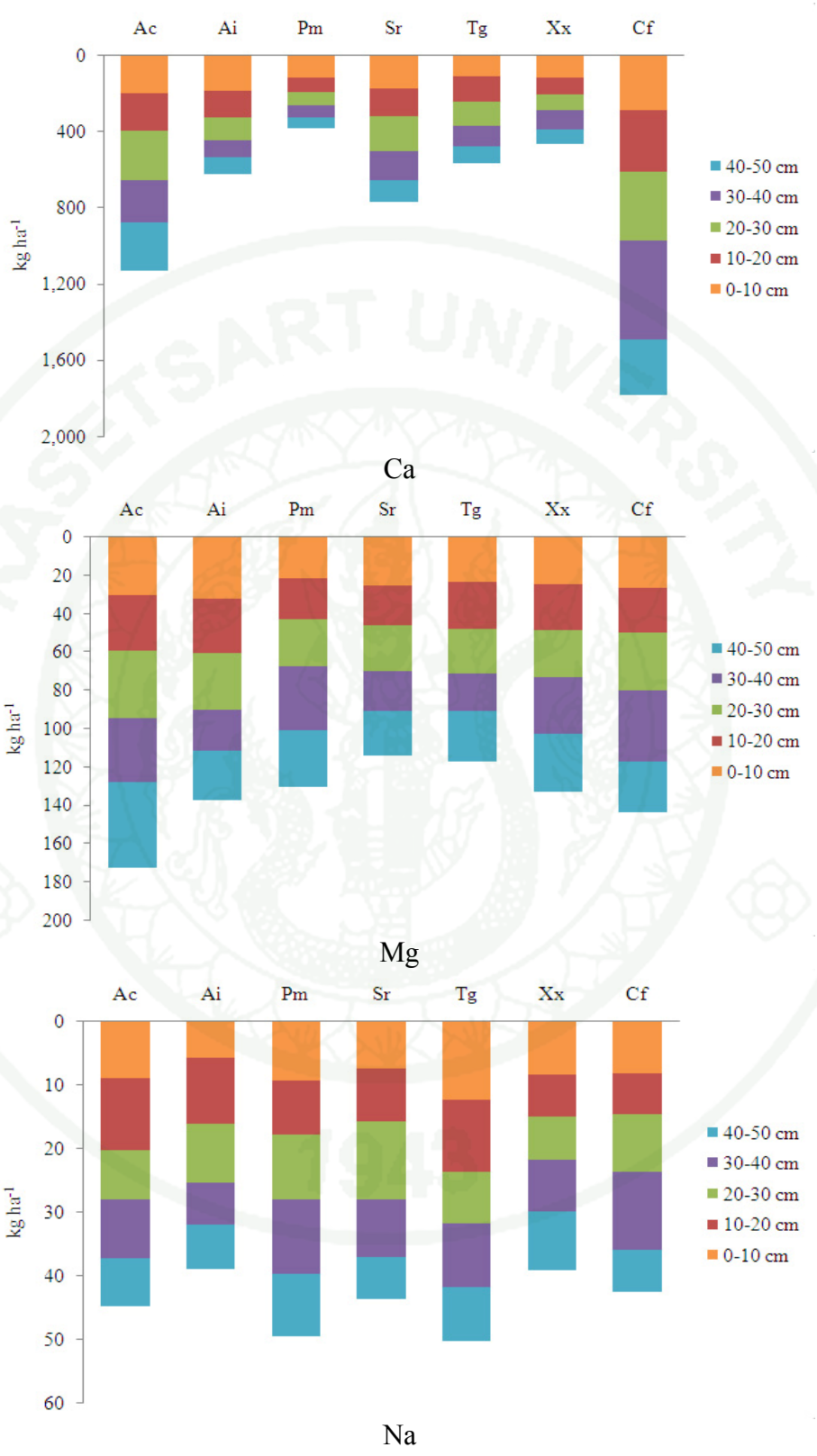



**Figure 27** (Continued)

**11. Plant nutrient pool in different tree parts of each species**

Plant nutrient pools were greatly varied with species (Table 27 and Figure 28). Differences of tree biomass and nutrient concentration were resulted in different nutrient pools. Total N pools ranged between 516.59 kg $ha^{-1}$ of Sr plot and 2,092.22 kg $ha^{-1}$ of *A. indica* plot. Even through *A. crassicarpa* (1,788.91 ton $ha^{-1}$) was the greatest of total biomass species (272.71 ton $ha^{-1}$), N pool in this plot was lower than *A. indica* plot (2,092.22 kg $ha^{-1}$). *P. macrocarpus* and *S. roxburghii* plots represented the resemble results of total N pools; 561.17 and 516.59 kg $ha^{-1}$, respectively. Furthermore, native tree species, *T. grandis* and *X. xylocarpa* plots also represented the resemble results with 849.76 and 882.55 kg $ha^{-1}$, respectively. Leaf part contain smallest amount of N pool. In spite of leaf was the smallest biomass representative part. The N pool of leaf part was ranged from 39.97 and 298.99 kg $ha^{-1}$ with obtained from *P. macrocarpus* and *A. crassicarpa* plots, respectively. The N pool of branch part in *X. xylocarpa* plot was 153.87 kg $ha^{-1}$, even the branch biomass of this species contain only 15.28 ton $ha^{-1}$. This result must be explained by the different N concentration in branch of *X. xylocarpa* which higher than other species. Stem part was the greatest pool of all elements, even N. The result of N pools in stem part was ranged from 182.88 to 1,030.48 kg $ha^{-1}$, in *S. roxburghii* and *A. indica* plot, respectively. For below-ground N pool, all species plots represented the higher results in fine root compared to coarse root. These different results were due to higher fine root biomass of all species. Even *A. indica* plot which was slightly higher biomass of coarse root than fine root (25.01 and 24.92 ton $ha^{-1}$). Nevertheless, the result of below-ground N pools was higher in fine root compared to coarse root (398.47 vs. 304.12 kg $ha^{-1}$). This greater result due to higher N concentration in fine root (1.62 %) compared to coarse root part (1.22 %).

P pools were varied from species to species. Total pool of P was greatest in *A. indica* plot with 409.06 kg $ha^{-1}$. While, the lowest result was 62.57 kg $ha^{-1}$ in *X. xylocarpa* plot. P pool represented the greatest results in stem part, according to the largest value of stem biomass. P pools in stem part of. *A. crassicarpa* and *A. indica* plots represented the greater results than other species. In addition, there were the resemble results of the two species with 210.69 and 217.69 kg $ha^{-1}$, respectively. Leaf P pools of all species represented similarly results (11.86-21.80 kg $ha^{-1}$), except in *P. macrocarpus* plot (3.97 kg $ha^{-1}$). P pools of below-ground parts were greatly varied from 8.53 to 126.01 kg $ha^{-1}$, of *X. xylocarpa* and *A. indica* plot, respectively. For *A. crassicarpa* plot, below-ground P pool was only 19.65 kg $ha^{-1}$. The paltry result of this species were due to small root biomass (18.54 ton $ha^{-1}$), and minimum of P concentration (0.02%). Total above- and below-ground P pools in *P. macrocarpus* plot represented the resemble proportion results with 25.99 and 30.22 kg $ha^{-1}$. Meanwhile, another plots represented greater difference of P pools between above- and below ground parts. The total K pools were ranged from 433.27 to 1,937.38 kg $ha^{-1}$, which mostly distributed to above-ground part (i.e. leaf, branch and stem). Similarly results of N and P pools, K pool represented the greatest result for *A. indica* plot, followed by *A. crassicarpa*, *X. xylocarpa*, *T. grandis*, *P. macrocarpus* and *S. roxburghii* plots, respectively. The higher result in *A. indica* plot was due to high

concentration of K, especially in leaf and fine root parts. Leaf of *A. crassicarpa* represented the greatest result of K pool with 151.72 kg ha$^{-1}$. While, *A. indica*, *T. grandis* and *X. xylocarpa* represented the similar results and ranged between 66.47 and 78.32 kg ha$^{-1}$. Branch and stem parts represented the largest pools of K. Stem part of *A. indica* plot was 1,115.49 kg ha$^{-1}$and branch part was 219.18 kg ha$^{-1}$. Below ground K pools still represented the greater results in *A. indica* plot than others. The results of below-ground K pools were greatest in *A. indica* plot followed by *T. grandis*, *P. macrocarpus*, *S. roxburghii*, *A. crassicarpa* and *X. xylocarpa* plots with 524.39, 258.91, 161.01, 126.92, 87.74 and 73.77 kg ha$^{-1}$, respectively. Most of below-ground K pool was distributed in fine root part.

All plots represented the large pools of Ca. The quantities of Ca pools were roughly equal to N pools for each tree species. In *A. indica* plot, the largest of Ca pool was found (2,340.79 kg ha$^{-1}$). Ca pools of Ca plot consisted of 139.96, 268.91, 1,136.10, 555.47 and 240.35 kg ha$^{-1}$ for leaf, branch, stem, fine- and coarse root parts, respectively. A plenty volume of Ca pool also found in *A. crassicarpa* and *T. grandis* plots with 1,326.31 and 1,171.74 kg ha$^{-1}$, respectively. Most Ca pools in plant part were distributed to stem and fine root. Whereas, leaf and coarse root represented very small proportion when compare to others, e.g. 828.97 kg ha$^{-1}$of Ca pool in *X. xylocarpa* plot was distributed to leaf and coarse root only 59.51 and 24.01 kg ha$^{-1}$, respectively. Meanwhile, Ca pools of branch, stem and fine root were 282.99, 408.60 and 53.87 kg ha$^{-1}$, respectively. These results would be explained by the large proportion of branch, stem and coarse root biomass compared to the other parts. In addition, many published revealed that the woody parts usually contain more Ca concentration than the soft tissue e.g. leaf. The smallest pools of Ca represented in *P. macrocarpus* plot (433.27 kg ha$^{-1}$) and *S. roxburghii* plot (644.48 kg ha$^{-1}$), which result from the small biomass volume and low intensity of tissue in tree parts. *X. xylocarpa* plot represented the distinctive differences of Ca pool between above- and below-ground parts (751.09 vs. 77.87 kg ha$^{-1}$, respectively). Differently, it might be due to the above ground biomass was nearly ten times of below ground biomass (114.22 vs. 9.40 ton ha$^{-1}$, respectively).

Mg pools represented the greatest result in *A. indica* plot (472.55 kg ha$^{-1}$) that consisted of 40.90, 76.49, 197.50, 114.38 and 46.27 kg ha$^{-1}$ for leaf, branch, stem, fine- and coarse root, respectively. The greater next amount of total Mg pools were in *T. grandis*, *X. xylocarpa*, *A. crassicarpa*, *S. roxburghii* and *P. macrocarpus* with values of 172.84, 167.39, 164.25, 123.80 and 103.70 kg ha$^{-1}$, respectively. Mg pool in leaf part of *A. crassicarpa* plot represented the larger amount than other parts with in species; even the biomass of leaf was obviously smaller than those due to the concentration of leaf part of *A. crassicarpa* was higher than that of other parts (0.33 % vs. 0.02-0.26%). In addition, leaf part of other species also played an important role to amount of Mg pools. For Na pools, all species plots were showed the paltry amount of total Na pools. Moreover, when compared to other elements, Na pools were showed the smallest in volume. The total Na pools of tree biomass from this studied was ranged from 23.60 kg ha$^{-1}$ in *P. macrocarpus* plot to 106.73 kg ha$^{-1}$ in *A. crassicarpa* plot.

Due to biomass of all species were orderly distributed into stem, branch, leaf, fine root and coarse root. In addition, nutrient concentrations between species were nearly the same. Hence, the results of present study revealed that most nutrients accumulation was largest in stem and followed by branch, leave, fine root and coarse root, respectively, which were consistent with studies of Sahunalu *et al*. (1984); Chinsukjaiprasert (1994) and Glumphabutr (2004). Qin *et al*. (2007) advocated that the total storage of nutrient element in *A. crassicarpa* plantation increased with the biomass accumulation in the processes of the stand growth. The distribution of nutrient accumulations varied with the different stand growth stages. In young stand, most nutrient elements accumulated in leaves and branches. Thereafter, in the older stand, they gradually moved to branches and roots. Furthermore, *A. crassicarpa* produced mostly biomass at low nutrient costs that was presumably due to higher nutrient use efficiency than other *Acacia* spp. Nutrient pool in *A. crassicarpa* and *A. indica* were similar to the results from the study of Chinsukjaiprasert (1994) and Glumphabutr (2004). However, the current results were higher than results that reported by Punsatha (2002) for *A. indica* plantation; Suksawang (1988) for dry evergreen forest and Sahunalu *et al*. (1984) for dry dipterocarp forest. Because of the higher total biomass in plantation plot and probably due to the higher soil nutrient pool in forest plantation compared to the soil nutrient pool of the dry dipterocarp forest (Junmahasatien *et al*., 2004). Therefore, deciduous tree species plots i.e. *P. macrocarpus*, *S. roxburghii* and *X. xylocarpa*, nutrient pools were higher than nutrient pool of these species in dry dipterocarp forest at Sakaerat, Nakhon Ratchasima province, North Eastern of Thailand (Nualngam, 2004).

**Table 27** Nutrient pool in different tree parts of each species plantation.

| Species | Tree component | Nutrient pools (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| *A. crassicarpa* | Leaf | 298.99 | 21.80 | 151.72 | 119.17 | 47.61 | 11.47 |
| | Branch | 264.11 | 35.97 | 158.62 | 301.14 | 35.70 | 14.49 |
| | Stem | 977.06 | 210.69 | 504.74 | 703.85 | 55.57 | 64.83 |
| | Fine root | 230.19 | 19.04 | 82.82 | 195.05 | 24.77 | 15.17 |
| | Coarse root | 18.57 | 0.61 | 4.93 | 7.10 | 0.61 | 0.77 |
| | **Total above ground pool** | 1,540.15 | 268.45 | 815.08 | 1,124.16 | 138.87 | 90.79 |
| | **Total below ground pool** | 248.76 | 19.65 | 87.74 | 202.15 | 25.38 | 15.94 |
| | **Total pool** | 1,788.91 | 288.11 | 902.82 | 1,326.31 | 164.25 | 106.73 |
| *A. indica* | Leaf | 147.86 | 19.06 | 78.32 | 139.96 | 40.90 | 1.39 |
| | Branch | 211.29 | 46.31 | 219.18 | 268.91 | 76.49 | 6.17 |
| | Stem | 1,030.48 | 217.69 | 1,115.49 | 1,136.10 | 194.50 | 39.93 |
| | Fine root | 398.47 | 79.94 | 297.30 | 555.47 | 114.38 | 9.97 |
| | Coarse root | 304.12 | 46.27 | 227.09 | 240.35 | 46.27 | 5.00 |
| | **Total above ground pool** | 1,389.63 | 283.05 | 1,412.99 | 1,544.98 | 311.89 | 47.50 |
| | **Total below ground pool** | 702.59 | 126.01 | 524.39 | 795.81 | 160.65 | 14.97 |
| | **Total pool** | 2,092.22 | 409.06 | 1,937.38 | 2,340.79 | 472.55 | 62.47 |

**Table 27** (Continued)

| Species | Tree component | Nutrient pools (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| *P. macrocarpus* | Leaf | 39.97 | 3.79 | 18.15 | 22.66 | 9.36 | 0.33 |
| | Branch | 71.88 | 7.22 | 76.40 | 76.40 | 16.99 | 1.82 |
| | Stem | 198.76 | 24.98 | 258.72 | 148.79 | 34.14 | 6.11 |
| | Fine root | 173.57 | 22.24 | 110.38 | 135.96 | 32.36 | 11.57 |
| | Coarse root | 76.99 | 7.98 | 50.64 | 49.46 | 10.85 | 3.77 |
| | **Total above ground pool** | 310.61 | 35.99 | 353.28 | 247.86 | 60.49 | 8.26 |
| | **Total below ground pool** | 250.56 | 30.22 | 161.01 | 185.42 | 43.21 | 15.34 |
| | **Total pool** | 561.17 | 66.21 | 514.29 | 433.27 | 103.70 | 23.60 |
| *S. roxburghii* | Leaf | 82.66 | 14.85 | 44.58 | 41.24 | 17.42 | 1.34 |
| | Branch | 81.62 | 17.38 | 81.20 | 104.30 | 24.27 | 2.97 |
| | Stem | 182.88 | 30.84 | 170.89 | 155.04 | 29.98 | 11.99 |
| | Fine root | 161.91 | 32.28 | 123.01 | 335.89 | 51.48 | 13.59 |
| | Coarse root | 7.51 | 0.77 | 3.92 | 8.00 | 0.64 | 0.66 |
| | **above ground pool** | 347.16 | 63.07 | 296.66 | 300.59 | 71.68 | 16.30 |
| | **below ground pool** | 169.43 | 33.05 | 126.92 | 343.90 | 52.12 | 14.26 |
| | **Total pool** | 516.59 | 96.12 | 423.59 | 644.48 | 123.80 | 30.56 |

**Table 27** (Continued)

| Species | Tree component | Nutrient pools (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| *T. gradis* | Leaf | 110.57 | 18.38 | 66.47 | 66.20 | 29.82 | 1.31 |
| | Branch | 81.74 | 9.05 | 108.56 | 153.69 | 17.66 | 2.91 |
| | Stem | 328.06 | 49.17 | 427.17 | 607.73 | 60.70 | 14.60 |
| | Fine root | 194.48 | 27.18 | 175.52 | 257.24 | 50.00 | 13.26 |
| | Coarse root | 134.90 | 9.95 | 83.39 | 86.89 | 14.66 | 3.63 |
| | **Total above ground pool** | 520.37 | 76.59 | 602.20 | 827.62 | 108.18 | 18.82 |
| | **Total below ground pool** | 329.38 | 37.14 | 258.91 | 344.12 | 64.66 | 16.89 |
| | **Total pool** | 849.76 | 113.73 | 861.11 | 1,171.74 | 172.84 | 35.71 |
| *X. xylocarpa* | Leaf | 142.58 | 11.86 | 66.80 | 59.51 | 18.77 | 1.52 |
| | Branch | 153.87 | 10.39 | 122.85 | 282.99 | 29.03 | 4.58 |
| | Stem | 474.98 | 31.79 | 609.62 | 408.60 | 97.24 | 29.92 |
| | Fine root | 80.36 | 6.53 | 51.32 | 53.87 | 15.99 | 3.67 |
| | Coarse root | 30.75 | 2.00 | 22.45 | 24.01 | 6.36 | 1.02 |
| | **Total above ground pool** | 771.43 | 54.04 | 799.27 | 751.09 | 145.04 | 36.03 |
| | **Total below ground pool** | 111.11 | 8.53 | 73.77 | 77.87 | 22.35 | 4.69 |
| | **Total pool** | 882.55 | 62.57 | 873.04 | 828.97 | 167.39 | 40.71 |

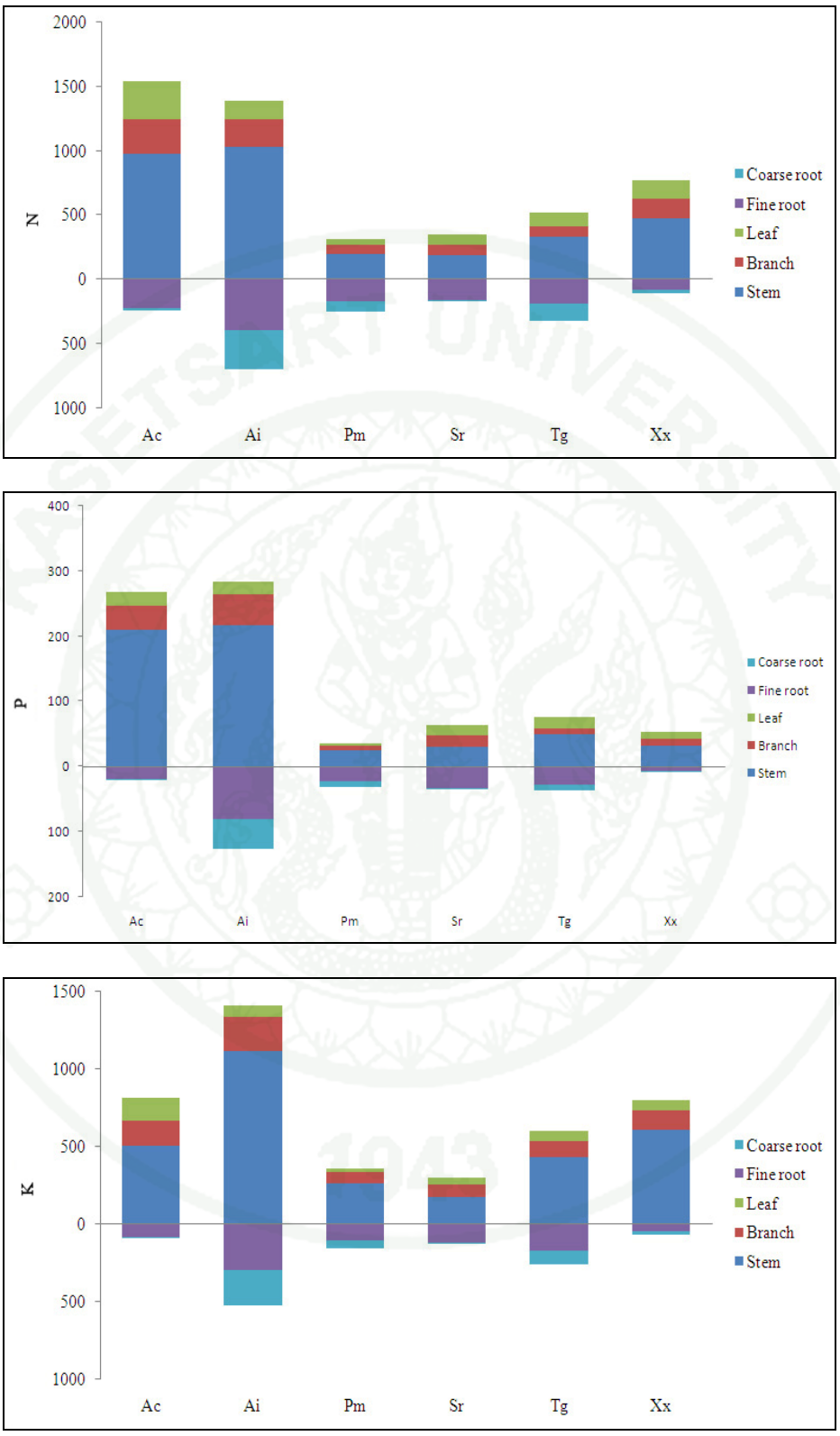



**Figure 28** Plant nutrient pool in different species plantation (kg $ha^{-1}$).

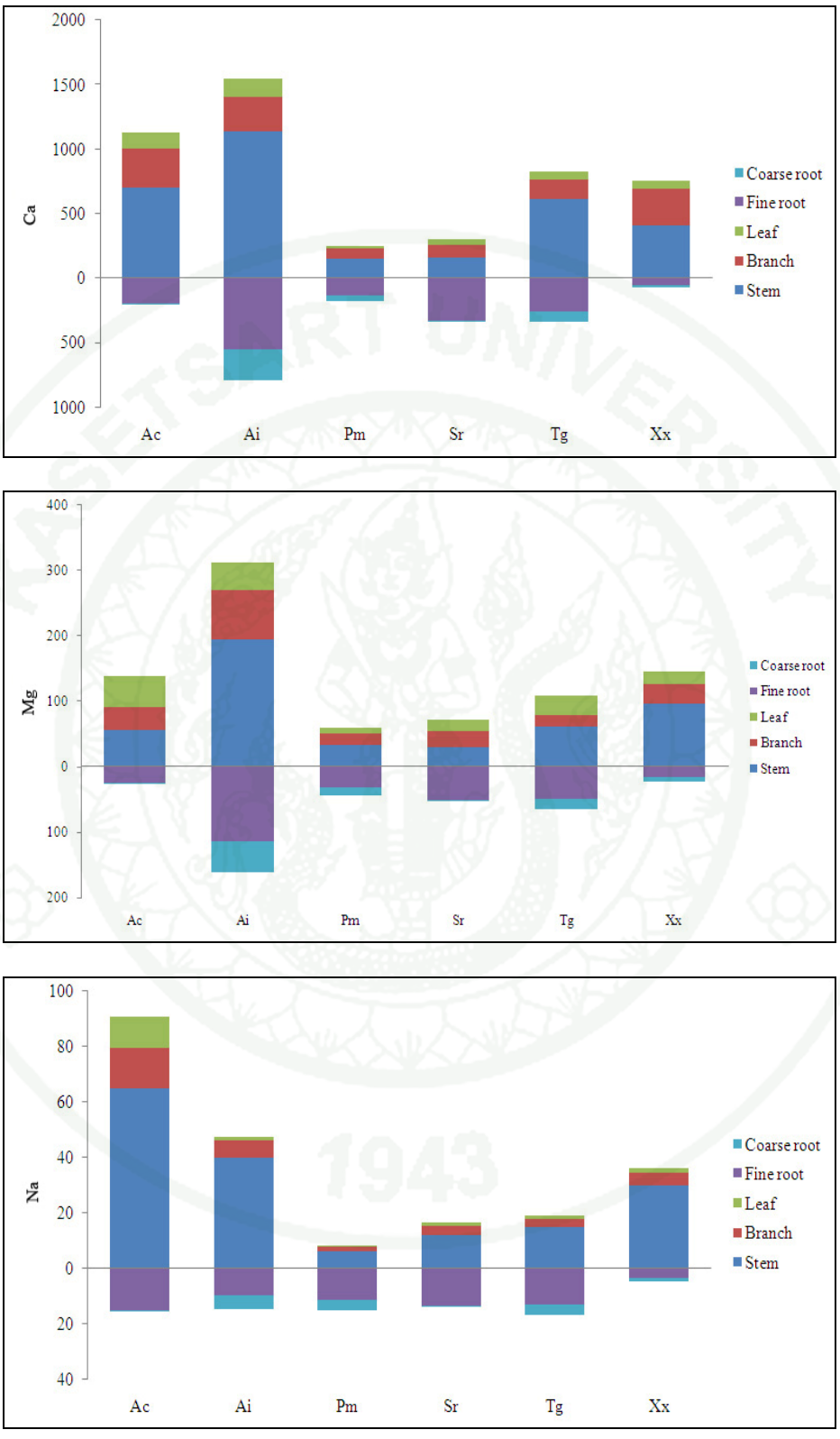



**Figure 28** (Continued)

## 12. Nutrient content in plant and soil system

The amounts of nutrient storage in plant and soil systems were shown in Table 28 and Figure 29. The results revealed that, *A. crassicarpa* plot expressed the higher nutrient retention than other plots while *P. macrocarpus* and *S. roxburghii* showed lowest nutrient retention. In *A. crassicarpa* plot, the contents of N, P, K, Ca, Mg and Na retained in total plant and soil systems were 7,799.86, 348.20, 1,074.71, 2,468.63, 341.667 and 152.41 kg $ha^{-1}$, respectively, and *A. indica* plot, the content of those were 7,374.83, 462.27, 2,143.73, 2,971.77, 611.56 and 101.57 kg $ha^{-1}$, respectively. In native tree plots, the content of those nutrients of *P. macrocarpus* plot were 5,863.85, 114.16, 725.82, 818.46, 235.14 and 73.18 kg $ha^{-1}$, respectively, while the contents of those nutrients in *S. roxburghii* were 6,715.74, 122.68, 584.71, 1,416.64, 239.09 and 74.50 kg $ha^{-1}$, respectively. Accumulation of N, P, K, Ca, Mg and Na in total plant and soil system of *T. grandis* were 6,813.04, 149.54, 1,022.42, 1,741.30, 290.60 and 86.14 kg $ha^{-1}$, respectively. The accumulation of those nutrients in *X. xylocarpa* plot, results was 6,402.88, 96.27, 1,022.64, 1,297.36, 302.42 and 80.26 kg $ha^{-1}$, respectively. The accumulation of total nutrient in abandoned crop field occurred only in soil system due to vegetation was cleared by fire every year. The results showed that N, P, K, Ca, Mg and Na that retained in soil system were 5,307.52, 54.58, 504.66, 1,782.21, 143.55 and 42.58 kg $ha^{-1}$, respectively. The total nutrient accumulation in plant and soil systems and percentage were shown in Table 28 and Figure 29. The results showed that N and Na mostly accumulated in soil systems of every plot. In contrast, other elements including P, K, Ca and Mg were mostly distributed to plant systems. Anyhow, in *P. macrocarpus* and *S. roxburghii* the proportion of Ca, Mg and Na seemed to be equal.

From data that mentioned in Table 29 and Figure 30, total nutrient accumulations in total system were greatly varied between plot to plot. Total accumulations of N, P, Mg and Na in soil system seemed to be similar. In addition, the resemble results of nutrient content in total soil system between plantation and control plots were found. Therefore, the differences of N, P, Mg and Na accumulations in total system were depended upon tree mass. On contrast, clearly different results of K and Ca accumulations in soil systems between plantation and abandoned crop field control plots were found. Control plot showed higher results of these elements in soil system. Data in Table 28 revealed that, in soil system, K storage in control plot was 504.66 kg $ha^{-1}$. That result was higher than the results from plantation plots, which were ranged from 149.60 kg $ha^{-1}$ in *X. xylocarpa* plot to 211.53 kg $ha^{-1}$ in *P. macrocarpus* plot. Total system of K accumulation in control plot seemed to be equal to the result from small tree mass plots i.e. *P. macrocarpus* and *S. roxburghii* (504.66 vs. 725.82 and 584.71 kg $ha^{-1}$, respectively). Ca in control plot also expressed the equal or excess storage of whole system comparing to other native tree plots. In addition, if only soil system was taken into account, Ca storage in control plot was showed the excess results when compared to others. Change of K and Ca amount in soil system after established the forest plantation that might be the results from nutrient translocation.

**Table 28** Nutrient storage in plant and soil systems.

| Species | sources | Nutrient accumulation (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Ac | plant | 1,788.91 | 288.11 | 902.82 | 1,326.31 | 164.25 | 106.73 |
| | % | 22.94 | 82.74 | 84.01 | 53.73 | 48.07 | 70.03 |
| | soil | 6,010.95 | 60.09 | 171.89 | 1,142.32 | 177.42 | 45.68 |
| | % | 77.06 | 17.26 | 15.99 | 46.27 | 51.93 | 29.97 |
| | total | 7,799.86 | 348.20 | 1,074.71 | 2,468.63 | 341.67 | 152.41 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |
| Ai | plant | 2,092.22 | 409.06 | 1,937.38 | 2,340.79 | 472.55 | 62.47 |
| | % | 28.37 | 88.49 | 90.37 | 78.77 | 77.27 | 61.50 |
| | soil | 5,282.61 | 53.21 | 206.35 | 630.98 | 139.01 | 39.10 |
| | % | 71.63 | 11.51 | 9.63 | 21.23 | 22.73 | 38.50 |
| | total | 7,374.83 | 462.27 | 2,143.73 | 2,971.77 | 611.56 | 101.57 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |
| Pm | plant | 561.17 | 66.21 | 514.29 | 433.27 | 103.7 | 23.6 |
| | % | 9.57 | 58.00 | 70.86 | 52.94 | 44.10 | 32.25 |
| | soil | 5,302.68 | 47.95 | 211.53 | 385.19 | 131.44 | 49.58 |
| | % | 90.43 | 42.00 | 29.14 | 47.06 | 55.90 | 67.75 |
| | total | 5,863.85 | 114.16 | 725.82 | 818.46 | 235.14 | 73.18 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |
| Sr | plant | 516.59 | 96.12 | 423.59 | 644.48 | 123.8 | 30.56 |
| | % | 7.69 | 78.35 | 72.44 | 45.56 | 51.78 | 41.02 |
| | soil | 6,199.15 | 26.56 | 161.12 | 770.16 | 115.29 | 43.94 |
| | % | 92.31 | 21.65 | 27.56 | 54.44 | 48.22 | 58.98 |
| | total | 6,715.74 | 122.68 | 584.71 | 1,414.64 | 239.09 | 74.50 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |

**Table 28** (Continued)

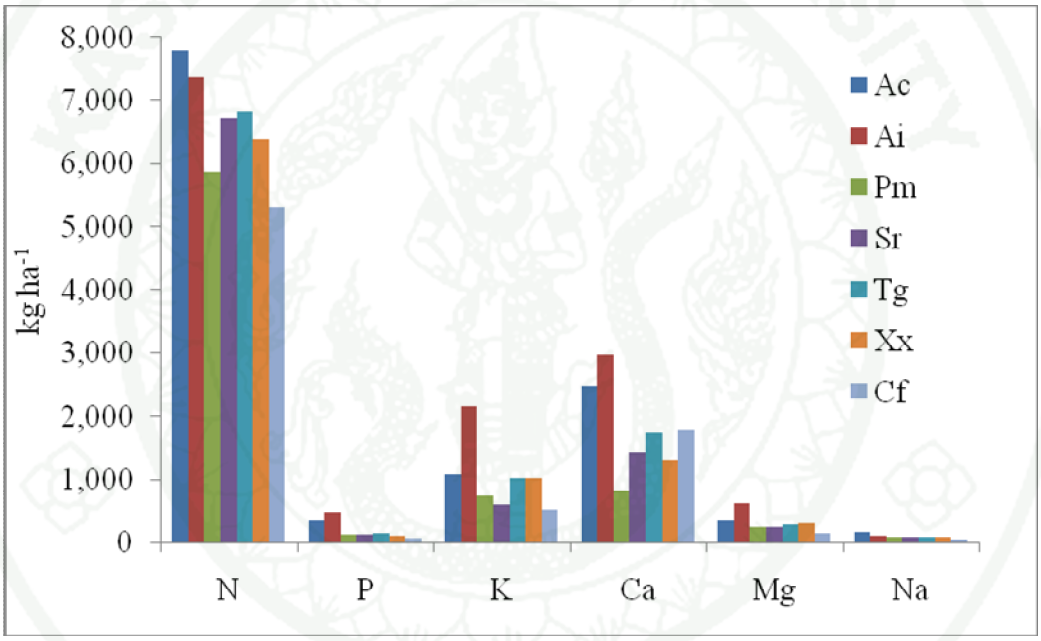
| Species | sources | Nutrient accumulation (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Tg | plant | 849.76 | 113.73 | 861.11 | 1,171.74 | 172.84 | 35.71 |
| | % | 12.47 | 76.05 | 84.22 | 67.29 | 59.48 | 41.46 |
| | soil | 5,963.28 | 35.808 | 161.311 | 569.558 | 117.763 | 50.43 |
| | % | 87.53 | 23.95 | 15.78 | 32.71 | 40.52 | 58.54 |
| | total | 6,813.04 | 149.54 | 1,022.42 | 1,741.30 | 290.60 | 86.14 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |
| Xx | plant | 882.55 | 62.57 | 873.04 | 828.97 | 167.39 | 40.71 |
| | % | 13.78 | 64.99 | 85.37 | 63.90 | 55.35 | 50.72 |
| | soil | 5,520.33 | 33.70 | 149.60 | 468.34 | 135.03 | 39.55 |
| | % | 86.22 | 35.01 | 14.63 | 36.10 | 44.65 | 49.28 |
| | total | 6,402.88 | 96.27 | 1,022.64 | 1,297.31 | 302.42 | 80.26 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |
| Cf | plant | 0 | 0 | 0 | 0 | 0 | 0 |
| | % | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | soil | 5,307.52 | 54.58 | 504.66 | 1,782.21 | 143.55 | 42.58 |
| | % | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| | total | 5,307.52 | 54.58 | 504.66 | 1,782.21 | 143.55 | 42.58 |
| | % | 100 | 100 | 100 | 100 | 100 | 100 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis*; Xx: *X. xylocarpa* and Cf : Abandoned crop field


**Figure 29** Percentage of nutrient accumulation in total plant and soil systems.

**Table 29** Total nutrient accumulation in plant and soil systems (kg $ha^{-1}$).

| Nutrients | Ac | Ai | Pm | Sr | Tg | Xx | Cf |
|---|---|---|---|---|---|---|---|
| N | 7,799.86 | 7,374.83 | 5,863.85 | 6,715.74 | 6,813.04 | 6,402.88 | 5,307.52 |
| P | 348.20 | 462.27 | 114.16 | 122.68 | 149.54 | 96.27 | 54.58 |
| K | 1,074.71 | 2,143.73 | 725.82 | 584.71 | 1,022.42 | 1,022.64 | 504.66 |
| Ca | 2,468.63 | 2,971.77 | 818.46 | 1,414.64 | 1,741.30 | 1,297.31 | 1,782.21 |
| Mg | 341.67 | 611.56 | 235.14 | 239.09 | 290.60 | 302.42 | 143.55 |
| Na | 152.41 | 101.57 | 73.18 | 74.50 | 86.14 | 80.26 | 42.58 |




**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis*; Xx: *X. xylocarpa* and Cf : Abandoned crop field

**Figure 30** Total nutrient accumulation in plant and soil systems (kg $ha^{-1}$).

## 13. Carbon concentration and pool in plant and soil systems

The results of plant and soil carbon concentration were shown in Table 30. The results showed that the average carbon concentration in tree component (leaf, branch, stem, fine- and coarse root) of each species were similar. For aboveground biomass, carbon concentration was similar trend and was in sequence of stem>leaf>branch. The belowground plant carbon concentration varied between fine and coarse roots. *A. indica*, *P. macrocarpus* and *X. xylocarpa* showed the greater carbon concentration in fine root. The average carbon concentration of ranged from 44.90 in leaf of *P. macrocarpus* to 51.90 % in leaf of *A. crassicarpa*.

The carbon concentration in mineral soil was studied from 0 to 50 cm depth in every treatments and control plot. The results showed that soil carbon content was highest at 0- 10 cm depth and declined with increasing soil depth. Regarding to the first soil horizon, *A. crassicarpa* showed the greatest value (1.44%), followed by *S. roxburghii* (1.24 %) and *P. macrocarpus* (1.13 %). The variation was probably due to the fact that *A. crassicarpa* had greatest amount of leaf and branch that later these component had fell as litter and decomposed on the forest floor. Consequently these litter affected the carbon concentration in mineral soil, especially in the surface soil (0 to 10 cm depth). Carbon pool of biomass and mineral soil were shown in Table 30 and Figure 31. The carbon pool of total biomass was highest in *A. crassicarpa* plot (177.20 ton $ha^{-1}$) followed by in *A. indica* plot (91.37 ton $ha^{-1}$) and *X. xylocarpa* (58.85 ton $ha^{-1}$). The total carbon pool in mineral soil layers was highest in *S. roxburghii* plot (62.64 ton $ha^{-1}$) followed by in *A. crassicarpa* plot (58.63 ton $ha^{-1}$) and in *A. indica* plot (44.49 ton $ha^{-1}$). In addition, the carbon content in surface soil was higher than sub-surface for every treatments. Carbon concentrations of aboveground biomass from this present studies were similar trend and being the sequences of stem>leaf>branch, as same as the study of Sakuntaluk (1999), Nualngam (2002) and Glumphabutr (2004). Bin *et al*. (2009) researched in 7-years-old *A. crassicarpa* plantation and found that carbon concentration of different organs orderly were leaf>branch>stem>root>bark. The result was similarly to the result from this present study. However, carbon concentrations in soil of the present study were lower than those in report of Sakurai *et al*. (1998) and Glumphabutr (2004), which were studied in natural evergreen forest in eastern and north-eastern part of Thailand. The results ranged from 2.48 to 4.16% and 2.42 to 3.63%, respectively. Therefore, the results compared with the report of Nualngam (2002) that studied in the forest plantation where established on the abandoned crop field originated from the dry evergreen forest, the carbon concentration of soil was the similar trend of the present study. He also reported the carbon concentration of soil at 0 to 5 cm depth ranged from 1.23 to 1.95% that was the same range of this study, 0.96 to 1.44%. These results indicated that the efficiency of aboveground carbon storage for all tree species largely depended on aboveground biomass because the concentration of carbon in the plant tissues between studied species were comparable between species which was consistent with the results of Nualngam (2002) and Glumphabutr (2004).

**Table 30** Carbon concentration (%) in plant and soil of different species plots (standard deviations in parentheses).

| Species | | Ac** | Ai ns | Pm* | Sr ns | Tg** | Xx* | Control plot |
|---|---|---|---|---|---|---|---|---|
| Tree part | Leaf | 51.49$^{a}$ (0.94) | 44.89 (0.82) | 44.86$^{c}$ (0.78) | 48.28 (0.37) | 45.43 $^{c}$ (0.13) | 48.44$^{a}$ (0.70) | na. |
| | Branch | 48.34$^{b}$ (0.34) | 44.96 (0.25) | 46.63$^{ab}$ (0.25) | 47.40 (0.10) | 46.78$^{b}$ (0.19) | 45.40$^{c}$ (0.25) | na. |
| | Stem | 48.01$^{b}$ (0.82) | 45.86 (1.53) | 47.41$^{a}$ (0.34) | 48.52 (0.83) | 47.20$^{a}$ (0.26) | 47.96$^{a}$ (0.17) | na. |
| | Fine root | 45.18$^{c}$ (0.93) | 44.38 (1.20) | 46.15$^{b}$ (0.94) | 46.36 (1.43) | 45.14$^{c}$ (1.19) | 47.65$^{ab}$ (0.77) | na. |
| | Coarse root | 47.83$^{b}$ (0.36) | 43.68 (1.10) | 45.11$^{bc}$ (1.09) | 47.59 (0.51) | 46.28$^{b}$ (0.47) | 46.44$^{bc}$ (1.79) | na. |
| Species | | Ac** | Ai** | Pm** | Sr ns | Tg** | Xx** | Control plot* |
| Soil depth (cm) | 0-10 | 1.44$^{a}$ (0.32) | 1.01 $^{a}$ (0.25) | 1.13$^{a}$ (0.22) | 1.24 (0.28) | 1.03$^{a}$ (0.08) | 0.96$^{a}$ (0.15) | 0.80$^{a}$ (0.13) |
| | 10-20 | 0.66$^{b}$ (0.14) | 0.67$^{b}$ (0.16) | 0.67$^{b}$ (0.04) | 0.93 (0.19) | 0.91$^{a}$ (0.15) | 0.64$^{b}$ (0.09) | 0.87$^{a}$ (0.26) |
| | 20-30 | 0.53$^{b}$ (0.09) | 0.49$^{bc}$ (0.15) | 0.49$^{bc}$ (0.06) | 0.73 (0.38) | 0.68$^{ab}$ (0.17) | 0.50$^{bc}$ (0.16) | 0.66$^{a}$ (0.18) |
| | 30-40 | 0.50$^{b}$ (0.08) | 0.43$^{bc}$ (0.01) | 0.39$^{c}$ (0.10) | 0.58 (0.15) | 0.60$^{b}$ (0.10) | 0.45$^{c}$ (0.24) | 0.46$^{b}$ (0.06) |
| | 40-50 | 0.66$^{b}$ (0.08) | 0.28$^{c}$ (0.14) | 0.30$^{c}$ (0.05) | 0.64 (0.38) | 0.19$^{c}$ (0.11) | 0.25 $^{d}$ (0.17) | 0.33$^{b}$ (0.12) |

**Remark**: Ac: *A. crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa* and na.: data not available

ANOVA results; ns: non significant; *: $p<0.05$; **: $p<0.01$. Similar letter denoted groups of significantly similar ($p < 0.05$)

**Table 31** Carbon pool (ton $ha^{-1}$) in plant and soil of different species plots.

| species | | Ac | Ai | Pm | Sr | Tg | Xx | Control plot |
|---|---|---|---|---|---|---|---|---|
| Tree part | Leaf | 7.38$^{c}$ (0.78) | 2.61 (0.65) | 0.60$^{c}$ (0.31) | 1.75 (0.65) | 2.38$^{c}$ (0.71) | 2.63$^{c}$ (0.37) | na. |
| | Branch | 25.49$^{b}$ (1.85) | 7.71 (2.39) | 3.40$^{b}$ (1.69) | 5.02 (2.33) | 5.04$^{bc}$ (1.88) | 6.94$^{b}$ (1.05) | na. |
| | Stem | 135.87$^{a}$(17.33) | 59.07 (18.67) | 13.16$^{a}$ (6.48) | 20.78 (9.83) | 36.26$^{a}$ (12.29) | 44.84$^{a}$ (6.85) | na. |
| | Fine root | 6.99$^{c}$ (0.59) | 11.06 (1.66) | 4.17$^{b}$ (1.30) | 7.88 (2.07) | 7.58$^{b}$ (0.94) | 2.96$^{c}$(0.20) | na. |
| | Coarse root | 1.46$^{d}$ (0.08) | 10.92 (0.86) | 2.54$^{bc}$ (0.54) | 0.51 (0.22) | 6.22$^{b}$ (1.70) | 1.48$^{d}$ (0.19) | na. |
| | significant | ** | ns | * | ns | ** | * | na. |
| | total | 177.20 | 91.37 | 23.86 | 35.94 | 57.49 | 58.85 | na. |
| Soil depth (cm) | 0-10 | 22.18$^{a}$ (4.92) | 16.12$^{a}$ (4.12) | 18.19$^{a}$ (4.92) | 18.56 (4.34) | 17.81$^{a}$ (1.43) | 16.51$^{a}$ (2.83) | 12.94$^{a}$ (3.14) |
| | 10-20 | 10.51$^{b}$ (2.18) | 10.08$^{b}$ (2.28) | 10.11$^{ab}$ (2.44) | 14.06 (3.35) | 14.48$^{ab}$ (3.23) | 11.09$^{ab}$(2.08) | 13.28$^{a}$ (3.30) |
| | 20-30 | 8.03$^{bc}$ (0.97) | 7.32$^{bc}$ (1.85) | 7.44$^{bc}$ (1.64) | 10.90 (5.81) | 11.26$^{bc}$ (3.14) | 7.75$^{b}$ (2.18) | 10.65$^{ab}$(3.24) |
| | 30-40 | 7.28$^{c}$ (0.93) | 6.18$^{c}$ (0.35) | 6.40$^{cd}$ (1.78) | 9.10 (2.50) | 9.93$^{c}$ (2.15) | 9.60$^{ab}$(7.92) | 7.58$^{b}$ (1.23) |
| | 40-50 | 10.63$^{b}$ (1.58) | 4.78$^{d}$ (2.43) | 4.64$^{d}$ (0.90) | 10.02 (5.75) | 3.30$^{d}$ (2.59) | 4.06$^{c}$ (2.59) | 5.42$^{b}$ (1.68) |
| | significant | ** | ** | ** | ns | ** | * | * |
| | total | 58.63 | 44.49 | 46.78 | 62.64 | 56.77 | 49.00 | 49.87 |

**Remark**: Ac: *A. crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa* and na.: data not available

ANOVA results; $^{ns}$: non significant; *: $p<0.05$; **: $p<0.01$. Similar letter denoted groups of significantly similar ($p < 0.05$)

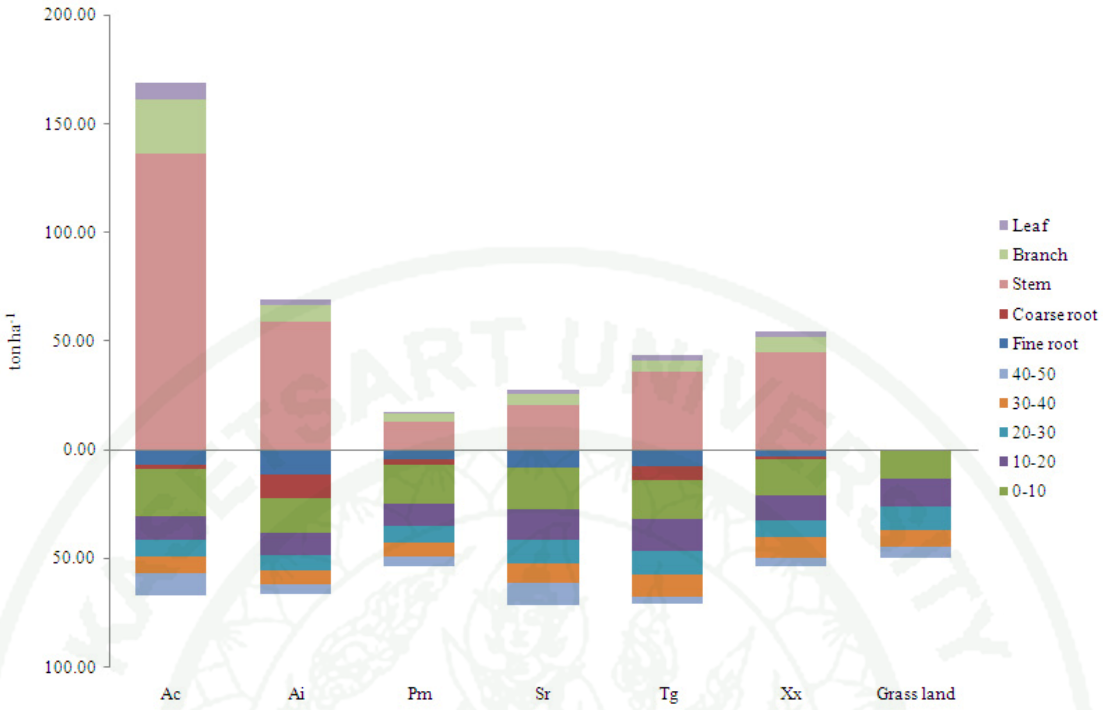



**Figure 31** Carbon pool (ton $ha^{-1}$) in plant and soil up to 50 cm depth of different species plots.

The largest new carbon store, after the establishment of the plantation is the trees themselves. Larger amount of plant carbon was located in aboveground part. In addition, most carbon was also stored in the soil. For some species, such as *P. macrocarpus* and *S. roxburghii*, carbon was stored in the soil more than in the stand biomass. The aboveground mean carbon storage of each tree species in this present study was lower than 100 ton $ha^{-1}$ except for *A. crassicarpa* was more than 177 ton $ha^{-1}$. Carbon storage for native species in current study was lowers than 20-years-old teak (*T. grandis*) planted in Panama, of which 120 ton $ha^{-1}$ was stored (Kraenzel *et al.*, 2003). By contrast, the result of this study compared to the results of Petsri (2004) who's reported that aboveground carbon pool of 6 to 24-years-old teak plantation ranged from 29.76 to 37.58 ton $ha^{-1}$. Nualngam (2002) found that *A. mangium* plantation stored the highest aboveground carbon content (94.45 ton $ha^{-1}$), followed by *A. auriculaeformis* plantation (56.74 ton $ha^{-1}$), *Eucalyptus camaldulensis* plantation (55.66 ton $ha^{-1}$), *X. xylocarpa* plantation (41.89 ton $ha^{-1}$), *Dalbergia cochinchinensis* plantation (38.46 ton $ha^{-1}$) and *P. macrocarpus* plantation (24.72 ton $ha^{-1}$). His result appeared lower for *Acacia spp.*, and *X. xylocarpa* but more or less the same for *P. macrocarpus,* which compared to the results of this study. This is probably due to the individual differences of growth rate, spacing, stand density or topography of the study sites.

It is necessary to compare the aboveground carbon content estimated in the plantation of this study with the carbon content in the natural forest stand. The aboveground carbon contents in the eastern Thailand for moist evergreen forest, dry evergreen forest and hill evergreen forest were 215.2, 170.1 and 51.9 ton $ha^{-1}$, respectively (Glumphabutr, 2004). Petsri (2004) reported that the aboveground carbon content of mixed deciduous forest was 60.06 ton $ha^{-1}$. Comparingly, the results of this present study, aboveground carbon content in the plantation was lower than the natural evergreen forest, but it was greater than that of dry land natural forest. Evergreen forest structure composed of many tree layers that contained many life forms, in the other hand forest plantation contained only one species. Therefore, carbon stored in the aboveground biomass between natural evergreen forest and plantation was different.

For soil carbon pools in natural forest, Glumphabutr (2004) reported the carbon pools in the 100 cm depth soil ranged from 120.9 to 179.9 ton $ha^{-1}$. Kraenzel *et al*. (2004) reported the carbon content in soil to 100 cm depth was 225 ton $ha^{-1}$. Nualngam (2002) reported that soil carbon content (30 cm depth) in plantation ranged from 37.2 to 48.9 ton $ha^{-1}$. The soil carbon content in this study (to 50 cm depth), was lower than that in the natural forest and teak plantation in other region, but storage was similar to that of the forest plantation located in the north eastern of Thailand (Nualngam, 2002). The different results were probably due to the larger litterfall volume of natural evergreen forest. Litterfall was the source and supplying soil carbon store. Carbon could release from litter through litter decomposition process. Besides, the soil carbon pools were compared between unplanted control plot and plantation, the results were varied; *A. crassicarpa*, *S. roxburghii* and *T. grandis* expressed larger volume of carbon content. In the other hand, *A. indica*, *P. macrocarpus* and *X. xylocarpa* showed the slightly lower the volume of carbon content. Litter volume and decomposition rate of each tree species might be the reason of variations. Anthony *et al*. (2007) advocated that short rotation woodlot system after 5-years fallow period, soil carbon in tree fallows (0.8-1.3 %) were significantly higher than the continuous cropping treatment (0.06 %). The importance of soil carbon presumably resulted from litter accumulation and fine root turn over as reported by Rao *et al*. (1998) and Tien *et al*. (2001). In addition, the results in Table 31 indicated that soil carbon content was decreasing with increasing soil depth. In surface soil, especially at 0-10 cm depth, the result was distinctly different from the deeper soil layer. This result was probably due to effects of supplement of carbon releasing processes e.g. litter decomposition. A publication, e.g. Bin *et al*. (2009) revealed the decreasing trend of soil carbon via depth. He also found that total carbon storage in *A. crassicarpa* plantation was 141.05 ton $ha^{-1}$, with in over storey, under storey, litter floor and soil accounting for 33.30, 1.47, 3.18 and 65.23 %, respectively. The different result in the present study was the proportion of carbon stock between plant and soil systems. According to Bin *et al*. (2009) reported larger carbon stock distributed to soil system than plant (65.23 and 34.77 %, respectively). Whereas, the results in present study calculated to 24.78 and 75.12 % of total soil and plant systems, respectively. The adversary might be due to the differences of initial soil properties and stand biomass.

## 14. Nutrient dynamics

The major processes of nutrient dynamics or nutrient cycling in a forest plantation include nutrient uptake by root system; nutrient accumulation in various tree components; return of organic matter and nutrients to the soil by litterfall, foliar leaching, stem flow, root sloughing and mortality; and release of nutrients from organic matter by decomposition processes. The differences of tree species are indicated the approach of nutrient retention, nutrient uptake, nutrient release and nutrient utilization for tree growth (Cole, 1986). In nutrient cycling study, the necessary data used for analyzing the nutrient cycling processes are 1) the amounts of nutrient accumulate in biomass of plant and in soil system. 2) The amount of nutrient release from plant to soil per year (annual return). 3) Rate of annual nutrient uptake from soil by plants (Petmark, 1983). In present study, nutrient dynamics of each species plantation were determined by evaluating the nutrient fluxes in term of nutrient return, release, uptake, retain and turn over rate as the same method of Sahunalu *et a*l. (1984); Chinsukjaiprasert (1984); Suksawang (1988); Jutikidecha (1996); Punsatha (2002) and Glumphabutr (2004) that were investigated as follows:

### 14.1 Annual return of nutrients by plants.

In the present study, the annual returns of nutrients were derived from the content of nutrients that accumulated in litterfall. Table 32 showed the amount of nutrient that return to soil in the form of litterfall. The results showed that the annual return of nutrient in *A. crassicarpa* plots seemed to be highest due to largest volume of annual litter fall. There were 140.57, 9.95, 45.28, 87.20, 30.23 and 10.45 kg $ha^{-1}$ for N, P, K, Ca, Mg and Na, respectively. While those elements from *A. indica* plot were 57.66, 8.05, 20.25, 63.16, 13.63 and 0.76 kg $ha^{-1}$, respectively. Data from *P. macrocarpus* plot indicated that all elements except K and Ca seemed to be equivalent the results derived from *A. indica* plot, even smaller amount of annual litterfall. There were 44.99, 8.58, 14.53, 36.41, 10.12 and 0.47 kg $ha^{-1}$, for those elements respectively. The results of annual nutrients return in *S. roxburghii* and *T. grandis* plots were appeared on the same range of all elements. The annual nutrients return of *S. roxburghii* plot were 35.71, 12.38, 11.35, 38.91, 11.49 and 0.98 47 kg $ha^{-1}$, while the data from *T. grandis* plot were 27.58, 3.29, 11.16, 22.52, 8.50 and 0.46 47 kg $ha^{-1}$ for N, P, K, Ca, Mg and Na, respectively. *X. xylocarpa* showed the great value of N return, 73.70 kg $ha^{-1}$. While, P, K, Ca, Mg and Na were 20.32, 19.61, 52.32, 10.58 and 1.39 kg $ha^{-1}$, respectively. The major factor that played an important role to different results of nutrient annual return was the volume of litterfall. Data in Table 17 showed clearly that the results of litter fall volume from *A. crassicarpa* and *X. xylocarpa* plots which were higher than other plots. The second factor was the nutrient concentration of litter. *Leguminosae* spp. i.e. *A. crassicarpa* showed both high volume of litterfall and nutrient concentration in litterfall, especially N. Hence, this plot demonstrated the highest results of annual nutrient.

**Table 32** Annual return of nutrients in forest plantation.

| spp | Nutrient return (kg $ha^{-1}$ $yr^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | Na |
| Ac | 140.57 | 9.95 | 45.28 | 87.20 | 30.23 | 10.45 |
| Ai | 57.66 | 8.05 | 20.25 | 63.16 | 13.63 | 0.76 |
| Pm | 44.99 | 8.58 | 14.53 | 36.41 | 10.12 | 0.47 |
| Sr | 35.71 | 12.38 | 11.35 | 38.91 | 11.49 | 0.98 |
| Tg | 27.58 | 3.29 | 11.16 | 33.52 | 8.50 | 0.46 |
| Xx | 73.79 | 10.32 | 19.61 | 52.32 | 10.58 | 1.39 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

14.2 Annual release of nutrients to soil.

Nutrients releasing to soil were estimated from nutrient that released from decomposition of both litter fall and litter on soil surface. From annual period of study, the result revealed that *A. crassicarpa* plot expressed the greatest result of litter decomposition which was 11.56 ton $ha^{-1}$ $yr^{-1}$. While, annual litter decomposition of *A. indica*, *P. macrocarpus*, *S. roxburghii*, *T. grandis* and *X. xylocarpa* were 4.30, 2.76, 2.77, 2.35 and 4.62 ton $ha^{-1}$ $yr^{-1}$, respectively. Nutrient contents were released to soil in each plot were estimated from nutrient that released from decomposition of litter fall and litter on soil surface as shown in Table 33. The results found that, *A. crassicarpa* plot released 116.27, 10.63, 34.29, 70.93, 24.40 and 7.55 kg $ha^{-1}$ $yr^{-1}$ for N, P, K, Ca, Mg and Na, respectively. *A. indica* plot released 52.51, 7.33, 18.27, 59.06, 12.81 and 0.73 kg $ha^{-1}$ $yr^{-1}$, for those elements respectively. Furthermore, *P. macrocarpus* released 39.36, 7.49, 12.99, 32.10, 8.94 and 0.43 kg $ha^{-1}$ $yr^{-1}$. While, 32.62, 10.71, 9.77, 35.07, 10.61 and 0.95 kg $ha^{-1}$ $yr^{-1}$ for N, P, K, Ca, Mg and Na were released from *S. roxburghii* plot. *T. grandis* plot represented the amount of those elements released which were 25.16, 3.05, 10.16, 30.99, 7.82 and 0.42 kg $ha^{-1}$ $yr^{-1}$, respectively. Finally, *X. xylocarpa* plot released N, P, K, Ca, Mg and Na in values of 58.59, 8.27, 16.25, 43.48, 9.34 and 1.27 kg $ha^{-1}$ $yr^{-1}$, respectively.

**Table 33** Annual release of nutrient to soil by decomposition of litter and litter on soil surface.

| Species | Source | Litter (ton ha$^{-1}$) | Nutrient released (kg ha$^{-1}$ year$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | Ca | Mg | Na |
| Ac | Decomposition | 8.08 | 91.36 | 6.47 | 29.43 | 56.67 | 19.65 | 6.79 |
| | Litter on soil surface | 3.48 | 24.91 | 4.16 | 4.86 | 14.26 | 4.75 | 0.76 |
| | Total | 11.56 | 116.27 | 10.63 | 34.29 | 70.93 | 24.40 | 7.55 |
| Ai | Decomposition | 3.63 | 46.85 | 6.54 | 16.45 | 51.32 | 11.08 | 0.62 |
| | Litter on soil surface | 0.67 | 5.66 | 0.79 | 1.82 | 7.74 | 1.73 | 0.11 |
| | Total | 4.30 | 52.51 | 7.33 | 18.27 | 59.06 | 12.81 | 0.73 |
| Pm | Decomposition | 2.40 | 36.50 | 6.96 | 11.79 | 29.54 | 8.21 | 0.38 |
| | Litter on soil surface | 0.36 | 2.86 | 0.53 | 1.20 | 2.56 | 0.73 | 0.05 |
| | Total | 2.76 | 39.36 | 7.49 | 12.99 | 32.10 | 8.94 | 0.43 |
| Sr | Decomposition | 2.37 | 29.37 | 10.19 | 9.33 | 32.00 | 9.45 | 0.81 |
| | Litter on soil surface | 0.40 | 3.25 | 0.52 | 0.44 | 3.07 | 1.16 | 0.14 |
| | Total | 2.77 | 32.62 | 10.71 | 9.77 | 35.07 | 10.61 | 0.95 |
| Tg | Decomposition | 2.28 | 24.83 | 2.96 | 10.05 | 30.19 | 7.65 | 0.41 |
| | Litter on soil surface | 0.07 | 0.33 | 0.09 | 0.11 | 0.80 | 0.17 | 0.01 |
| | Total | 2.35 | 25.16 | 3.05 | 10.16 | 30.99 | 7.82 | 0.42 |
| Xx | Decomposition | 3.59 | 51.28 | 7.17 | 13.63 | 36.36 | 7.35 | 0.97 |
| | Litter on soil surface | 1.03 | 7.61 | 1.10 | 2.62 | 7.12 | 1.99 | 0.30 |
| | Total | 4.62 | 58.89 | 8.27 | 16.25 | 43.48 | 9.34 | 1.27 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

14.3 Annual retain of nutrients in each part of the plantation.

In present study, annual retain of nutrients in aboveground biomass of trees was estimated from the amount of nutrient that accumulated in the annual increment of aboveground biomass (Table 34). The results from *A. crassicarpa* plot showed that amounts of nutrient retain in above ground biomass were in comparative sequence of N>Ca>K>P>Mg>Na with 11.91, 8.89, 6.41, 1.84, 1.27 and 0.74 kg ha$^{-1}$ yr$^{-1}$, respectively. For *A. indica* plot, the results of annual retain of nutrients in sequence were Ca>K>N>P>Mg>Na with 83.44, 76.75, 74.88, 19.37, 16.72 and 2.59 kg ha$^{-1}$ yr$^{-1}$, respectively. The results of K>N>Ca>Mg>P>Na were derived from *P. macrocarpus* plot with 35.56, 31.53, 24.99, 6.12, 3.63 and 0.83 kg ha$^{-1}$ yr$^{-1}$, respectively. Results from *S. roxburghii* were 65.04, 57.36, 56.53, 13.32, 11.76 and 3.17 kg ha$^{-1}$ yr$^{-1}$ for N>Ca>K>Mg>P>Na, respectively. While, Ca> K> N> Mg>P>Na were found in *T. grandis* plot with 54.08, 39.23, 33.70, 6.93, 4.91 and 0.20

kg $ha^{-1}$ $yr^{-1}$, respectively. Finally, annual retains of nutrients of *X. xylocarpa* plot were K>Ca>N>Mg>P>Na with 58.78, 55.07, 54.64, 15.03, 3.76 and 2.69 kg $ha^{-1}$ $yr^{-1}$, respectively. All results were shown in Table 34.

**Table 34** Annual retain of nutrients in each part of the plantation.

| Species | Tree part | Nutrient content kg $ha^{-1}$ $yr^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Ac | Stem | 5.33 | 1.16 | 2.77 | 3.86 | 0.30 | 0.36 |
| | Leaf | 3.34 | 0.24 | 1.69 | 1.33 | 0.53 | 0.20 |
| | Branch | 3.23 | 0.44 | 1.95 | 3.70 | 0.44 | 0.18 |
| | total | 11.91 | 1.84 | 6.41 | 8.89 | 1.27 | 0.74 |
| Ai | Stem | 56.56 | 11.95 | 61.23 | 62.36 | 10.68 | 2.19 |
| | Leaf | 6.89 | 0.89 | 3.64 | 6.50 | 1.90 | 0.06 |
| | Branch | 11.44 | 6.54 | 11.89 | 14.58 | 4.15 | 0.33 |
| | total | 74.88 | 19.37 | 76.75 | 83.44 | 16.72 | 2.59 |
| Pm | Stem | 20.09 | 2.51 | 26.00 | 14.95 | 3.43 | 0.61 |
| | Leaf | 4.21 | 0.40 | 1.91 | 2.39 | 0.99 | 0.04 |
| | Branch | 7.23 | 0.72 | 7.65 | 7.65 | 1.70 | 0.18 |
| | total | 31.53 | 3.63 | 35.56 | 24.99 | 6.12 | 0.83 |
| Sr | Stem | 36.64 | 6.13 | 33.99 | 30.84 | 5.96 | 2.39 |
| | Leaf | 12.54 | 2.25 | 6.75 | 6.25 | 2.64 | 0.20 |
| | Branch | 15.86 | 3.38 | 15.78 | 20.27 | 4.72 | 0.58 |
| | total | 65.04 | 11.76 | 56.53 | 57.36 | 13.32 | 3.17 |
| Tg | Stem | 21.46 | 3.19 | 27.74 | 39.47 | 3.94 | 0.95 |
| | Leaf | 6.54 | 1.09 | 3.92 | 3.91 | 1.76 | 0.08 |
| | Branch | 5.70 | 0.63 | 7.56 | 10.70 | 1.23 | 0.20 |
| | total | 33.70 | 4.91 | 39.23 | 54.08 | 6.93 | 1.23 |
| Xx | Stem | 36.31 | 2.42 | 46.42 | 31.11 | 7.40 | 2.28 |
| | Leaf | 6.81 | 0.57 | 3.19 | 2.84 | 0.90 | 0.07 |
| | Branch | 11.51 | 0.78 | 9.17 | 21.11 | 6.73 | 0.34 |
| | total | 54.64 | 3.76 | 58.78 | 55.07 | 15.03 | 2.69 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

14.4 Annual uptake of nutrients by plants and return/uptake ratio.

In present study, the amounts of nutrient uptake by trees were derived from summation of nutrient that accumulated in annual litterfall and nutrient accumulation in annual growth of tree. The results showed that, in *A. crassicarpa* plot, nutrient that annual accumulations in aboveground biomass were 11.91, 1.84, 6.41, 8.89, 1.27 and 0.74 kg $ha^{-1}$, for N, P, K, Ca, Mg and Na, respectively. While, returns of those nutrients to the soil were 140.57, 9.95, 45.28, 87.20, 30.23 and 10.45 kg $ha^{-1}$, respectively. The proportion of return and uptake ratio for N, P, K, Ca, Mg and Na from this plot were 0.92, 0.84, 0.88, 0.91, 0.96 and 0.93, respectively. These ratios were higher than the results from *A. indica* plot which were 0.44, 0.29, 0.21, 0.43, 0.45 and 0.23, respectively. All results were shown in Table 35. These ratio, which <0.50 derived from retain rate that exceeded return rate due to high growth rate and less litterfall comparing to *A. crassicarpa* plot. Retain rate of N, P, K, Ca, Mg and Na from *A. indica* plot were 74.88, 19.37, 76.75, 83.44, 16.72 and 2.59 kg $ha^{-1}$, respectively. While, return rate of those elements were 57.66, 8.05, 20.25, 63.16, 13.63 and 0.76 kg $ha^{-1}$, respectively.

Data derived from *P. macrocarpus* indicated that return uptake ratio of K and Na were less than 0.50 (0.29 and 0.36, respectively). In the other hand, >0.50 ratios were found for N, P, Ca and Mg (0.59, 0.70, 0.59 and 0.62 kg $ha^{-1}$). Retain rate of *S. roxburghii* plot were higher than return rate. Thus, return uptake ratios derived from this plot were ≤ 0.50. The ratio of N, P, K, Ca and Mg were 0.35, 0.51, 0.17, 0.40, 0.46 and 0.24, respectively. Results from *T. grandis* plot were; retain rate of M, P, K, Ca, Mg and Na were 33.70, 4.91, 39.23, 54.08, 6.93 and 1.23 kg $ha^{-1}$, respectively. While, return rate of those elements were 27.58, 3.29, 11.16, 33.52, 8.50 and 0.46 kg $ha^{-1}$, respectively. Return uptake ratios were 0.45, 0.40, 0.22, 0.38, 0.55 and 0.27 kg $ha^{-1}$, respectively. Finally, the results from *X. xylocarpa* plot expressed that retain rate were 54.64, 3.76, 58.78, 55.07, 15.03 and 2.69 kg $ha^{-1}$, respectively. While, return rate were 73.79, 10.32, 19.61, 52.32, 10.58 and 1.39 kg $ha^{-1}$, respectively. Return uptake ratios were 0.57, 0.73, 0.25, 0.49, 0.41 and 0.34, respectively. Tsutsumi (1971) concluded that return/uptake ratio of N, P, K, Ca and Mg were ranged between 40-60 %. Rapp *et al*. (1999) studied in Oak forest and stated that turnover of N, P, K, Ca and Mg in Quercus spp. stand were 9.1-13.1, 5.2-10.9, 5.3-12.8, 2.6-7.8 and 8.7-23.1 %, respectively.

**Table 35** Annual nutrient uptake and return uptake ratio.

| Species | source of nutrient | Nutrient content (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Ac | retain | 11.91 | 1.84 | 6.41 | 8.89 | 1.27 | 0.74 |
| | return | 140.57 | 9.95 | 45.28 | 87.20 | 30.23 | 10.45 |
| | total uptake | 152.48 | 11.79 | 51.69 | 96.09 | 31.50 | 11.19 |
| | return/uptake ratio | 0.92 | 0.84 | 0.88 | 0.91 | 0.96 | 0.93 |
| Ai | retain | 74.88 | 19.37 | 76.75 | 83.44 | 16.72 | 2.59 |
| | return | 57.66 | 8.05 | 20.25 | 63.16 | 13.63 | 0.76 |
| | total uptake | 132.54 | 27.42 | 97.00 | 146.60 | 30.35 | 3.35 |
| | return/uptake ratio | 0.44 | 0.29 | 0.21 | 0.43 | 0.45 | 0.23 |
| Pm | retain | 31.53 | 3.63 | 35.56 | 24.99 | 6.12 | 0.83 |
| | return | 44.99 | 8.58 | 14.53 | 36.41 | 10.12 | 0.47 |
| | total uptake | 76.52 | 12.21 | 50.09 | 61.40 | 16.24 | 1.30 |
| | return/uptake ratio | 0.59 | 0.70 | 0.29 | 0.59 | 0.62 | 0.36 |
| Sr | retain | 65.04 | 11.76 | 56.53 | 57.36 | 13.32 | 3.17 |
| | return | 35.71 | 12.38 | 11.35 | 38.91 | 11.49 | 0.98 |
| | total uptake | 100.75 | 24.14 | 67.88 | 96.27 | 24.81 | 4.15 |
| | return/uptake ratio | 0.35 | 0.51 | 0.17 | 0.40 | 0.46 | 0.24 |
| Tg | retain | 33.70 | 4.91 | 39.23 | 54.08 | 6.93 | 1.23 |
| | return | 27.58 | 3.29 | 11.16 | 33.52 | 8.50 | 0.46 |
| | total uptake | 61.28 | 8.20 | 50.39 | 87.60 | 15.43 | 1.69 |
| | return/uptake ratio | 0.45 | 0.40 | 0.22 | 0.38 | 0.55 | 0.27 |
| Xx | retain | 54.64 | 3.76 | 58.78 | 55.07 | 15.03 | 2.69 |
| | return | 73.79 | 10.32 | 19.61 | 52.32 | 10.58 | 1.39 |
| | total uptake | 128.43 | 14.08 | 78.39 | 107.39 | 25.61 | 4.08 |
| | return/uptake ratio | 0.57 | 0.73 | 0.25 | 0.49 | 0.41 | 0.34 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

**15. Turnover rate and nutrient dynamic processes.**

The turnover rate is a rate that indicated rate of nutrients released or entered into systems (plant system or soil system). In forest ecosystem, most nutrients are retained in soil. The turnover rate of nutrient can be calculated from the ratio of nutrients increased to the system and nutrient retained in system. Turnover rates in each system were shown in Table 34.

15.1 Turnover rate in plant systems, N, P, K, Ca, Mg and Na turnover rate of plant system in *A. crassicarpa* plot were 8.52, 4.09, 5.73, 7.25, 19.18 and 9.87 % $yr^{-1}$, respectively. While in *A. indica* plot,turnover rates of those elements of plant system were 6.34, 5.14, 5.01, 6.26, 6.42 and 1.63 % $yr^{-1}$, respectively. All native tree species e.g. *P. macrocarpus*, *S. roxburghii*, *T. grandis* and *X. xylocarpa* expressed the higher results of nutrient turnover rate in total plant systems than the other exotics. The results from *P. macrocarpus* were 13.64, 18.45, 9.74, 14.17, 15.66 and 5.51 % $yr^{-1}$, respectively, while *S. roxburghii* were 19.50, 25.12, 16.02, 14.94, 20.04 and 8.85 % $yr^{-1}$, respectively. In *T. grandis* plot, the results of plant systems turnover rate were 7.21, 7.21, 5.85, 7.48, 8.93 and 4.73 % $yr^{-1}$, respectively. Lastly, *X. xylocarpa* expressed the results ranged from 8.98 to 22.51 % $yr^{-1}$. N, P, K, Ca, Mg and Na turnover rate of *X. xylocarpa* were 14.55, 22.51, 8.98, 12.95, 11.21 and 10.03 % $yr^{-1}$, respectively. The results from the present study seemed to be equivalent to the results that reported by Glumphabutr (2004). He was studied in natural evergreen forest and reported that turnover rates of N, P, K, Ca and Mg were 7.35-10.57, 8.68-21.96, 6.85-11.65, 5.82-11.55 and 8.30-14.59 % $yr^{-1}$, respectively. In contrast these results were higher than Fir and Hemlock stands which less than 10 % of turnover rate. Anyhow, Petmark (1983) reported the higher results from fast growing tree plantation, of *Acacia auricuraformis*, *Eucalyptus camaldulensis* and *Peltophorum dasyrachis* that were 40-80 % $yr^{-1}$.

15.2 Turnover rate in litter on soil surface. The results from *P. macrocarpus* and *S. roxburghii* expressed the highest results that were due to small amount of remaining litter on soil surface (see Table 17 and 18). The results showed that turnover rate of N, P and K of *S. roxburghii* were 1,098.77, 2,380.77 and 2,579.55 % $yr^{-1}$, respectively. *P. macrocarpus* expressed the highest results with Ca and Mg (1,422.27 and 1,386 % $yr^{-1}$, respectively). While Na turnover rate was highest in *A. crassicarpa* with the result of 1,375.00 % $yr^{-1}$. These present results seemed to be higher that the results reported by Punsatha (2001). He revealed that turnover rate of N, P, K, Ca and Mg from *A. indica* stand was 599.64, 735.38, 1,605.43, 361.50 and 1,129.09 % $yr^{-1}$, respectively.

15.3 Turnover rate in mineral soil system (50 cm depth). In *A. crassicarpa* plot, K and Na were the highest results of nutrient turnover rate which were 17.62 and 15.12 % $yr^{-1}$, respectively. While, turnover rate of other elements e.g. N, P, Ca and Mg were 1.53, 11.57, 5.02 and 11.38 % $yr^{-1}$, respectively. Similarly trend of N turnover rate in mineral soil was found in *A. indica* plot, which was lowest than other

elements (0.89 % $yr^{-1}$). P, K, Ca, Mg and Na were 12.48, 8.04, 8.23, 8.07 and 1.59 % $yr^{-1}$, respectively. N and Na turnover rates of *P. macrocarpus* expressed equivalently results. The data were 0.69 and 0.77 % $yr^{-1}$, respectively. P from *S. roxburghii* expressed the highest turnover rate of the mineral soil systems. The result was 39.13 % $yr^{-1}$. While other elements were 0.47, 5.81, 4.17, 8.28 and 1.85 % $yr^{-1}$, respectively. Turnover rate of P from *X. xylocarpa* plot expressed the higher result than other elements as well. Turnover rate of N, P, K, Ca, Mg and Na from *X. xylocarpa* were 0.93, 21.99, 9.27, 7.88, 5.52 and 2.47 % $yr^{-1}$, respectively. The results from the present study seemed to be the similar trend of the results from Glumphabutr (2004). He revealed that turnover rate of mineral soil system (100cm depth) was highest with P (21.68-84.12 % $yr^{-1}$). On the other hand, N was the lowest turnover rate of mineral soil system. In addition, K, Ca and Mg turnover rates in mineral soil system were fluctuated depending on many factors i.e. litter quality, climate and soil parent materials.

15.4 Turnover rate in total soil system, turnover rate of N, P, K, Ca and Mg derived from *A. crassicarpa* were 2.35, 17.79, 27.11, 7.73, 17.51 and 23.26 % $yr^{-1}$, respectively. While, the results from *A. indica* were 1.09, 15.36, 9.90, 10.13, 9.93 and 1.95 % $yr^{-1}$, respectively. Turnover rate of those element in *P. macrocarpus* were 0.85, 18.09, 6.91, 9.52, 7.74 and 0.95 % $yr^{-1}$, respectively. The highest result of turnover rate from these present studied was found in *S. roxburghii* plot, that was 47.54 % $yr^{-1}$ for P. When as, turnover rates of N, K, Ca, Mg and Na were 0.58, 7.06, 5.07, 10.07 and 2.24 % $yr^{-1}$, respectively. The results from *T. grandis* were 0.46, 9.26, 6.93, 5.91, 7.25 and 0.91 % $yr^{-1}$, respectively, while the results from *X. xylocarpa* were 1.34, 31.66, 13.34, 11.34, 7.95 and 3.54 % $yr^{-1}$, respectively. The results of present study revealed that P was the highest turnover rate in total soil system. This evidence was similarly result that was reported by Glumphabutr (2004). He revealed that P expressed the highest turnover rate in total soil system and the results ranged from 4.73 and 62.28 % $yr^{-1}$. He also explained this evidence due to most of P tended to accumulate in plant tissue especially in aboveground biomass of trees and in litterfall that affected the return rate of P. in addition, P turnover rate of the present study was equal ranged which the results reported by Katagiri *et al*. (1978) and Suksawang (1988). Anyhow, the results from present study were higher than that of Punsatha (2001). He stated that turnover rate of N, P, K, Ca, Mg and Na of total soil system in *A. indica* plantation were 0.25-0.54, 3.78-8.37, 3.60-7.73, 0.05-0.11 and 0.43-0.09 % $yr^{-1}$, respectively.

From the results as mentioned above, nutrient dynamic processes, nutrient fluxes in each part of forest plantation (see Figure 32) and various trend of turnover rate in plants and soil systems were investigate as shown in Table 36-42 and Figure 33-38.

**Table 36** Turnover rates of nutrients in plants, mineral soil (50 cm depth) and total soil system.

| Species | Source | Turnover Rate ( % $yr^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Ac | Plant system | 8.52 | 4.09 | 5.73 | 7.25 | 19.18 | 9.87 |
| | Litter on soil surface | 564.31 | 239.18 | 931.69 | 611.50 | 636.42 | 1,375.00 |
| | Mineral soil system | 1.53 | 11.57 | 17.62 | 5.02 | 11.38 | 15.12 |
| | Total soil system | 2.34 | 16.56 | 26.34 | 7.63 | 17.04 | 22.88 |
| Ai | Plant system | 6.34 | 5.14 | 5.01 | 6.26 | 6.42 | 1.63 |
| | Litter on soil surface | 1,018.73 | 1,018.99 | 1,112.64 | 816.02 | 787.86 | 690.91 |
| | Mineral soil system | 0.89 | 12.48 | 8.04 | 8.23 | 8.07 | 1.59 |
| | Total soil system | 1.09 | 15.13 | 9.81 | 10.01 | 9.81 | 1.94 |
| Pm | Plant system | 13.64 | 18.45 | 9.74 | 14.17 | 15.66 | 5.51 |
| | Litter on soil surface | 1,573.08 | 1,618.87 | 1,210.83 | 1,422.27 | 1,386.30 | 940.00 |
| | Mineral soil system | 0.69 | 14.68 | 5.61 | 7.72 | 6.28 | 0.77 |
| | Total soil system | 0.85 | 17.89 | 6.87 | 9.45 | 7.70 | 0.95 |
| Sr | Plant system | 19.50 | 25.12 | 16.02 | 14.94 | 20.04 | 8.85 |
| | Litter on soil surface | 1,098.77 | 2,380.77 | 2,579.55 | 1,267.43 | 990.52 | 700.00 |
| | Mineral soil system | 0.47 | 39.13 | 5.81 | 4.17 | 8.28 | 1.85 |
| | Total soil system | 0.58 | 46.61 | 7.04 | 5.05 | 9.97 | 2.23 |

**Table 36** (Continued)

| Species | Source | Turnover Rate (% $yr^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | Na |
| Tg | Plant system | 7.21 | 7.21 | 5.85 | 7.48 | 8.93 | 4.73 |
| | Litter on soil surface | 823.28 | 335.71 | 962.07 | 412.30 | 485.71 | 418.18 |
| | Mineral soil system | 0.42 | 8.33 | 6.24 | 5.32 | 6.52 | 0.81 |
| | Total soil system | 0.46 | 9.01 | 6.88 | 5.83 | 7.14 | 0.91 |
| Xx | Plant system | 14.55 | 22.51 | 8.98 | 12.95 | 11.21 | 10.03 |
| | Litter on soil surface | 969.65 | 938.18 | 748.47 | 734.83 | 531.66 | 463.33 |
| | Mineral soil system | 0.93 | 21.99 | 9.27 | 7.88 | 5.52 | 2.47 |
| | Total soil system | 1.34 | 30.62 | 13.11 | 11.17 | 7.84 | 3.51 |

**Remark**: Ac: *A. crassicarpa*; A: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

**Table 37** Dynamic processes of Nitrogen (N) in forest plantation.

| Systems | Processes | Species | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ac | Ai | Pm | Sr | Tg | Xx |
| Plants | (1) Storage in aboveground biomass (kg $ha^{-1}$) | 1,788.91 | 2,092.22 | 561.17 | 516.59 | 849.76 | 882.55 |
| | (2) Retain (kg $ha^{-1}$) | 11.91 | 74.88 | 31.53 | 65.04 | 33.70 | 54.64 |
| | (3) Return (kg $ha^{-1}$ $yr^{-1}$) | 140.57 | 57.66 | 44.99 | 35.71 | 27.58 | 73.79 |
| Soils | (4) Storage of litter on soil surface (kg $ha^{-1}$) | 24.91 | 5.66 | 2.86 | 3.25 | 3.35 | 7.61 |
| | (5) Storage in mineral soil (kg $ha^{-1}$) | 5,986.04 | 5,276.95 | 5,299.82 | 6,195.90 | 5,962.29 | 5,512.72 |
| | (6) Uptake by plant (kg $ha^{-1}$ $yr^{-1}$) | 152.48 | 132.54 | 76.52 | 100.75 | 61.28 | 128.43 |
| | (7) Released by litter decomposition (kg $ha^{-1}$ $yr^{-1}$) | 91.36 | 46.85 | 36.50 | 29.37 | 24.83 | 51.28 |
| Turnover rate | (8) Plant systems (% $yr^{-1}$) | 8.52 | 6.34 | 13.64 | 19.50 | 7.21 | 14.55 |
| | (9) Litter on soil surface (% $yr^{-1}$) | 564.31 | 1,018.73 | 1,573.08 | 1,098.77 | 823.28 | 969.65 |
| | (10) Mineral soil system (% $yr^{-1}$) | 1.53 | 0.89 | 0.69 | 0.47 | 0.42 | 0.93 |
| | (11) Total soil system (% $yr^{-1}$) | 2.34 | 1.09 | 0.85 | 0.58 | 0.46 | 1.34 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

(8) = [(6)/(1)] x 100
(9) = [(3)/(4)] x 100
(10) = [(7)/(5)] x 100
(11) = [(3)/(4)+(5)] x 100

**Table 38** Dynamic processes of Phosphorous (P) in forest plantation.

| Systems | Processes | Species | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ac | Ai | Pm | Sr | Tg | Xx |
| Plants | (1) Storage in aboveground biomass (kg $ha^{-1}$) | 288.11 | 533.16 | 66.21 | 96.12 | 113.73 | 62.57 |
| | (2) Retain (kg $ha^{-1}$) | 1.84 | 19.37 | 3.63 | 11.76 | 4.91 | 3.76 |
| | (3) Return (kg $ha^{-1}$ $yr^{-1}$) | 9.95 | 8.05 | 8.58 | 12.38 | 3.29 | 10.32 |
| Soils | (4) Storage of litter on soil surface (kg $ha^{-1}$) | 4.16 | 0.79 | 0.53 | 0.52 | 0.98 | 1.10 |
| | (5) Storage in mineral soil (kg $ha^{-1}$) | 55.93 | 52.42 | 47.42 | 26.04 | 35.54 | 32.60 |
| | (6) Uptake by plant (kg $ha^{-1}$ $yr^{-1}$) | 11.79 | 27.42 | 12.21 | 24.14 | 8.20 | 14.08 |
| | (7) Released by litter decomposition (kg $ha^{-1}$ $yr^{-1}$) | 6.47 | 6.54 | 6.96 | 10.19 | 2.96 | 7.17 |
| Turnover rate | (8) Plant systems (% $yr^{-1}$) | 4.09 | 5.14 | 18.45 | 25.12 | 7.21 | 22.51 |
| | (9) Litter on soil surface (% $yr^{-1}$) | 239.18 | 1,018.99 | 1,618.87 | 2,380.77 | 335.71 | 938.18 |
| | (10) Mineral soil system (% $yr^{-1}$) | 11.57 | 12.48 | 14.68 | 39.13 | 8.33 | 21.99 |
| | (11) Total soil system (% $yr^{-1}$) | 16.56 | 15.13 | 17.89 | 46.61 | 9.01 | 30.62 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

(8) = [(6)/(1)] x 100
(9) = [(3)/(4)] x 100
(10) = [(7)/(5)] x 100
(11) = [(3)/(4)+(5)] x 100

**Table 39** Dynamic processes of Potassium (K) in forest plantation.

| Systems | Processes | Species | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ac | Ai | Pm | Sr | Tg | Xx |
| Plants | (1) Storage in aboveground biomass (kg $ha^{-1}$) | 902.82 | 1,937.38 | 514.29 | 423.59 | 861.11 | 873.04 |
| | (2) Retain (kg $ha^{-1}$) | 6.41 | 76.75 | 35.56 | 56.53 | 39.23 | 58.78 |
| | (3) Return (kg $ha^{-1}$ $yr^{-1}$) | 45.28 | 20.25 | 14.53 | 11.35 | 11.16 | 19.61 |
| Soils | (4) Storage of litter on soil surface (kg $ha^{-1}$) | 4.86 | 1.82 | 1.20 | 0.44 | 1.16 | 2.62 |
| | (5) Storage in mineral soil (kg $ha^{-1}$) | 167.03 | 204.53 | 210.33 | 160.68 | 160.98 | 146.98 |
| | (6) Uptake by plant (kg $ha^{-1}$ $yr^{-1}$) | 51.69 | 97.00 | 50.09 | 67.88 | 50.39 | 78.39 |
| | (7) Released by litter decomposition (kg $ha^{-1}$ $yr^{-1}$) | 29.43 | 16.45 | 11.79 | 9.33 | 10.05 | 13.63 |
| Turnover rate | (8) Plant systems (% $yr^{-1}$) | 5.73 | 5.01 | 9.74 | 16.02 | 5.85 | 8.98 |
| | (9) Litter on soil surface (% $yr^{-1}$) | 931.69 | 1,112.64 | 1,210.83 | 2,579.55 | 962.07 | 748.47 |
| | (10) Mineral soil system (% $yr^{-1}$) | 17.62 | 8.04 | 5.61 | 5.81 | 6.24 | 9.27 |
| | (11) Total soil system (% $yr^{-1}$) | 26.34 | 9.81 | 6.87 | 7.04 | 6.88 | 13.11 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

(8) = [(6)/(1)] x 100
(9) = [(3)/(4)] x 100
(10) = [(7)/(5)] x 100
(11) = [(3)/(4)+(5)] x 100

**Table 40** Dynamic processes of Calcium (Ca) in forest plantation.

| Systems | Processes | Species | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ac | Ai | Pm | Sr | Tg | Xx |
| Plants | (1) Storage in aboveground biomass (kg $ha^{-1}$) | 1,326.31 | 2,340.79 | 433.27 | 644.48 | 1171.74 | 828.97 |
| | (2) Retain (kg $ha^{-1}$) | 8.89 | 83.44 | 24.99 | 57.36 | 54.08 | 55.07 |
| | (3) Return (kg $ha^{-1}$ $yr^{-1}$) | 87.20 | 63.16 | 36.41 | 38.91 | 33.52 | 52.32 |
| Soils | (4) Storage of litter on soil surface (kg $ha^{-1}$) | 14.26 | 7.74 | 2.56 | 3.07 | 8.13 | 7.12 |
| | (5) Storage in mineral soil (kg $ha^{-1}$) | 1,128.06 | 623.24 | 382.63 | 767.09 | 567.16 | 461.22 |
| | (6) Uptake by plant (kg $ha^{-1}$ $yr^{-1}$) | 96.09 | 146.60 | 61.40 | 96.27 | 87.60 | 107.39 |
| | (7) Released by litter decomposition (kg $ha^{-1}$ $yr^{-1}$) | 56.67 | 51.32 | 29.54 | 32.00 | 30.19 | 36.36 |
| Turnover rate | (8) Plant systems (% $yr^{-1}$) | 7.25 | 6.26 | 14.17 | 14.94 | 7.48 | 12.95 |
| | (9) Litter on soil surface (% $yr^{-1}$) | 611.50 | 816.02 | 1,422.27 | 1,267.43 | 412.30 | 734.83 |
| | (10) Mineral soil system (% $yr^{-1}$) | 5.02 | 8.23 | 7.72 | 4.17 | 5.32 | 7.88 |
| | (11) Total soil system (% $yr^{-1}$) | 7.63 | 10.01 | 9.45 | 5.05 | 5.83 | 11.17 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

(8) = [(6)/(1)] x 100
(9) = [(3)/(4)] x 100
(10) = [(7)/(5)] x 100
(11) = [(3)/(4)+(5)] x 100

**Table 41** Dynamic processes of Magnesium (Mg) in forest plantation.

| Systems | Processes | Species | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ac | Ai | Pm | Sr | Tg | Xx |
| Plants | (1) Storage in aboveground biomass (kg $ha^{-1}$) | 164.25 | 472.55 | 103.70 | 123.80 | 172.84 | 228.51 |
| | (2) Retain (kg $ha^{-1}$) | 1.27 | 16.72 | 6.12 | 13.32 | 6.93 | 15.03 |
| | (3) Return (kg $ha^{-1}$ $yr^{-1}$) | 30.23 | 13.63 | 10.12 | 11.49 | 8.5 | 10.58 |
| Soils | (4) Storage of litter on soil surface (kg $ha^{-1}$) | 4.75 | 1.73 | 0.73 | 1.16 | 1.75 | 1.99 |
| | (5) Storage in mineral soil (kg $ha^{-1}$) | 172.67 | 137.28 | 130.71 | 114.13 | 117.25 | 133.04 |
| | (6) Uptake by plant (kg $ha^{-1}$ $yr^{-1}$) | 31.50 | 30.35 | 16.24 | 24.81 | 15.43 | 25.61 |
| | (7) Released by litter decomposition (kg $ha^{-1}$ $yr^{-1}$) | 19.65 | 11.08 | 8.21 | 9.45 | 7.65 | 7.35 |
| Turnover rate | (8) Plant systems (% $yr^{-1}$) | 19.18 | 6.42 | 15.66 | 20.04 | 8.93 | 11.21 |
| | (9) Litter on soil surface (% $yr^{-1}$) | 636.42 | 787.86 | 1,386.30 | 990.52 | 485.71 | 531.66 |
| | (10) Mineral soil system (% $yr^{-1}$) | 11.38 | 8.07 | 6.28 | 8.28 | 6.52 | 5.52 |
| | (11) Total soil system (% $yr^{-1}$) | 17.04 | 9.81 | 7.70 | 9.97 | 7.14 | 7.84 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

(8) = [(6)/(1)] x 100
(9) = [(3)/(4)] x 100
(10) = [(7)/(5)] x 100
(11) = [(3)/(4)+(5)] x 100

**Table 42** Dynamic processes of Sodium (Na) in forest plantation.

| Systems | Processes | Species | | | | | |
|---|---|---|---|---|---|---|---|
| | | Ac | Ai | Pm | Sr | Tg | Xx |
| Plants | (1) Storage in aboveground biomass (kg $ha^{-1}$) | 113.33 | 205.92 | 23.60 | 46.87 | 35.71 | 40.71 |
| | (2) Retain (kg $ha^{-1}$) | 0.74 | 2.59 | 0.83 | 3.17 | 1.23 | 2.69 |
| | (3) Return (kg $ha^{-1}$ $yr^{-1}$) | 10.45 | 0.76 | 0.47 | 0.98 | 0.46 | 1.39 |
| Soils | (4) Storage of litter on soil surface (kg $ha^{-1}$) | 0.76 | 0.11 | 0.05 | 0.14 | 0.11 | 0.30 |
| | (5) Storage in mineral soil (kg $ha^{-1}$) | 44.92 | 38.99 | 49.53 | 43.80 | 50.4 | 39.25 |
| | (6) Uptake by plant (kg $ha^{-1}$ $yr^{-1}$) | 11.19 | 3.35 | 1.30 | 4.15 | 1.69 | 4.08 |
| | (7) Released by litter decomposition (kg $ha^{-1}$ $yr^{-1}$) | 6.79 | 0.62 | 0.38 | 0.81 | 0.41 | 0.97 |
| Turnover rate | (8) Plant systems (% $yr^{-1}$) | 9.87 | 1.63 | 5.51 | 8.85 | 4.73 | 10.03 |
| | (9) Litter on soil surface (% $yr^{-1}$) | 1,375.00 | 690.91 | 940.00 | 700.00 | 418.18 | 463.33 |
| | (10) Mineral soil system (% $yr^{-1}$) | 15.12 | 1.59 | 0.77 | 1.85 | 0.81 | 2.47 |
| | (11) Total soil system (% $yr^{-1}$) | 22.88 | 1.94 | 0.95 | 2.23 | 0.91 | 3.51 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*

(8) = [(6)/(1)] x 100
(9) = [(3)/(4)] x 100
(10) = [(7)/(5)] x 100
(11) = [(3)/(4)+(5)] x 100

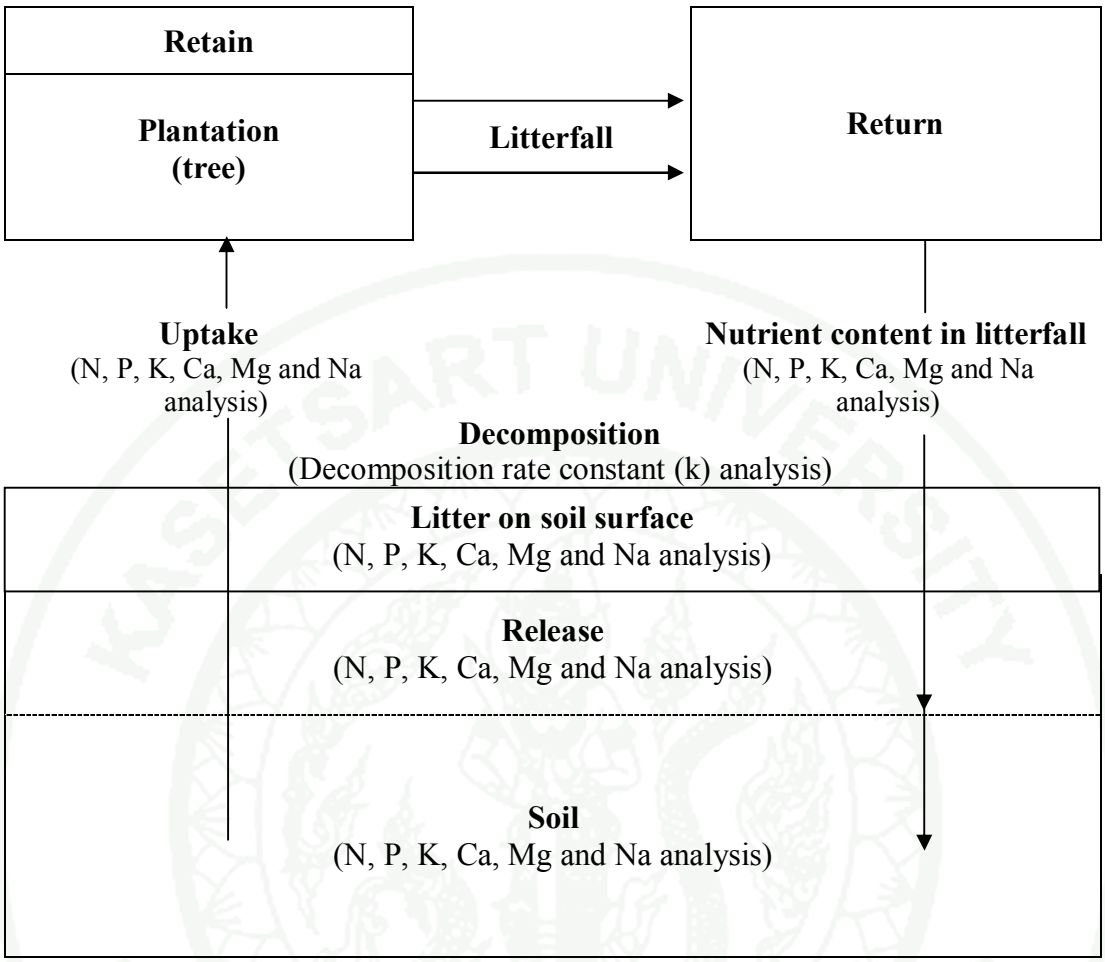
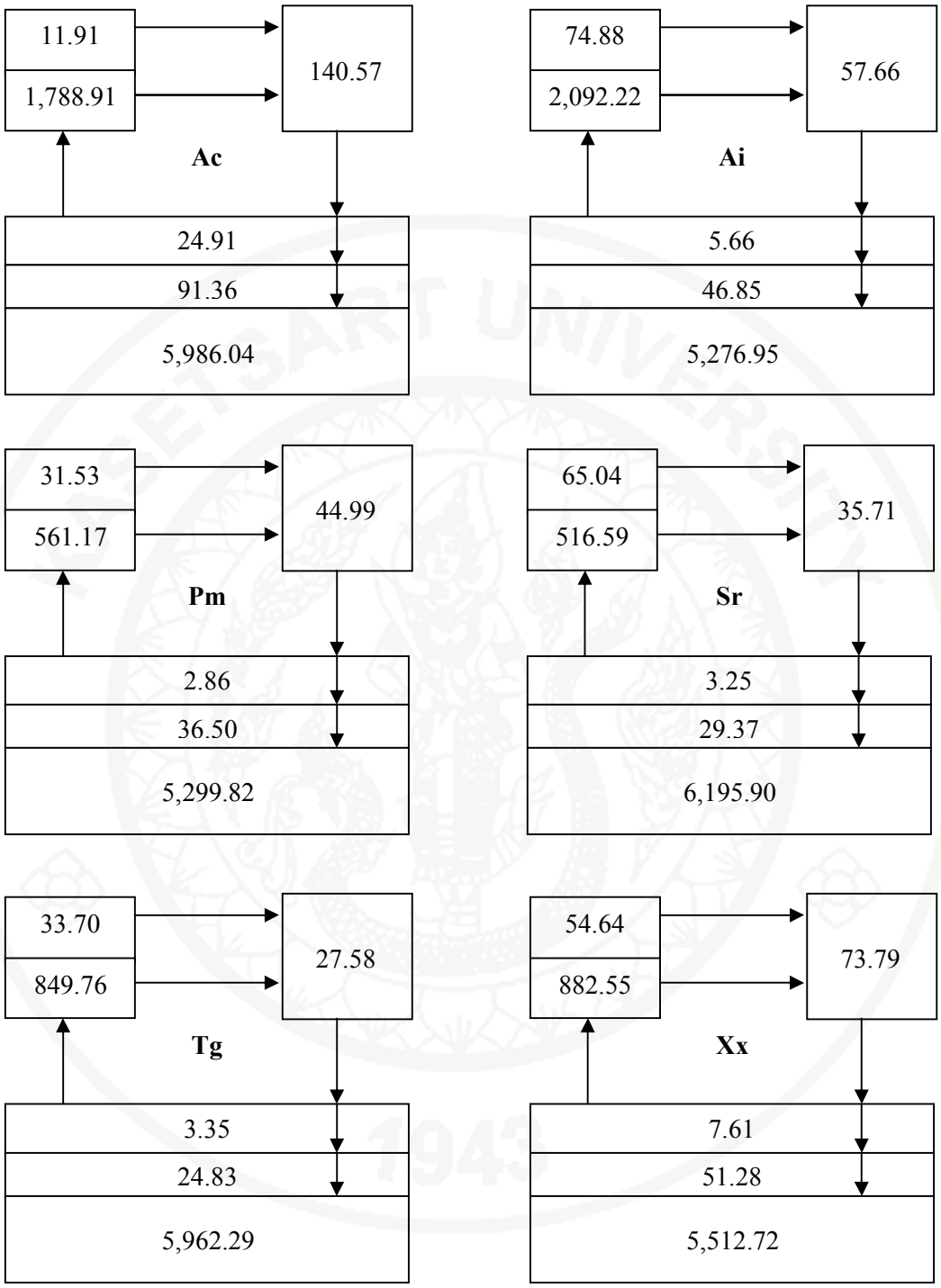
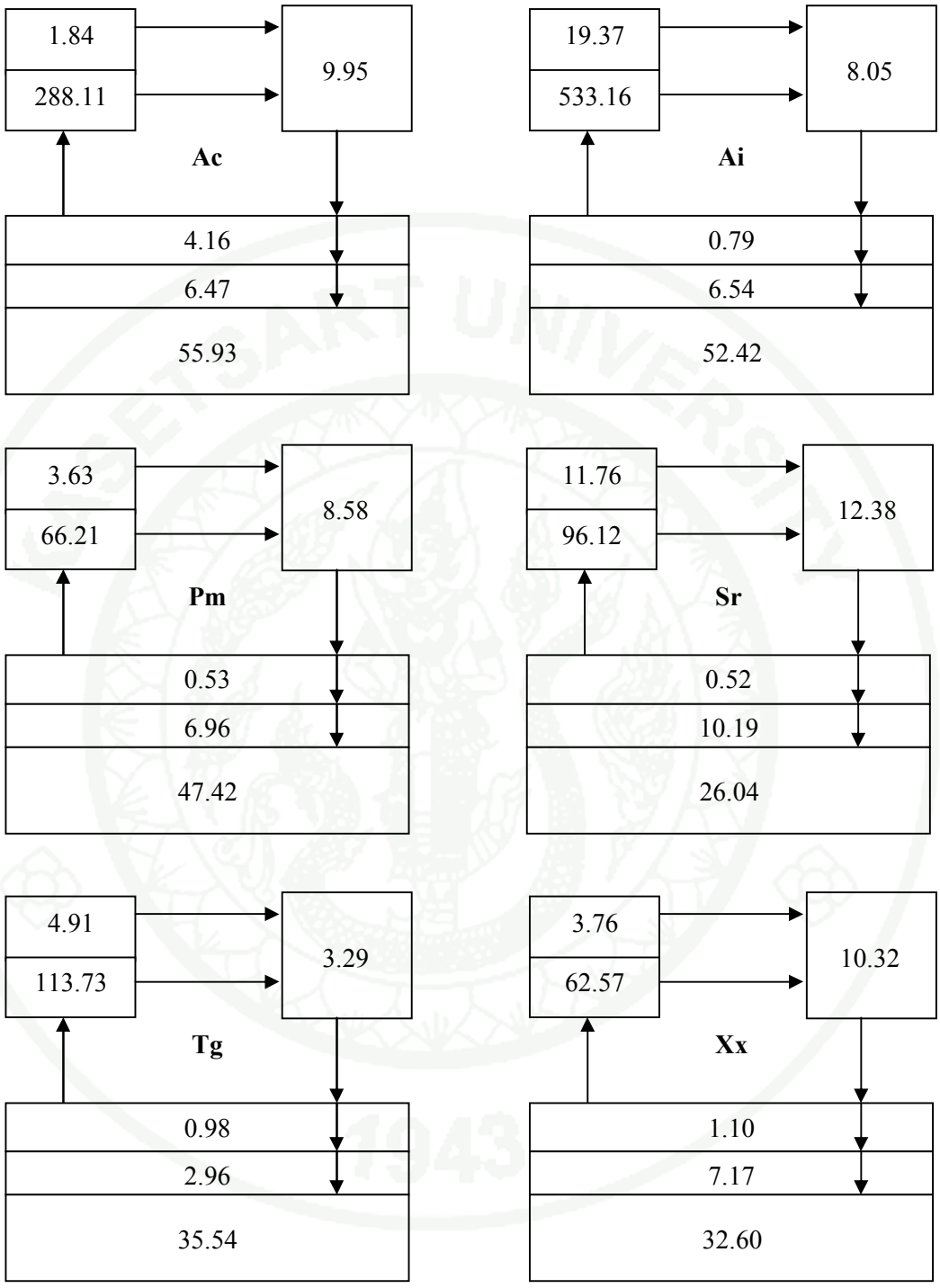



**Figure 32** Diagram of nutrient dynamic.



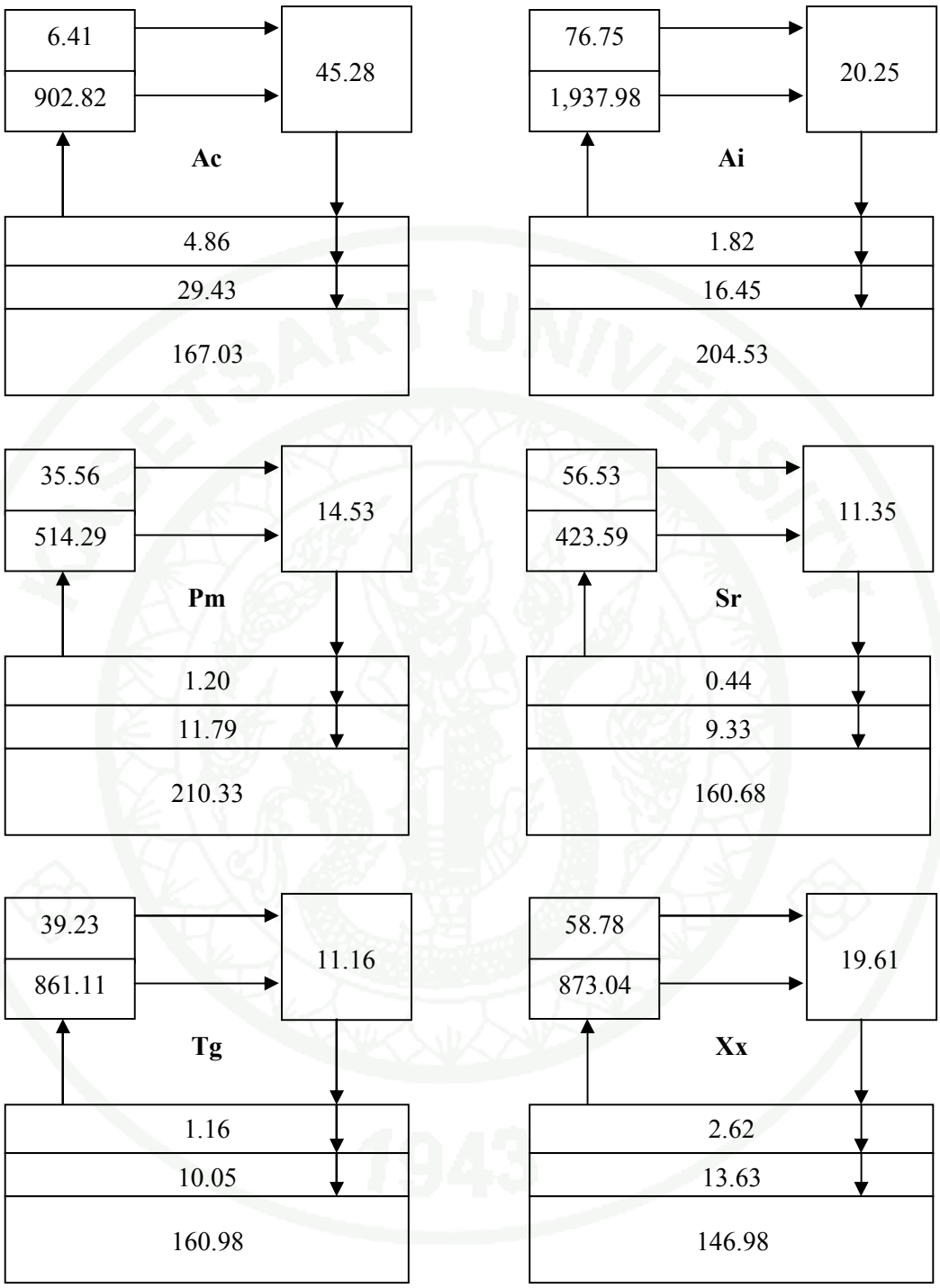

Unit: Retain, Return and Release; kg $ha^{-1}$ $yr^{-1}$, Tree and soil; kg $ha^{-1}$

**Figure 33** Dynamics of Nitrogen (N) in each part of plantation.



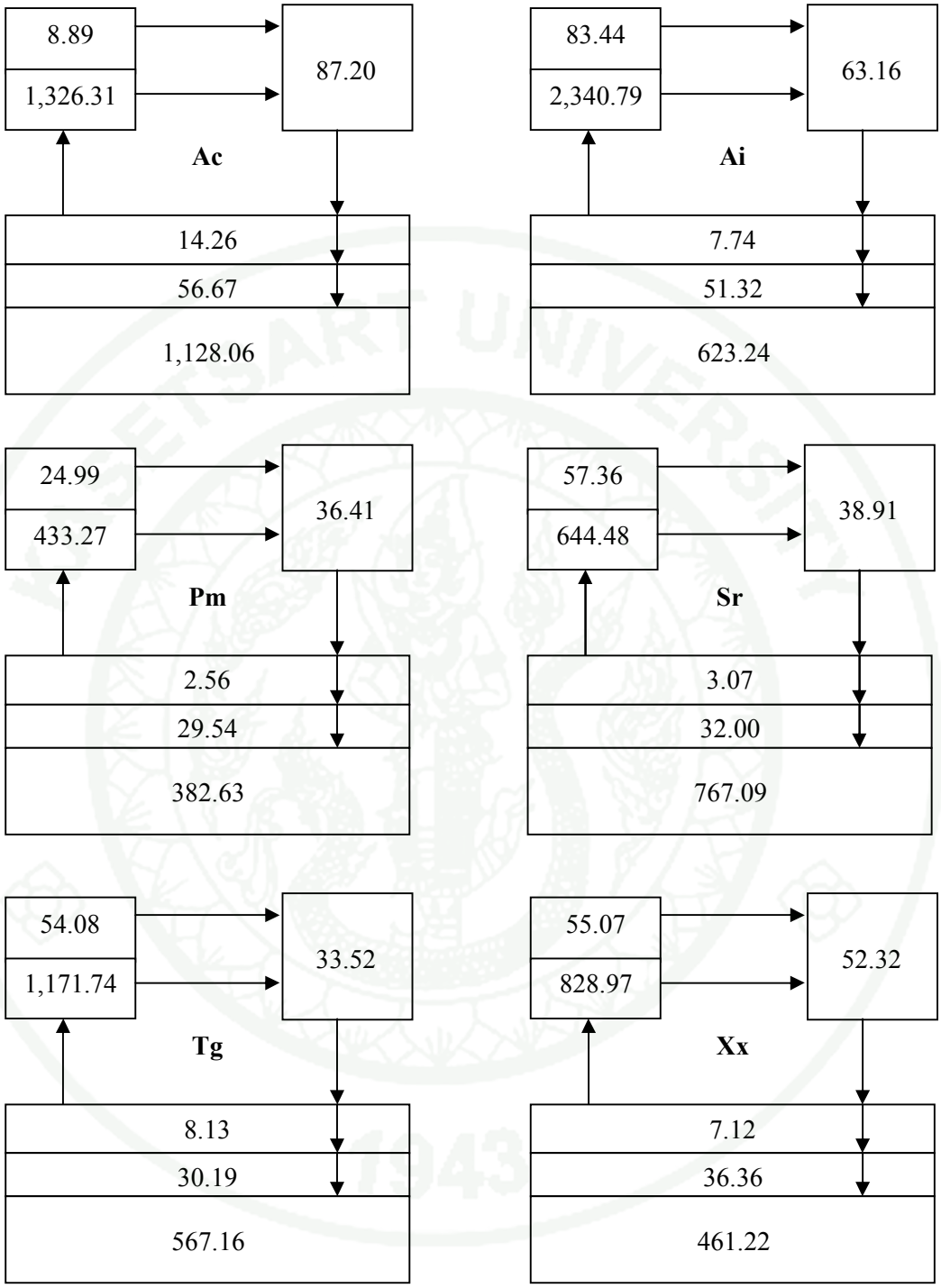

Unit: Retain, Return and Release; kg $ha^{-1}$ $yr^{-1}$, Tree and soil; kg $ha^{-1}$

**Figure 34** Dynamics of Phosphorous (P) in each part of plantation.



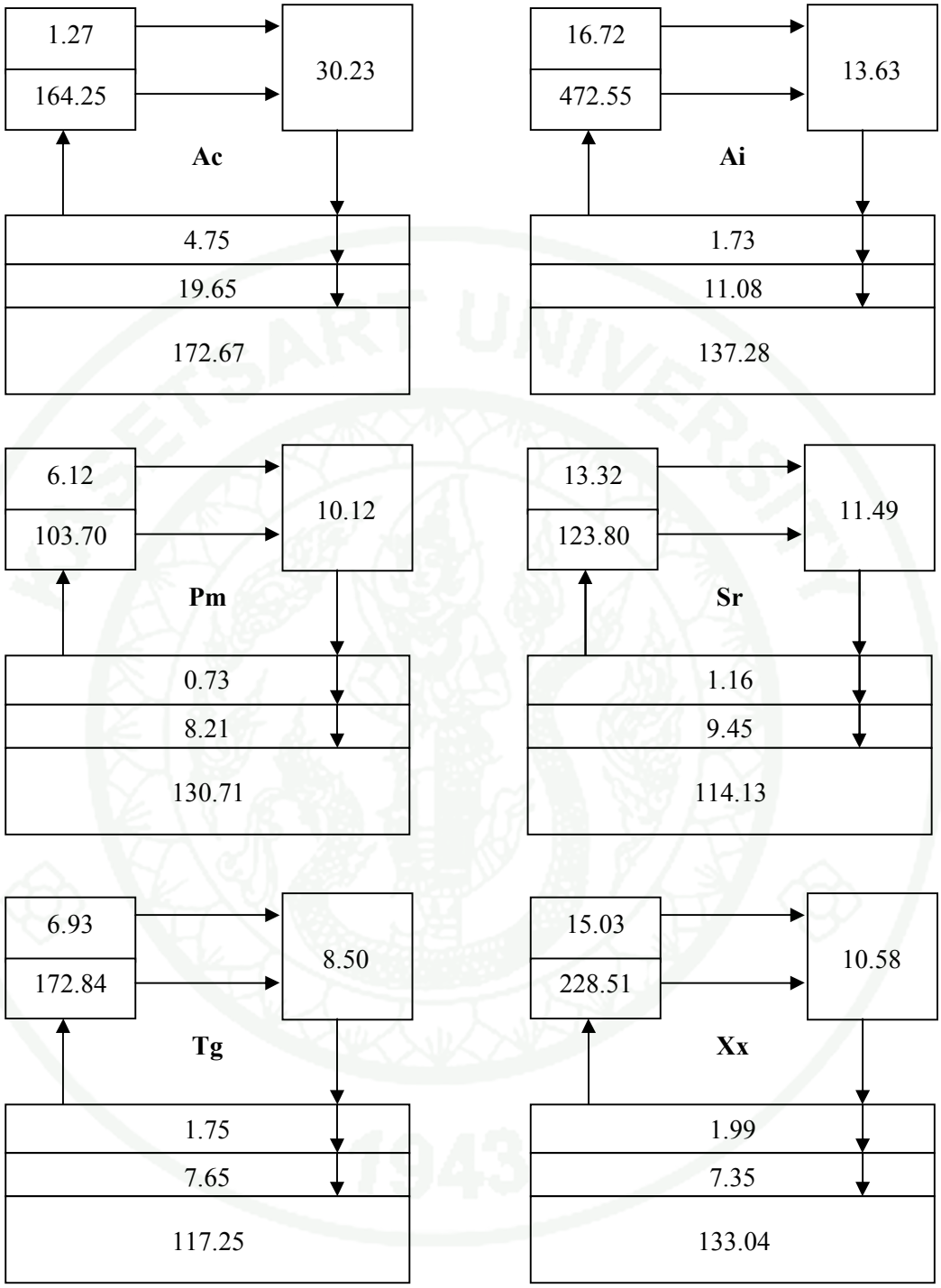

Unit: Retain, Return and Release; kg ha$^{-1}$ yr$^{-1}$, Tree and soil; kg ha$^{-1}$

**Figure 35** Dynamics of Potassium (K) in each part of plantation.



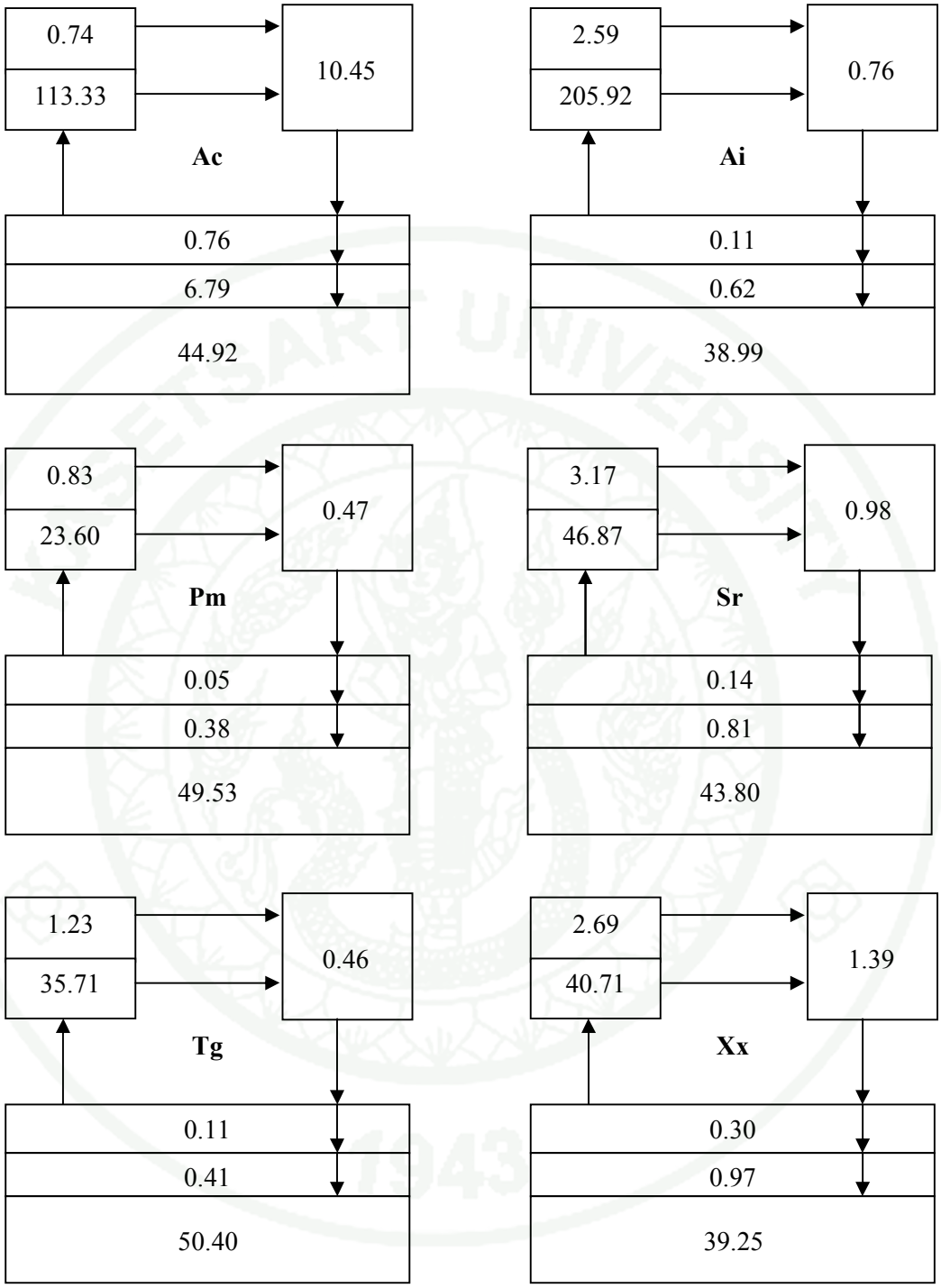

Unit: Retain, Return and Release; kg $ha^{-1}$ $yr^{-1}$, Tree and soil; kg $ha^{-1}$

**Figure 36** Dynamics of Calcium (Ca) in each part of plantation.




Unit: Retain, Return and Release; kg $ha^{-1}$ $yr^{-1}$, Tree and soil; kg $ha^{-1}$

**Figure 37** Dynamics of Magnesium (Mg) in each part of plantation.




Unit: Retain, Return and Release; kg $ha^{-1}$ $yr^{-1}$, Tree and soil; kg $ha^{-1}$

**Figure 38** Dynamics of Sodium (Na) in each part of plantation.

# CONCLUSION AND RECOMMENDATION

The study of nutrient and carbon storages in forest plantation was conducted at Prachuap Khiri Khan Silvicultural Research Station, Prachuap Khiri Khan Province. The 15-years-old plantation was located 300 kms-southern ward of Bangkok. The aims of this study were emphasize; the above and below ground biomass in term of carbon sequestration into the biomass, litter and soil carbon pool in the individual tree species. In addition, the nutrient dynamics of the forest plantation, by identifying structure characteristics of plantation stands and distinguished the nutrient dynamics in each part of plantation were investigated. All information was used to select the appropriated tree species for forest rehabilitation in Prachuap Khiri Khan Province, Thailand. The conclusion and recommendation of this study ware explained as follows;

1. Survival of tree species were varied from species to species from below 10 % to more than 90%. The 6 species which highest survival rate ranking were selected. Those species included both native- and exotic tree species i.e. *A. crassicarpa*, *A. indica* (exotic), *P. macrocarpus*, *S. roxburghii, T. grandis* and *X. xylocarpa* (native). Exotic tree species showed the greater growth rate, compared to native. Approximately 2 times differences with $D_0$, DBH and Ht were found, compared to the best and the worst species. Anyhow, the excellent growth rate, some time was the weak point. *A. crassicarpa*, the exotic species with highest growth rate, was damaged by wind throw in the rainy season. Above-ground biomass was mainly distributed to stem part followed by branch and leaf part, respectively. The results were greatly varied from 36.38 to 272.71 ton $ha^{-1}$. Belowground biomass was mostly distributed to top soil layer, especially from 0 to 20 cm depth. The results of total belowground biomass were ranged between 9.40 and 49.93 ton $ha^{-1}$. The results indicated that exotic tree species contained higher total tree biomass than native species e.g. *A. crassicarpa*>*A. indica*>*X. xylocarpa*>*T. grandis*>S. *roxburghii*>*P. macrocarpus*.

2. A large proportion of senescent leaves were recycled to the soil in the form of litterfall. Monthly amount of litterfall was fluctuated that depended on and strongly related to climatic condition. In addition, total amount of litterfall was depended on leaf mass. Thus, exotic trees i.e. *A. crassicarpa* and *A. indica* expressed higher litter production than those natives. Litter decomposition, all species were shown the rapid decomposition in the first four months. On the other hand, slow decomposition rate or stop decomposition process in the dry season. Anyhow, it was clearly that litters of different species did not decompose at the same rate even under similar environment condition.

3. There were very few differences in soil nutrient concentration both through soil depth and among species plots. Anyhow, soil nutrient concentration trended to slightly decrease with increasing soil depth. Data on available elements (P, K, Ca, Mg

and Na) indicated few differences in soil of plantation and abandoned crop field (control plots). Several apparent differences in soil properties, especially for the most top layers (0 to 20 cm) were probably due to pre-plantation site variability. The results from this present study of almost tree species had the highest concentration of N followed by Ca, K, Mg, P and Na, respectively. Nutrient content of soil expressed variable results through soil depth. Definitely, only upper soil layer (0 to 10 cm) expressed the highest results of soil nutrient content in almost treatments. In the other hand, uncertainly results were found in the lower soil layers. Available nutrient content in all plots could be arranged as followed; N >Ca >K >Mg >P >Na. Nutrient concentration in difference plant parts was greatly varied. For aboveground part, leaf was distinguishingly higher concentration than other parts of all elements. Fine root expressed higher concentration, compared to coarse root in case of belowground biomass. Branch and stem part were shown the lowest results of nutrient concentration. Thus, nutrients that contain in existing tree were varied from species to species. Moreover, nutrient contain in plantation affected from biomass volume which differed via species. The present results revealed that exotic tree e.g. *A. crassicarpa* and *A. indica* contained more nutrient than native tree species. Those results were due to greater tree biomass of exotic tree species than that of native tree species.

4. There were indistinct differences in the carbon concentration in the plant and soil from different species. The carbon pool in a plantation ecosystem depended on the relative biomass of components. Fast growing species, such as *A. crassicarpa* and *A. indica*, could store more carbon, compared to slow growing species, such as *P. macrocarpus* or *S. roxburghii*. As the size of the carbon pool depended on biomass productivity, fast-growing tree species that could achieve greater levels of biomass productivity should be chosen for any nutrient conservation or carbon sequestration programme.

5. Nutrient dynamic processes included annual return through litter fall, released of nutrient to soil by decomposition processes and nutrient retain in tree biomass. The results revealed that the major factors affecting annual nutrient return was the amount of litterfall. *A. crassicarpa* and *X. xylocarpa* showed the higher nutrient return rates. Another factor was their nutrient concentration in litter. However, only slight difference of nutrient concentration was found from present study. Therefore, litter mass was mainly factor that played an important role on the nutrient return rate. Afterward, annual nutrient released to soil was studied by discover decomposition rate and total amount of nutrient release. Exotic tree species seemed to be highly rate of nutrient release to soil due to huge litter mass and rapid decomposing rate. Nutrient retain in biomass was conducted among 14- to 15-years-old tree. On this period, *S. roxburghii* expressed dramatically growth rate. Hence, highest rate of annual nutrient retain was detected from this plot. On the contrary, a few sight of annual growth of *A. crassicarpa* plot affected the poorest annual nutrient retain. It could be obviously concluded that nutrient dynamics rate depended on biomass production, amount of litter fall, litter decomposition rate and soil nutrient

stock. Thus, *A. crassicarpa* and *A. indica* showed the distinguished nutrient dynamics. Furthermore, *T. grandis* ad *X. xylocarpa* seemed to be the outstanding native tree species. For whole nutrient dynamic process, N trend to accumulate through soil profile. By contrast, P and K were mainly distributed to plant system. While, Ca, Mg and Na dynamics were greatly varied. Nevertheless, these elements seemed to be comparable between soil and plant system.

6. According to the results from this study, it identified that forest plantation played the significant roles to the carbon cycle. Re- and Afforestation had great influences on the reduction of $CO_2$ in the atmosphere. Climate caused tree growth rapidly, especially in the tropical area. Moreover, estimate of carbon sequestration of plantation separated by individual species was useful to identify the potential of each species for carbon sequestration plantation projects. This information would be very beneficial for the carbon sequestration database, and would be applied to establish the carbon cycle models. From the results of the current study, *A. crassicarpa* and *A. indica* appeared to be the appropriate species for such programs. In addition, two native tree species, *T. grandis* and *X. Xylocarpa*, were also alternative choices for such purposes

7. Nutrient dynamic processes in an important function to make the forest plantation become sustaining yield both environmental and economic aspects. Therefore, intensively plantation management and silvicultural practices might be used for making excellent plantation programme. According to the results from this study, massively stock of nutrient remaining in tree biomass. Hence, forest logging programme resulted on nutrient loss and nutrient deficiency. Plantation management should be intensive done for nutrient conservation aspect. Residual including some part of remained trunk, branches and leaves should be leave on the ground after logging. Burning out of residual should be avoided. These remaining residual will keeping and afterward, releasing nutrients through decomposition processes. Moreover, it could be functioning as forest ground cover to avoiding soil erosion and nutrient loss through surface runoff.

8. The results of nutrient cycling from this study might be an underestimation because neglecting some information such as nutrient return and release from standing death and large litter decomposition e.g. branch or dead stem, loss of nutrient through many path ways e.g. leaf leaching and stem flow. The study should be extended in the near future.

# LITERATURE CITED

Alexander, T.G. and J.A. Robertson. 1970. Ascobic acid as a reductant for inorganic phosphorous determination in change and Jackson fractionation procedure. **Soil Sci**. 110: 361-362.

Andariese, S.W. and P.M. Vitousek. 1988. Soil nitrogen turn over is altered by herbicide treatment in a north Carolina piedmont forest soil. **For. Ecol. Manage.** 23: 119-125.

Anderson, J.M., J. Proctor and H.W. Vallack. 1993. Ecological studies in four contrasting lowland rain forests in Ganung Mulu national park, Sarawak III. decomposition processes and nutrient losses from leaf litter. **Ecol.** 71: 503-527.

Anegbe, P.O. 2006. **Complete Excavation and Root Distribution of Some Agroforestry Tree Legumes in Nigeria**. IUFRO.

Anoop, U., T. Eid and P.L. Sankhayan. 2005. Construction of site index equations for even aged stands of *Tectona grandis* (teak) from permanent plot data in India. **For. Ecol. Manage.** 212: 14-22.

Anthony, A.K., V.R. Timmer, A.G. Mugasha, S.A.O. Chamshama and D.A. Kimaro. 2007. Nutrient use efficiency and biomass production of tree species for rotational woodlot systems in semi-arid Morogoro, Tanzania. **Agro. For. Syst**. 71: 175-184.

Attignon, S.E., D. Weibel, C. Lachat, B. Sinsin, P. Nagel and R. Peveling. 2004. Leaf litter breakdown in natural and plantation forests of the Lama forest reserve in Benin. **App. Soil Ecol.** 27: 109-124.

Augustto, L., J. Ranger, D. Binkey and A. Rothe. 2002. Impact of several common tree species of European temperate forests on soils fertility. **Ann. For. Sci.** 59: 233-253.

Awang, K., N.A.A. Shukor and A. L. Senin. 1997. Two-year performance of *Acacia crassicarpa* provenances at Serdang, Malaysia. Pertanika. **J. Trop. Agr. Sci.** 18: 177-181.

Barbour, M.G., J.H. Burk and W.D. Pitts. 1988. **Terrestrial Plant Ecology**. The Benjamin/Lummings publishing company Inc., Menro Park.

Barnes, B.R., D.R. Zek, S.R. Denton and S.H. Spurr. 1988. **Forest Ecology**. JohnWiley&Sons Inc., New York.

Baumer, M. 1983. **Notes on Trees and Shrubs in Arid and Semi-arid Regions**. FAO. Rome.

Bhat, K. M. and O. M. Hwan. 2001. **Teak Growers Unite.** ITTO Tropical Forest Update. Yokohama.

Bellamy, P.H., P.J. Loveland, R.I. Bradley, L.R. Murray and G.J.D. Kirk. 2005. Carbon losses from all soils across England and Wales 1978-2003. **Nature**. 437: 245–248.

Berg, B. and H. Staaf. 1980. Decomposition rate and chemical changes in decomposing needle litter in Scot pine. **Ecol. Bull.** 32: 373-390.

Bernhard-reversat, F. 1993. Dynamics of litter and organic matter at the soil-litter interface in fast-growing tree plantations on sandy fertile soil (Congo). **Acta. Oecol.** 14: 179-1005.

_____. and J.J. loumeto. 2002. **Management of Tropical Plantation Forests and Their Soil-Litter System.** Science Publishes. En Field.

Bin, H., C.H. Yu, W.A.Wu, L.J. Peng, C.Y. Ping and R. Yi. 2009. Carbon storage and distribution in *Acacia crassicarpa* plantation ecosystem. **J. of Nanjing For. Univ**. 33: 46-50 .

Binkey, D. 1997. Bioassays of the influence of *Eucalyptus saligna* and *Albizia falcataria* on soil nutrient supply and limitation. **For. Ecol. Manage.** 91: 229-234.

Boonyawat, S. and C. Ngampongsai. 1974. Analysis of accumulation and decomposition of litter in a hill evergreen forest, Doi Pui, Chiang Mai. **Kogma Watershed Research Bull.** 17.

Bouillett, J.P., G. Nizinski, J.D. Nzila and J. Ranger. 1997. **Silviculture and Genetic Improvement of Eucalyptus Vol.4: Environmental and Social Impacts of Eucalyptus Plantation.** IUFRO.

Bubb, K.A., Z.H. Xub, J.A. Simpson and P.G. Saffigna. 1998. Some nutrient dynamics associated with litterfall and litter decomposition in hoop pine plantations of southeast Queensland, Australia. **For. Ecol. Manage.** 110: 343-352

Bunyavejchewin, S. and T. Nuyim. 1996. Litterfall and nutrient content in Toh-daeng primary peat swamp forest at Narathiwat province. **Thai J. For**. 15: 37-47.

Bray, J.R. and E. Gorham. 1964. Litter production in forest of the world. **Adv. Ecol. Res**. 2: 101-157.

Brown, S. and A.E. Lugo. 1992. Tropical forest as sinks of atmospheric carbon. **For. Ecol. Manage**. 54: 239-255.

Byard, R., K.C. Lewis and F. Montagain, 1996. Leaf litter decomposition and mulch performance from mixed and mono specific plantations of native tree species in Costa Rica. **Agri. Ecol. Envir.** 58: 145-155.

Cambodia Tree Seed Project. 2001. **Some Endangered Species of Cambodia**. Hanoi.

Chinsukjaiprasert, T. 1984. **Nutrient Circulation of the Dry Evergreen Forest at Sakaerat**. M.S. Thesis, Kasetsart University..

Chittachumnonk, P., C. Sutthisrisinn, S. Samran, C. Viriyabuncha and K. Peawsad. 2002. **Improving Estimation of Annual Biomass Increment and Aboveground Biomass of Teak Plantation Using Site Specific Allometric Regressions in Thailand**. Royal Forest Department. Bangkok.

Chunkaew, K and S. Boonyawat. 1980. An accumulation of litterfall and some nutrients in dry-evergreen forest Sakaerat. **For. Res. Bull**. 66.

Cole, D.W. 1986. Nutrient cycling in world forest, pp. 103-113. *In* S.P. Gessel, ed. **Forest Site and Productivity**. Mortinus Nijhoff Pub., Dordrecht, Netherland.

Comforth, J.S. 1970. Leaf-fall in atropical rain forest. **App. Ecol.** 7: 603-608.

Courteaux, M.M., P. Bottner and B. Berg. 1995. Litter decomposition, climate and litter quality trend. **Ecol. Evol.** 10: 63-66.

Cuevas, E. and A.E. Lugo. 1998. Dynamics of organic matter and nutrient return from litter fall in stands of ten tropical tree plantation species. **For. Ecol. Manage.** 112: 263-279.

Curlin, J.W. 1970. Nutrient cycling as a factor in site productivity and forest fertilization, pp. 313-325. *In* C.T. Youngberg and C.B. Davey, eds. **Tree Growth and Forest Soils proceeding of the third North America Forest Soil Conference**. Oregon state university press.

Craswell, E.T. and R.D.B Lefroy. 2001. The role and function of organic matter in tropical soils. **Nutr. Cyc. Agro Eco Syst**. 61: 7-18.

DeBell, D.S., C.D. Whitesell and T.H. Schubert. 1989. Using $N_2$-fixing *Albizia* to increase growth of Eucalyptus plantations in Hawaii. **For. Sci.** 35: 64-75.

Deborah, A.M., N.B. Comerford and M.L Duryea. 2000. Litter dynamics and monthly fluctuations in soil phosphorus availability in an Amazonian agro-forest. **For. Ecol. Manage.** 131: 167-181.

Department of forest. 1998. **Teak in The Lao People's Democratic Republic**. Paper proceeding of the second regional seminar on Teak. Yangon.

Department of Silviculture. 1994. **Exotic Fast Growing Trees**. Faculty of Forestry, Kasetsart University. Bangkok.

Doran, C.J. and J.W. Turnbull. 1997. Australian Trees and Shrubs: Species for Land Rehabilitation and Farm Planting in the Tropics. **ACIAR monograph No. 24**.

Dorji. C. 1998. **Management of Teak Plantations in Bhutan**. Paper proceeding of the second regional seminar on Teak. Yangon.

Dutta, R.K. and P. Agrawal. 2003. Restoration of opencast coal mine spoil by planting exotic tree species: a case study in dry tropical region. **Ecol. Eng.** 21: 143-151.

Edward, P.J. 1977. Studies of mineral cycling in a montane rain forest in New Guinea II: the production and disappearance of litter. **J. Ecol.** 65: 971-922.

Egunjobi, J.K. 1974. Litterfall and mineralization in a Teak (*Tectona grandis*) stand. **Oikos.** 25: 222-226.

Elfers, S.C. 1988. **Element Stewardship Abstract for *Casuarina equisetifolia*.** The nature conservancy. Virginia.

Eswaran, H., R. Lal and P.F. Reich. 2001. Land degradation: and over view, pp. 97-114. *In* E.M. Bridge, I.D. Hannam, L.R. Oldeman, F.W.T. Pening de Vries, S.J. Scherr and S.ompatpanit, eds. **Responses to Land Degradation. International Conference on Land Degradation and Desertification, Khon Kaen, Thailand**. Oxford Press, New Delhi, India.

Evans, J. 1986. **Plantation Forestry in the Tropics.** Clarendon Press. Oxford.

FAO. 1981. Map of the fuel wood situation in the developing countries. **Unasylva**. 33.

_____. 2001. **Global Forest Resources Assessment 2000.** FAO forestry papers no 140. Food and agriculture organization of the United Nations. Rome.

_____. 2009. **State of the World's Forest**. Food and agriculture organization of the United Nations. Rome.

Faridah, H and I. V. Maesen. 1997. **Plant Resources of South-East Asia No 11; Auxillary Plants**. Backhuys Pub., Leiden.

Field, C.B., M.J. Behrenfeld, J.T. Randerson, and P. Falkowski. 1998. Primary production of the biosphere: Integrating terrestrial and oceanic components. **Sci**. 281: 237-240.

Foelster, H. and P.K., Khanna. 1997. Dynamics of nutrient supply in plantation soils, pp. 33-378. *In* E.K.S. Nambiar, A.G. Brown, eds. Management of Soil, Water and Nutrients in Tropical Plantation Forests. **ACIAR Monograph No. 43**. Australian centre for international agricultural research, Canberra.

Forest Inventory and Planning Institute. 1996. **Vietnam Forest Tree and Cambodian Tree Species**. DANIDA. Hanoi.

Forest Science Sub-Institute of Southern Vietnam. 1998. **The Management and Prospects of *T. grandis* in Vietnam**. Yangon, Myanmar.

France, B. and D. Schwartz. 1998. Change in lignin content during litter decomposition in tropical forest soils (Congo): comparison of exotic plantations and native stands. **Earth & Planetary Sci.** 325: 427-432.

Frioretto, A., G.A. Musacchio and A.V. De Santo. 1998. Decomposition dynamics of litters of various pine species in a Corsican pine forest. **Soil Biol. Biochem.** 30: 721-727.

Ganjegunte, G.K., L.M. Condron, P.W. Clinton, M.R. Davis and N. Mahieu. 2004. Decomposition and nutrient release from radiata pine (*Pinus radiata*) coarse woody debris. **For. Ecol. Manage**. 187: 197-211.

Garcia-Montiel, D.C. and D. Binkey. 1998. Effect of *Eucalyptus saligna* and *Albizia falcataria* on soil processes and nitrogen supply in Hawaii. **Ocecologia.** 113: 547-556.

Gawinchan, N., S. Suwanrat and S. Sonthichai. 2004. **Effects of Forest Restoration on Plant Litter dynamic and Soil Invertebrate Diversity of Doi Suthep-Pui National Park**. http://www.forru.org/PDF_Files/Publications. Available 28/11/2008.

Ghosh, R., C. Kaul and S. Rao. 1982. Environmental effects of forests in India. **Indian For. Bull**. No. 275.

Glumphabutr, P. 2004. **Nutrients Dynamics of Natural Evergreen Forests in Eastern Region of Thailand.** Ph.D. Thesis, Kasetsart University.

Goncalves, J.L.M., N.F. Barros, E.K.S. Nambiar and R.F. Novais. 1997. Soil and stand management for short-rotation plantations, pp. 379-417. *In* E.K.S. Nambiar and A.G. Brown, eds. Management of Soil, Water and Nutrients in Tropical Plantation Forests. **ACIAR Monograph No. 43**. Australian Centre for International Agricultural Research, Canberra, Australia.

Gyi, M.K.K. 1992. **Teak in Burma**. Paper proceeding of the CHINA/ESCAP/FAO Regional Seminar on Research and Development of Teak. Guangzhou, China.

Hansen, E.A. and J.O. Dawson. 1982. Effect of *Alnus glotinosa* on hybrid poplar height growth in a short-rotation intensively cultures plantations. **For. Sci.** 28: 49-59.

Hanum, I. F. and M. Van. 1997. **Plant Resources of South-East Asia 11, Auxiliary Plants.** LIPI Press, Jakarta.

Hardivinoto, S., D. Arianto and Y. Okimori. 1996. **Litter production and nutrient input of logged over forest in the tropical rain forest of Jambi, Sumatra**. Paper proceeding of the FORTROP'96: Tropical Forestry in the 21th century. Kasetsart University, Bangkok.

Heald, E. 1971. The production of organic detritus in south Florida estuaries. **Uni. Miami. Sea Grant Tech. Bull**. 6.

Hesse, P.R. 1972. **A Textbook of Soil Chemical Analysis**. Chemical Pub. Com., New York.

Hobbie S. E. 1996. Temperate and plant spp. control over litter decomposition in Alaska tundra. **Ecol. Monog.** 66: 503-522.

Hong, T.D., S. Linington and R. H. Ellis. 1996. Seed Storage Behavior: A Compendium. **Handbooks for Gene banks: No.4**. IPGRI.

Hugues, R.F., J.B. Kauffman and D.L. Cummings. 2002. Dynamics of aboveground and soil carbon and nitrogen stocks and cycling of available nitrogen along a land-use gradient in Rondonia, Brazil. **Ecosystems**. 5: 244-259.

IPCC. 2006. **Carbon Dioxide Capture and Storage**. A special report of working group III of the intergovemental panel on climate change. Montreal, Canada.

Jackson, M.L. 1967. **Soil Chemical Analysis**. Prentice-Hall of India Private Ltd., New Delhi.

Jacobs, M.R. 1955. **Growth habits of the Eucalypts.** Forest and timber bureau, common wealth of Australia. Canberra.

Jamroenprucksa, M. 1981. **Net Primary Production of Dry Evergreen Forest at Namprom Basin, Chaiyapoom province**. M.S. Thesis, Kasetsart University.

Jongsuksuntigool, P. and V. Lertnitiwong. 1999. **Evaluation of Leguminous Tree Species Using as Soil Improver at Nhong Koo Gene Conservation Center in Surin Province.** Royal Forest Department, Bangkok.

Jordan, C.F. 1989. **Mineral Nutrient in Tropical Forest and Savanna Ecosystem**. Blackwell Sci. Pub., Oxford.

Jorgensen, J.R. and C.G. Wells. 1986. Tree nutrition and fast-growing plantations in developing countries. **Intl. Tree Crops J.** 3: 225-244.

Joseph, G. and F. Bernhard-Reversat. 2006. Comparison of litter dynamics in three plantations of an indigenous timber-tree species (*Terminalia superba*) and a natural tropical forest in Mayombe, Congo. **For. Ecol. Manage.** 229: 304-313.

Jutikidecha, S. 1996. **Nutrient Circulation in *Eucalyptus camaldulensis* Dehn. Stands Planted with Different Density**. M.S. Thesis, Kasetsart University.

Kadeba, G., E.A. Aduayi. 1985. Litter production, nutrient recycling and litter accumulation in *Pinus caribea* Morelet var. *hondurensis* stands in the northern Guinea savanna of Nigeria. **Plant and Soil**. 86: 197–206.

Kanzaki, M., H. Kawaguchi, T. Yoneda, H. Yada, P. Sahunalu, P. Dhanmanonda, V. Tanpibal, B. Prachaiyo, B. Puriyakorn, K. Muangnil, P. Preechapanya and S. Thoranisorn. 1991. Root system plasticity of *E. camaldulensis* planted on various soils of tropical waste lands, pp. 93-114. *In* K. Yoda and P. Sahunalu eds. **Improvement of Biological Productivity of Tropical waste lands in Thailand**. Report of the Thai-Japan Cooperative Research.

Kaosa-ard, A. 1991. **Teak.** Thai Youth Encyclopedia vol. 15. Damsuntha Printing, Bangkok.

_____. 1992. **Teak in Thailand**. Paper proceeding of the CHINA/ESCAP/FAO Regional Seminar on Research and Development of Teak. Guangzhou, China.

Katagiri, S. and T. Tsutsumi. 1983. The relationship between site condition and circulation of nutrient in forest ecosystem (I): litterfall and nutrient content. **Jap. For. Soc**. 55: 83-90.

Kausik, B., I. Chattopadhyay, R. K. Banerjee and U. Bandyopadhyay. 2002. Biological activities and medicinal properties of neem (*Azadirachta indica*). **Current Sci**. 2(11).

Keppler, F., J.T.G. Hamilton, M. Brass and T. Rockmann. 2006. Methane emissions from terrestrial plants under aerobic conditions. **Nature**. 439: 187-191.

Khorn, S. 2002. **Distribution of Selected Tree Species for Gene Conservation in Cambodia**. Hanoi.

Kikuzawa, K., T. Asai and M. Fukuchi. 1984. Leaf litter production in a plantation. **Ecol**. 72: 993-999.

Kira, T., H. Ogawa, K. Yoda and K. Ogino. 1967. Comparative ecological studies on three main types of forest vegetation in Thailand, IV: Dry matter production, with special reference to the Khao Chong rain forest. **Nature and Life in South East Asia**. 5: 149-174.

Kooha, B. 1983. **Production and Decomposition Rate of Litter in Mangrove Near Tin Mining Area and Natural Mangrove Forest, Ranong Province**. M.S. Thesis, Kasetsart University.

Kraenzel, M., A. Castillo, T. Moore and C. Potrin. 2003. Carbon storage of harvest-age Teak (*Tectona grandis*) plantations, Panama. **For. Ecol. Manage.** 174: 213-225.

Krishnapillay, B. 2000. Silviculture and Management of *T. grandis* Plantations. **For. For. Indust.** 51(2).

Kuers, K. and J. Simmons. 1998. **Leaf Litter Decomposition.** West Virginia Wesleyan College. Virginia.

Kumaravelu, G. 1992. **Teak in India**. Paper proceeding of the CHINA/ESCAP/FAO Regional Seminar on Research and Development of Teak. Guagzhou, China.

Kumer, B.M. and J.K. Deepu. 1992. Litter production and decomposition dynamics in moist deciduous forest of the western ghats in peninsular India. **For. Ecol. Manage.** 50: 181-201.

Ladpala, P. and S. Phanuthai. 2006. **Leaf Litter Decomposition of Mixed Deciduous Forest**. Dep. of National Park, Wild Life and Plant Conservation.

Lang, C. 2002. **The Pulp Invasion**. The international pulp and paper industry in the Mekong region. World Rainforest Movement. Montevideo.

Leigh, E.G. and D.M. Windsor. 1982. **Forest Production and Regulating of Primary Consumers on Barno Colorada Island.** Smithsonian Institute Press. Washington D.C.

Lemmens, R.H.M.J., I. Soerianegara and W.C. Wong. 1995. **Plant Resources of South-East Asia No 5(2). Timber trees: Minor commercial timbers.** Backhuys Pub., Leiden.

Liengsiri, C., F.C. Yeh, and T.J.B. Boyle. 1995. Isozyme analysis of a tropical forest tree, *Pterocarpus macrocarpus* Kurz, in Thailand. **For. Ecol. Manage.** 74: 13-22.

Lisanework, N. and A. Michelsen. 1994. Litterfall and nutrient release by decomposition in tree plantation compared with a natural forest in the Ethiopian highland. **For. Ecol. Manage.** 65: 149-164.

Lohmann, L. 1990. Commercial tree plantations in Thailand: deforestation by any other name. **Ecologist**. 20: 9-17.

Lonsdale, W.M. 1988. Predicting the amount of litterfall in forest of the world. **Ann. Bot**. 61: 319-324.

Lugo, A.E. 1992. Comparison of tropical tree plantations with secondary forests of similar age. **Ecol. Mono.** 62.

Luizao, F.J. and H.O.R. Schubart. 1987. Litter production and decomposition in a terra firme forest of central Amazonia**. Experientian**. 43: 259-265.

Ma, X., K.V. Heal, A. Liu and P.G. Jarvis. Nutrient cycling and distribution in different aged plantations of Chinese fir in southern China. **For. Ecol. Manage.** 243: 61-74

Mahannop, N. 2004. The development of forest plantations in Thailand, pp. 18-33. *In* E. Thomas and P.B. Durst, eds. **What does it take? The Role of Incentives in Forest Plantation Development in Asia and the Pacific**. FAO. Bangkok.

Marland, G. 1989. The role of forests in addressing the $CO_2$ greenhouse, pp.87-95. *In*: J.C. White, ed. **Global climate change linkages: acid rain, air quality and stratospheric ozone**. Elsevier Pub., New York.

McClaugherty, C.A. and B. Berg. 1987. Cellulose, lignin and nitrogen concentrations as rate regulating factors in late stages of forest litter decomposition. **Pedobiologia.** 30: 101-112.

McDonald, M.W. and B.R. Maslin. 2000. A revision of the salwoods: *Acacia aulacocarpa* Cunn. ex Benth. and its allies (Leguminosae: Mimosoideae: section Juliflorae). **Austral. Syst. Bot.** 13(1): 41-43

Meekaew, P., B. Boontawee and B. Kietvutinon. 1990. Species and seed sources trials of Acacias. **Thai J. For.** 9: 23-35.

Meentemeyer, V. 1978. Microclimate and lignin control of litter decomposition rates. **Ecol.** 59: 465-472.

Meentemeyer, V., E.O. Box and N.R. Thompson. 1982. World patterns and amounts of terrestrial plant litter products. **Bioscience**. 32: 125-128.

Melillo, J.M., J.D. Aber and J.F. Muratore. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. **Ecol.** 63: 621-626.

Meteorological Office. 2011. **Thailand Annual Weather Summary**. Available Source: http://www.tmd.go.th, July 11, 2011.

Miller, H.G. 1984. **Dynamics of nutrient Cycling in Plantation Ecosystem.** Academic Press, London.

Moorhead, D.L., W.S. Currie, E.B. Rastetter, W.J. Parton and M.E. Harmon. 1999. Climate and litter quality controls on decomposition: an analysis of modeling approaches**. Global Biogeochemical Cycles.** 13(2): 575-589.

Monsi, M. and T. Saeki. 1953. Uber den lichtfaktor inden Pflanzengase llschaten undseine Bedeutung fur die Stoff production. **Jap. J. Bot**. 14: 22-25.

Montagini, F. 2000. Accumulation in above-ground biomass and soil storage of mineral nutrients in pure and mixed plantations in a humid tropics lowland. **For. Ecol. Manage.** 134: 257-270.

Morisada, K., Y. Ohnuki, S. Nogushi, W.R.W.A. Kadir, S.A. Shamsuddin and A.R. Nik. 2005. Changed in topsoil nutrient status after slash burning for plantation at Bukit Tarek experimental Watershed, pp. 33-38. *In* T. Matsumoto, Y. Kinoto, E. Ueda and S. Kobayahsi, eds. **Proceeding of the International Workshop on the Landscape Level Rehabilitation of Degraded Tropical Forests**. Tsukuba.

Muoghalu, J.I., O.M. Adeloye and R.T. Balogun. 1994. Litter decomposition and inorganic element dynamics in a secondary rainforest at Ile-Ife, Nigeria. **Afr. J. Ecol.** 32: 208–221.

Murray, R.D., G. Coker, R.L. Parfitt, R. Simcockc, P.W. Clinton, L.G. Garrett and M.S. Wattt. 2007. Relationships between soil and foliar nutrients in young densely planted mini-plots of *Pinus radiata* and *Cupressus lusitanica*. **For. Ecol. Manage**. 240: 122–130.

Muthukumar, T., K. Udaiyan and V. Rajeshkannan. 2001. Response of neem (*Azadirachta indica* A. Juss) to indigenous arbuscular mycorrhizal fungi, phosphate-solubilizing and asymbiotic nitrogen-fixing bacteria under tropical nursery condition. **Biol. Fertil. Soils**. 34: 417–42

Myers, N. 1989. The greenhouse effect: a tropical forestry response. **Biomass**. 18: 73-78.

Nakamura, K. 2006. Micropropagation of *Shorea roxburghii* and *Gmelina arborea* by shoot-apex culture**. Plantation Tech. Trop. For. Sci**. 10: 137-150.

National Research Council. 1983. **Mangium and Other Acacias of the Humid Tropics, Innovations in Tropical Reforestation.** National Academy Press, Washington, DC.

_____. 1992. **Neem: A Tree For Solving Global Problems**. National Academy Press, Washington, D.C.

*Natural Resources Conservation. 2007.* ***Soil Survey Office Laboratory References****. U.S. Department of Agriculture.*

Newbould, P.J. 1967. **Methods for Estimating the Primary Production of Forest**. Blackwell, Oxford.

Ngoran, A., N. Zakr, K. Ballo, C. Kouam, F. Zapata, G. Hofman and O.V. Cleemput. 2006. Litter decomposition of *Acacia auriculiformis* Cunn. Ex Benth. and *Acacia mangium* Willd. under coconut trees on quaternary sandy soils in Ivory Coast. **Biol. Fertil. Soils**. 43: 102–106.

Ngulube, M.R., G.B.J. Chapola and L. Mwabumba. 1993. The potential of Australian dry zone acacias for agroforestry in Malawi. **For. Ecol. Manage.** 56: 83-97.

Nwoboshi, L.C. 1980. Nitrogen cycling in a teak plantation ecosystem in Nigeria, pp. 353-361. *In* T. Rosswall, ed. **Nitrogen Cycling in West Africa.** . SCOPE/UNEP, Stockholm.

Nyadzi, G.I., R.M. Otsyina, F.M. Banzi, S.S. Bakengesa, B.M. Gama and L. Mawambo. 2003. Rotational woodlot technology in northwestern Tanzania: tree species and crop performance**. Agro. Syst.** 59: 253-263.

_____., R.M. Otsyina and C.K. Ong. 2002. **Growth and Water Resource Utilization of *Acacia Crassicarpa*, *Senna Siamea* and *Leucaena pallida* Tree Species Established in Rotational Woodlots Agroforestry System in Western Tanzania**. 12th ISCO Conference . Beijing

Office of the Forest Land Management. 2010. **Forest Statistic 2010**. Royal Forest Department. Bangkok.

Olsen, S.R, and L.E. Sommers. 1982. Phosphorus, pp. 38-45. *In* D.R. Keeney, L. Page and R.H. Miller, eds. **Methods of Soil Analysis Part 2**. Madison.

Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. **Ecol.** 44: 322-331.

Pandey, R.R., G. Sharma, S.K. Tripathi and A.K. Singh. 2007. Litterfall, litter decomposition and nutrient dynamics in a subtropical natural oak forest and managed plantation in northeastern India. **For. Ecol. Manage.** 240: 96-104.

Paovongsa, S. 1976. **Litterfall and Mineral Nutrient Content of Litter in Dry Dipterocarp Forest**. M.S. Thesis, Kasetsart University.

Papa, N., D. Mailly, M. Pineau and H.A. Margolis. 1993. Growth and yield of *Casuarina equisetifolia* plantations on the coastal sand dunes of Senegal as a function of microtopography. **For. Ecol. Manage.** 56: 13-28.

Parrotta, J.A. 1999. Productivity, nutrient cycling and succession in single- and mixed-species plantations of *Casuarina equisetifolia*, *Eucalyptus robusta* and *Leucaena leucocephala* in Puerto Rico. **For. Ecol. Manage.** 124: 45-77.

Peck, A. J., and D. R. Williamson. 1987. Effects of forest clearing on groundwater. **J. Hydrol.** 94: 47-65.

Perhutani, P. 1992. **Teak in Indonesia**. Paper proceeding of the CHINA/ESCAP/FAO regional seminar on research and development of Teak. Guangzhou, China.

Petmark, P. 1978. **Primary Production of Thinned and Unthinned Teak Plantation at Ngao, Lampang**. M.S. Thesis, Kasetsart University.

_____. 1983. **Primary Productivity, Nutrient cycling and Organic matter turnover of Tree Plantation after Agriculture Inter-Cropping Practices in Northeast Thailand**. Ph.D. Thesis, UPLB.

_____. and P. Sahunalu. 1978. Primary production of teak plantation I: net primary production of thinned and unthinned plantation at Ngao, Lampang. **For. Res. Bull**. 50.

Petsri, P. 2004. **Aboveground Carbon Content in Mixed deciduous Forest in Teak Plantation.** M.S. Thesis, Mahidol University.

Phompate, C. 1993. **Teak for trade.** Agro communication, Bangkok.

Piananurak, P. 1995. **Analysis of Teak Seed Orchards in Thailand.** M.S. Thesis, Kasetsart University.

Pousajja, R. 1996. Eucalyptus plantation in Thailand, pp. 145-152. *In* M. Kashio, and K. White, eds. **Reports Submitted to the Regional Expert Consultation on Eucalyptus vol. II**. FAO. Bangkok.

Prachaiyo, B., P. Sahunalu, P. Dhammanonda, W. Suwannapinunt and M. Jamroenprueksa. 1980. Litter production in dry evergreen forest above Namprom dam, Chaiyapoom province. **For. Res. Bull**. 71.

Pregitzer, K. and S. Euskirchen. 2004. Carbon cycle and storage in world forest: biome patterns related to forest age. **Global Change Biol**. 10: 2052-2077.

Proctor, J. 1983. Tropical litterfall; problems of data comparison, pp. 267-273. *In* S.L. Sutton, T.C. Whitmore and A.C. Chadwick, eds. **Tropical Rain Forest: Ecology and Management**. Blackwell Sci. Pub., Oxford.

Punsatha, J. 2001. **Nutrient Circulation in *Azadirachata indica* A. Juss. var. *siamensis* Stands Planted with Different Density**. M.S. Thesis, Kasetsart University.

Puri, S. and S.L. Swamy. 2001. Growth and biomass production in *Azadirachta indica* seedlings in response to nutrients (N and P) and moisture stress. **Agro. For. Syst**. 51: 57-68.

Qin, W., H.E. Bin, Q. Shi-ying, H. Shi-fang, M. Ya-fang and Q. Yong-hua. 2007. Biological cycling of nutrients in *Acacia crassicarpa* plantation. **J. of Soil and Water Conserv**. 4: 17-24.

Raich, J.W., A.E. Russell and R.B. Arrieta. 2007. Lignin and enhanced litter turnover in tree plantations of lowland Costa Rica. **For. Ecol. Manage.** 239: 128-135.

Randhawa, N.S. and B.S. Parmar. 1993. **Neem Research and Development**. New Delhi: Society of Pesticide Science, India.

Rao, M.R., P.K.R. Nair and C.K. Ong. 1998. Biophysical interactions in tropical agroforestry systems. **Agrofor Syst**. 38: 3-50.

Rapp, M., I.S. Regina, M. Rico and H.A. Gallego. 1999. Biomass, nutrient content, litterfall and nutrient return to the soil in Mediterranean oak forests. **For. Ecol. Manage**. 119: 39-49.

Rarivoson, C., M. Vincelette and R. Mara. 2007. Growth results of five non-native fast growing species used to reforest sandy and nutrient poor soils, pp. 78-86. *In* A. Alonso, ed. **Biodiversity, Ecology and Conservation of Littoral Ecosystems in Southeastern Madagascar, Tolagnaro (Fort Dauphin).** Washington, DC.

Research Institute of Tropical Forestry. 1992. **Development of Teak in China**. Paper proceeding of The CHINA/ESCAP/FAO regional seminar on research and development of Teak. Guagzhou, China.

Rojo, J.P. 1977. Pantropic speciation of *Pterocarpus* ( Leguminosea-Papilionaceae) and the Malaysia-Pacific species. **Pterocarpus**. 3: 19–32.

Roongrattanakul, P., V. Luangviriyasaeng and K. Pitpreecha. 1999. **Results of *Acacia crassicarpa* Provenance Trial at Kanchanaburi Province.** Royal Forest Department. Bangkok.

_____., S. Nimpila and R. Thai-ngam. 1999**. Study on Five Australian *Acacia* spp. and *Eucalyptus camaldulensis* Dehnh. in Different Spacing for Control *Imperata cylindrica*. (L.)**. Royal Forest Department. Bangkok.

Roper, J. 2006. **Tropical Forest and Climate Change**. http://www.rcfa-cfan.org/english/ issues.13.html; available 2/26/2007.

Rouhi-Moghaddam, E., S.M. Hosseini, E. Ebrahimi, M. Tabari and A. Rahmani. 2008. Comparison of growth, nutrient and soil properties of pure stands of *Quercus castaneifolia* and mixed with *Zelkova carpinifolia* in the Hyrcanian Forests in Iran. **For. Ecol. Manage.** 255: 1149-1160.

Royal Forest Department. 2009. **Forest Statistics**. Royal Forest Department. Bangkok.

Rytter, R.M. and A.C. Hansson. 1996. Seasonal amount, growth and depth distribution of fine roots in an irrigated and fertilized *Salix viminalis* L. plantation. **Biomass and Bioenergy**. 11: 129-137.

Sahunalu, P. 1983. **Litterfall, Nutrient Flux and Nutrient Use Efficiency in a Seasonal Rain Forest, Northeast Thailand**. Kasetsart University. Bangkok.

_____. and M. Jamroenprucksa. 1980. Production and nutrient cycling in dry dipterocarp forest, Thailand. **For. Res. Bull.** 67.

_____., B. Thaiutsa, S. Sukwong., S. Aksornkoae and S. Kaitpraneet. 1984. **Nutrient Cycling of the Dry Dipterocarp Forest at Sakaerat.** Final report submitted to the National Research Council, Bangkok.

Sakai, M. and T. Tsutsumi. 1986. Carbon cycles of two soil types in cool temperate forest on Japan (I): Litterfall. **J. Jpn. For. Soc**. 68: 1-9.

Sakuntaluk, N. 1999. **Physiology.** Nophaburi Pub. Inc., Chiang Mai.

Sang-on, P. 2007**. Litterfall and Litter Decomposition in Exotic Tree Plantations at Doi Angkhang, Chiang Mai Province.** M.S. Thesis, Kasetsart University.

Satoo, T and M. Senda. 1958. Materials for the studies of growth in stands IV: Amount of leaves and production of wood in young plantation of *Chamaecyparis obtuse* . **Bull. Tokyo Univ. Forest**. 54: 71-100.

_____. 1970. A Synthesis of studies by the harvested method: Primary production relation in the temperate deciduous forest of Japan, pp. 175-124. *In* D.E. Reihle, ed. **Analysis of Temperate Forest Ecosystems**. Springer Verlag, New York.

Schenk, H. J. and R. B. Jackson. 2002. The global biogeography of roots. **Ecol. Mono**. 72(3): 311–-28.

Schroeder, P. and C. Ladd. 1991. Slowing the increase of atmospheric carbon dioxide: a biological approach. **Climate Change.** 19: 283-290.

_____. 1997. Carbon storage potential of short rotation tropical tree Plantations. **For. Ecol. Manage**. 50: 31-41.

Sedjo, R. 1989. Forests to offset the greenhouse effect. **J. For.** 87: 12-15.

Semwala, R.L., R.K. Maikhuria, K.S. Raob, K.K. Senb and K.G. Saxenac. 2003. Leaf litter decomposition and nutrient release patterns of six multipurpose tree species of central Himalaya, India. **Biomass and Bioenergy**. 24: 3-11.

Sheikh A.A. and M.T. Siddiqui. 2002. Growth response of Teak (*Tectona grandis* L.f .) seedlings to Nitrogen, Phosphorus and Potassium fertilizer. **J. Trop. Agric. Sci**. 25(2): 107-113.

Singh, A.N. 1999. **Structure, Function and Impact of Young Plantations of Four Native Woody Species on Coal Mine Spoil**. Ph.D. Thesis, Banaras Hindu University.

Singh, O., D.C. Sharma and J.K. Rawat. 1993. Production and decomposition of leaf litter in sal, teak, eucalyptus and popular forests in Uttar Pradesh. **Indian Forester**. 119: 112–121.

Six, J., R.T. Conant, E.A. Paul and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. **Plant and Soil**. 241: 155–176.

Smith, C.K., H.L. Gholz and F.A. Oliveira. 1998. Fine litter chemistry, early-stage decay, and nitrogen dynamics under plantation and primary forest in Lowland Amazonia. **Soil Biol. Biochem.** 30: 2159-2169.

Soerianegara, I. and R.H.M.J. Lemmens. 1994. **Timber trees: Major Commercial Timbers**. Wageningen Agricultural University, Netherlands.

Spain, A.V. 1984. Litterfall and the standing crop of litter in three tropical Australia rain forest. **Ecol**. 72: 942-961.

Srivastava, S. K., K. P. Singh and R. S. Upadhyay. 1986. Fine root growth dynamics in teak (*Tectona grandis* Linn. F.). **Can. J. For. Res.** 16: 1360-1364.

Stewart, B.A., L.K. Porter and W.E. Beard. 1964. Determination of total nitrogen and carbon in soils by commercial Dumas apparatus. **Soil Sci. Soc. America**. 28: 366-368.

Suksawang, S. 1988. **Nutrient Circulation of the Dry Evergreen Forest at Huay Hin Dard Watershed Research Station, Changwat Rayong.** M.S. Thesis, Kasetsart University.

Sulton, M. and L. Macumbal. 1992. **Teak in the Philippines**. Paper proceeding of The CHINA/ESCAP/FAO regional seminar on research and development of Teak. Guagzhou, China.

Sumantakul, V. and S. Viriyabuncha. 2007. **Studied on Net Primary Production of Teak (*Tectona grandis* L.f.) and Some Forest Growing Tree Species Plantations for Sustainable Conservation.** Dept. of National park, Wild Life and Plants Conservation, Bangkok.

Sumner, M.E. and W.P. Miller. 1996. Cation exchange capacity and exchange Coefficient, pp. 1201-1229. *In* D.L. Sparks, ed. **Methods of Soil analysis: Part 3**. Chemical Methods, SSSA and ASA, Madison.

Sun, D. and G.R. Dickinson. 1995. Salinity effects on tree growth, root distribution and transpiration of *Casuarina cunninghamiana* and *Eucalyptus camaldulensis* planted on a saline site in tropical north Australia. **For. Ecol. Manage.** 77: 127-138.

Takeda, H., B. Prachaiyo and T. Tsutsumi. 1984. Comparison of decomposition rates of several tree leaf litter in a tropical forest in the north-east Thailand. **Jap. J. Ecol.** 34: 311-319.

Tateno, R., N. Tokuchi, N. Yamanaka, S. Du, K. Otsuki, T. Shimamura, Z. Xue, S. Wang and Q. Hou. 2007. Comparison of litterfall production and leaf litter decomposition between an exotic black locust plantation and an indigenous oak forest Near Yunnan on the Loess Plateau, China. **For. Ecol. Manage**. 241: 84-90.

Taylor, A. K. and Q. Zisheng. 1987. Culm dynamic and dry matter production of bamboo in the Wolong and Tangjiahe Giant Panda reserves, Sichran, China. **J. Apply. Ecol**. 32: 817-826.

Taylor, B.R. and H.G. Jones. 1990. Litter decomposition under snow cover in a Balsam fir forest. **Can. J. For. Res.** 68: 112-120.

Terrell, T., I.J. Baker, L.B. Graeme, H.C. William, E. Calvin, J.S.A. Meier and K.B. Marianne. 2001. Leaf litter decomposition and nutrient dynamics in four southern forested flood plain communities. **Soil Soc. Am. J.** 5: 1334-1347.

Thaiutsa, B., W. Suwannapinunt and W. Kaitpraneet. 1978. Production and chemical composition of forest litter in Thailand. **For. Res. Bull.** 52.

_____. and O. Granger. 1979. Climate and decomposition rate of tropical forest litter. **Unasylva**. 3: 28-35.

Thomson, L.A.J. 1994**.** ***Acacia aulacocarpa*****,** ***A. cincinnata*****,** ***A. crassicarpa*** **and** ***A. wetarensis*****: an Annotated Bibliography**. CSIRO.

Tian, G., F.K. Salako and F. Ishida. 2001. Replenishment of C, N and P in a degraded Alfisol of fallow species and litter polyphenols. **Soil Sci**. 166: 614–621.

Tiessen, H., E. Cuevas and P. Chacon, 1994. The role of soil organic matter in sustaining soil fertility. **Nature**. 371: 783–785.

Toky, O.P. and R.P. Bisht. 1992. Observations on the rooting patterns of some agroforestry trees in an arid region of north-western India. **Agro. For. Syst.** 18(3): 245-263.

_____. and V. Singh. 1995. Nutrient dynamics in Leucaena, Acacia and Eucalyptus, short rotation, high density plantation in arid India. **J. Arid Environ.** 31: 401-413.

Tongtapao, T. 2008. **Some Soil Properties and Root Distribution of 16-year-old** ***Acacia aulacocarpa*** **and** ***Eucalyptus urophylla*** **Plantations at Saithong Silvicultural Research Station, Bang Saphan Noi District, Prachuap Khiri Khan Province**. M.S Thesis, Kasetsart University.

Tripathi, S.K. and K.P. Singh. 1995. Litter dynamics of recently harvested and mature bamboo savannas in a dry tropical region in India. **J. Trop. Ecol**. 11: 403-417.

Tsai, L.M. 1974**. Litterfall and Mineral Nutrient Content of Litter in Pasoh Forest Research**. IBP-Syathesis Meeting, KualaLumpur, Malaysia.

Tsuami, T. 1971. Accumulation and circulation of nutrient elements in forest ecosystem, pp. 43-51. *In* P. Duvigneaud ed. Productivity of Forest Ecosystem. **Proceeding Brussels Symp**. Paris.

Turnbull, J.W. 1986. Multipurpose Australian Trees and Shrubs: Lesser-Known Species for Fuel Wood and Agroforestry. **ACIAR Monograph No. 1**.

Vanlauwe, B., J. Diels, N. Songinga and R. Merckx. 1997. Residue quality and decomposition: an unsteady relationship, pp.157-166. *In* G. Cadisch and K.E. Galler, eds. **Driven by Native Plant Litter Quality and Decomposition.** Paris.

Varmola, M. 1998. **Teak (*Tectona grandis*) in Central America.** FAO working paper FW/19. Rome.

Versfel, D.B. and D.G.M. Donald. 1991. Litterfall and nutrient release in mature *Pinus radiate* in the south-western cape of south Africa. **For. J.** 156: 61-69.

Viriyabuncha, C. and K. Peawsa-ad. 2002. **Assessment of the Potentiality of Re-afforestation Activities in Climate Change Mitigation**. Royal Forest Dept., Bangkok.

Visaratana, T. 1983. **Structure Characteristics and Canopy gap Regeneration of Dry Evergreen Forest at Sakaerat Environmental Research Station**. M.S. Thesis, Kasetsart University.

Vitousek, P.M., T. Fahey, D.W. Johnson, and M.J. Swift. 1988. Element interactions in forest ecosystems: succession, allometry and input-output budgets. **Biogeochemistry**. 5: 7-34.

Wang, D., F.H. Bormann, A.E. Lugo and R.D. Bowden. 1991. Comparison of nutrient-use efficiency and biomass production in five tropical tree taxa. **For. Ecol. Manage.** 46: 1-21.

Watanabe, Y., T. Masunaga, O. Fashola, A. Agboola, P.K. Oviasuyi and T. Wakatsuki. 2009. *Eucalyptus camaldulensis* and *Pinus caribaea* growth in relation to soil physico-chemical properties in plantation forests in northern Nigeria. **Soil Sci. and Plant Nutrition.** 55: 132–141

Watt, M.J., G. Coker, P.W Clinton, M.R. Davis, R. Parfitt, R. Simcock, L. Garrett, T. Payn, B. Richardson and A. Dunningham, 2005. Defining sustainability of plantation forests through identification of site quality indicators influencing productivity-a national view for New Zealand. **For. Ecol. Manage**. 216: 51–63

Wesemael, B. 1993. Litter decomposition and nutrient distribution in humus profiles in some Mediterranean forests in southern Tuscany. **For. Ecol. Manage.** 57: 99–114.

Wienand, K.T. and W.D. Stock. 1995. Long term phosphorus effects on the litter dynamics of an age sequence of *Pinus elliottii* in the southern cape of south Africa. **For. Ecol. Manage.** 75: 135-146.

Willium, S.T. and T.R.G. Gray. 1974. Decomposition of Litter on Soil Surface, pp. 61 l-632. *In* C.H. Dickson and G.J.F. Pugh, eds. **Biology of Plant Litter Decomposition Vol.II**. Academic Press, New York.

Wise, P.K. and M.G. Pitman. 1981. Nutrient removal and replacement associated with short-rotation eucalypt plantations. **Aus. For**. 44: 142-152.

White, K.J. 1991. **Teak : Some Aspects of Research and Development.** FAO, Bangkok.

Whittaker, R.H. 1975. **Communities and Ecosystems**. MacMillan, New York,

Xu, X., T. Enoki, E. Hirata and Y. Tokashiki. 2003. Pattern and chemical composition of fine litterfall in a subtropical forest in northern Okinawa Island, Japan. **Appl. Ecol**. 4: 229-237.

Yamakura, T., A. Hagigara, S. Sukardjo and H. Ogawa. 1986. Above ground biomass of tropical rain forest stand in Indonesia Borneo. **Vegetation**. 68: 1-158.

Yamashita, N., O. Seiichi and H. Arisman. 2008. Soil changes induces by *Acacia mangium* plantation establishment: comparison with secondary forest and *Imperata cylindrical* grassland soils in south Sumatra, Indonesia. **For. Ecol. Manage.** 254: 362-370.

Yamashita, T. and H. Takeda. 1998. Decomposition and nutrient dynamics of leaf litter in litter bags of two mesh sizes set in two Dipterocarp forest sites in peninsular Malaysia. **Pedobiologie.** 42: 11-21.

Yang, K.C. and J.K. Chim. 2003. The decomposition of leaf litters of some tree species in temperate deciduous forest in Korea II: Changes in nutrient content during litter decomposition. **Korean J. Ecol**. 26: 313-319.

Zhang, Y., X. Peng, Y. Zheng and Y. Lai. 2008. Effort on planting and product development of *Azadirachta indica* in Southwest China. **For. Res.** 19(3): 252-256.

# APPENDIX

**Appendix Table 1** Characteristics of sample trees for stratified clip technique study.

| Spp. | Tree no. | $D_0$ (cm) | DBH (cm) | H (m) | crown cover ($m^2$) | Tree biomass (kg $tree^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | stem | branch | leaf | total |
| Ac | 1 | 15.37 | 10.53 | 11.00 | 14.43 | 40.14 | 12.26 | 3.85 | 56.25 |
| | 2 | 23.80 | 16.64 | 19.90 | 44.34 | 146.85 | 26.14 | 3.73 | 176.72 |
| | 3 | 41.75 | 29.53 | 20.56 | 102.29 | 472.06 | 65.18 | 17.00 | 554.24 |
| | 4 | 40.66 | 34.55 | 20.90 | 102.74 | 613.87 | 51.04 | 23.47 | 688.38 |
| | 5 | 58.13 | 40.66 | 20.56 | 102.29 | 755.37 | 75.41 | 37.24 | 868.02 |
| | average | 35.94 | 26.38 | 18.58 | 73.22 | 405.66 | 42.01 | 17.06 | 464.72 |
| Ai | 1 | 6.17 | 3.95 | 4.20 | 8.11 | 5.98 | 0.75 | 0.36 | 7.09 |
| | 2 | 12.03 | 10.37 | 11.72 | 18.10 | 24.57 | 5.05 | 1.42 | 31.04 |
| | 3 | 21.51 | 15.75 | 15.60 | 21.37 | 95.16 | 10.74 | 4.58 | 110.47 |
| | 4 | 23.04 | 20.84 | 20.77 | 13.86 | 215.58 | 26.24 | 5.13 | 246.94 |
| | 5 | 28.95 | 22.85 | 18.35 | 39.05 | 207.71 | 27.69 | 6.52 | 241.92 |
| | average | 18.34 | 14.75 | 14.13 | 20.10 | 109.80 | 14.09 | 3.60 | 127.49 |
| Pm | 1 | 5.41 | 2.39 | 3.40 | 3.86 | 0.72 | 0.13 | 0.03 | 0.88 |
| | 2 | 8.88 | 5.44 | 6.40 | 11.65 | 3.31 | 0.88 | 0.18 | 4.36 |
| | 3 | 17.02 | 12.82 | 12.00 | 35.53 | 35.39 | 9.09 | 1.62 | 46.10 |
| | 4 | 17.66 | 14.57 | 10.54 | 26.99 | 30.36 | 4.96 | 1.66 | 36.98 |
| | 5 | 30.64 | 20.75 | 15.61 | 41.30 | 119.71 | 24.90 | 8.33 | 152.94 |
| | average | 15.92 | 11.19 | 9.59 | 23.87 | 37.90 | 7.99 | 2.36 | 48.25 |
| Sr | 1 | 4.77 | 2.64 | 3.36 | 2.30 | 1.44 | 0.48 | 0.30 | 2.23 |
| | 2 | 8.37 | 6.11 | 9.00 | 15.52 | 8.18 | 0.86 | 0.64 | 9.69 |
| | 3 | 14.45 | 10.34 | 10.60 | 24.30 | 35.19 | 10.08 | 4.24 | 49.51 |
| | 4 | 16.10 | 12.66 | 10.86 | 28.52 | 48.27 | 11.20 | 3.82 | 63.30 |
| | 5 | 18.55 | 17.25 | 14.45 | 32.30 | 106.15 | 25.11 | 5.52 | 136.77 |
| | average | 12.45 | 9.80 | 9.65 | 20.59 | 39.85 | 9.55 | 2.91 | 52.30 |
| Tg | 1 | 8.40 | 6.94 | 8.50 | 10.67 | 8.05 | 1.25 | 0.76 | 10.06 |
| | 2 | 11.14 | 8.27 | 11.66 | 11.56 | 15.58 | 1.17 | 0.32 | 17.07 |
| | 3 | 18.87 | 14.16 | 17.45 | 17.58 | 59.48 | 6.78 | 2.57 | 68.83 |
| | 4 | 20.20 | 15.75 | 15.21 | 40.17 | 70.44 | 10.22 | 3.55 | 84.21 |
| | 5 | 26.66 | 21.83 | 19.71 | 42.85 | 170.99 | 28.01 | 5.19 | 204.20 |
| | average | 17.05 | 13.39 | 14.51 | 24.57 | 64.91 | 9.49 | 2.48 | 76.87 |
| Xx | 1 | 6.52 | 4.20 | 6.55 | 12.01 | 2.88 | 0.39 | 0.56 | 3.83 |
| | 2 | 10.72 | 6.62 | 9.60 | 15.73 | 17.28 | 3.72 | 1.45 | 22.44 |
| | 3 | 17.82 | 12.41 | 16.60 | 28.01 | 60.00 | 7.31 | 2.33 | 69.65 |
| | 4 | 22.21 | 16.67 | 14.72 | 32.79 | 88.25 | 22.31 | 5.61 | 116.16 |
| | 5 | 27.49 | 23.67 | 22.00 | 39.05 | 282.22 | 32.76 | 10.85 | 325.83 |
| | average | 16.95 | 12.71 | 13.89 | 25.52 | 90.13 | 13.30 | 4.16 | 107.58 |

**Remark**: Ac: *A. crassicarpa*; Ai: *A. indica*; Pm: *P. macrocarpus*; Sr: *S. roxburghii*; Tg: *T. grandis* and Xx: *X. xylocarpa*


**Appendix Figure 1** Above- and below ground biomass study.

**Appendix Figure 2** Litter bags placing and litter decomposition study.

**Appendix Figure 3** Litter on soil surface and soil sample collection.

**Appendix Figure 4** *A. crassicarpa* was broken and up rooted after strong wind throw.

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