DISSERTATION

STUDY ON THE GROWTH OF WHITE BAMBOO *(Dendrocalamus membranaceus Munro)* UNDER DIFFERENT ECOLOGICAL FACTORS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY TRUONG XUAN LE ENTITLED STUDY ON THE GROWTH OF WHITE BAMBOO *(Dendrocalamus membranaceus Munro)* UNDER DIFFERENT ECOLOGICAL FACTORS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

STUDY ON THE GROWTH OF WHITE BAMBOO *(Dendrocalamus membranaceus Munro)* UNDER DIFFERENT ECOLOGICAL FACTORS

White bamboo is one of the most popular and valuable forest products in mountainous areas of Northern Vietnam. Because of its commercial and economic values white bamboo has been planted widely in recent decades. Three levels of white bamboo management are common: pure plantations of bamboo with very little management investment, pure plantations with intensive management, and mixed plantations of bamboo with broad-leaved trees species. Most plantations are bamboo monocultures with low investment ("extensive" plantations, receiving no fertilization or advanced treatments). Extensive management can result in declining culm yield, low economic revenue, reduced soil fertility, and high risk of disease.

Long-term, sustainable management of white bamboo plantations will require improved knowledge about the ecological features of white bamboo in relation to growth. I examined patterns of bamboo growth and light interception in relation to topographic position and management intensity. I also determined how ecological factors relate to white bamboo growth, identifying possible nutrient limitation, and the efficiency of light use as a factor explaining growth patterns.

Topographic position had strong effects on white bamboo growth in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa but not in Luong Son-Hoa Binh. The differences between white bamboo growth on footslopes and hilltops in two these areas were in total culm

volume (42%) in 3-year-and-younger, DBH and height, and number of economically valuable culms in both all-age and 3-year-and-younger calculations.

Management intensity had significant effects on DBH and height in Luong Son-Hoa Binh. Management intensity also affected on total culm volume and culm wall volume in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa, as well as on dry culm mass in Cau Hai-Phu Tho. Pure intensive management had greatest white bamboo growth among the three management intensities.

Topographic position significantly affected culm volume light use efficiency in Cau Hai-Phu Tho; culm DBH and height light use efficiencies in Ngoc Lac-Thanh Hoa; and number of economically valuable culm light use efficiency in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa. Management intensity affected culm DBH light use efficiency in Cau Hai-Phu Tho and Luong Son-Hoa Binh; on culm height light use efficiency in Luong Son-Hoa Binh; on culm volume, culm wall volume; and on dry culm mass light use efficiencies in Cau Hai-Phu Tho.

The 29 plots spanned a range of soil and site conditions, and I examined growth (total culm volume, culm wall volume, dry culm mass, and number of economic valuable culm) in relation to soil moisture, density, bulk density, porosity, pH, organic matter, SiO_2, total and available content of nitrogen, potassium, and phosphorus). Total culm volume correlated well with soil moisture. Culm wall volume had strong correlation with soil pH, and a moderate correlation with pH was also demonstrated by dry culm mass. The number of economically valuable culms correlated moderately with soil pH and cation exchange capacity. A fertilization experiment of 4 fertilizers (nitrogen, potassium, phosphate, and N+P+K) in 12 plots in Cau Hai showed a growth increase in response to

N (for total culm volume, culm wall volume, and dry culm mass growth). The effects of other fertilizers were not significant, perhaps in part because of very high variation in growth among plots and limited time (one growing season). Light interception and light use efficiency showed only weak relationships with white bamboo growth, probably because my measures of light interception included light captured by non-bamboo vegetation in the plots.

In general, this study supported the hypothesis that topographic position and management intensity strongly influence white bamboo growth. Total culm volume correlated well with soil moisture, underscoring the fundamental importance of water supply in sustaining bamboo growth. Soil pH had strong and medium positive relationships with culm wall volume and dry culm mass, respectively. Number of economic valuable culm had medium regression with soil pH and cation exchange capacity. There was a difference in white bamboo growth across four fertilizer experiments but the difference was only significant for nitrogen. Light interception and light interception efficiency had weak relationships with white bamboo growth features (total culm volume, culm wall volume, dry culm mass, and number of economic value culm) and most of these regressions were not significant.

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Introduction

White bamboo is very popular, useful and valuable to farmers in rural mountainous areas of Southeast Asia. In recent decades white bamboo has attracted a great number of scientists focusing on silvicultural practices for propagation and cultivation methods, including nutrition management and mixed-species plantations with trees. This work has developed with a strong empirical approach, with little attention to ecological factors that determine growth.

I researched the effect of ecological factors on the growth of white bamboo in northern Vietnam. Specifically, I focused on light interception, soil nutrients (total and available nitrogen, phosphorus, and potassium), soil silica content, soil pH, soil cation exchange capacity, and soil physical properties (soil moisture, soil density, soil bulk density, and soil porosity), and tested the correlation between growth indicators and these ecological factors. The research was implemented in three concentrated areas of white bamboo plantation of Vietnam: Cau Hai- Phu Tho, Ngoc Lac- Thanh Hoa, and Luong Son- Hoa Binh in one year and two months (from October 2007 to November 2008).

The dissertation has four chapters:

Chapter 1: Biology, Ecology and Management of White Bamboo. This chapter provides a general view of white bamboo biological, ecological features and the status of recent white bamboo management in Vietnam and the research ideas.

Chapter 2: The growth of white bamboo in relation to topographic position and management intensity. This chapter compares the culm growth features (DBH, height, total volume, wall volume, fresh and dry mass, and number of economic valuable culm) in two topographic positions (footslope and hilltop) and in three management modes (Acacia- mixture, pure intensive, and pure extensive).

Chapter 3: The effects of ecological factors and fertilizers on white bamboo growth. This chapter elucidates the correlation between white bamboo culm growth (total culm volume, culm wall volume, fresh and dry mass, number of economic valuable culm) and ecological factors (total and available soil nitrogen, phosphorus, and potassium contents, soil SiO2 content, soil pH, soil cation exchange capacity, soil moisture, soil density, soil bulk density, and soil porosity).

Chapter 4: Conclusions and Management Recommendations. This chapter summarizes the major research results of the research, its limitations, and proposes approaches for further studies and future management of white bamboo.

Chapter 1

BIOLOGY, ECOLOGY AND MANAGEMENT OF WHITE BAMBOO

White bamboo is distributed throughout South Yunnan province of China, extending southward across much of Laos, Myanmar, Northern of Thailand, and northern Vietnam. This species is the most important and most extensive wild species of bamboo in subtropical China, occurring in pure bamboo forests or mixed with broad-leaved trees (Li Dezhu, Chris Stapleton 2006). In this chapter I provide an overview of white bamboo biology, its ecological interactions, and some aspects of silvicultural and use of products.

In Vietnam, white bamboo is very well known and widely used in rural areas. It grows naturally in scattered clumps along the banks of Ma River, Son La Province. In other places this species is found only in plantations. White bamboo plantations covered about 47,000 ha in Vietnam in 1999, accounting for 64% of the total area of bamboo plantations. Plantations of white bamboo expanded to over 80,000 ha by 2004, with 10-20% of the plantations for watershed protection and special uses, and the rest for production (Forest Ranger of Vietnam 2005).

Biological characteristics

White bamboo is a thornless, pachymorph (a short, thick type of rhizome) bamboo that grows into small clumps. Culms are straight, commonly attaining 14 m in height and occasionally 18-20 m height (Photo 1.1.1). The diameters of fully grown culms are typically 10-12 cm, with 25-35 cm between nodes (65-75 internodes/culm).

Culm walls are 1-2 cm thick; the thickness of culm wall is important for some uses of bamboo (particularly construction).

The leaves are typically 10-20 cm long and 1-2 cm wide, sharp saw-toothed edges. Leaf tapers from a round (or nearly round) bottom to a point. White bamboo sheaths are 20-25 cm long and deciduous, with brown hairs on the outer side. Auricles expand little, and ligules are triangle-shaped, 5-6 cm long, with hair in both sides (Photo 1.1.2).

White bamboo can flower in separate clumps or culms, but few seeds are produced (and most seeds are not viable). Culms die after flowering, but root systems persist.

The roots of white bamboo are fibrous, with diameters less than 1 mm. Roots develop from the base and lower portions of the culms, Roots can reach 60 cm depth and 10 m distant from the clump. Roots are concentrated in the upper soil, with more than half occurring in the top 20 cm (and 80% in the top 30 cm) (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

White bamboo mechanical properties: White bamboo has a density of 0.67 kg/L for culm walls (not including inside air space). The compression and tensile strength are very high because white bamboo has long fibers. Split strength is low. White bamboo can be used to manufacture bamboo-based boards. White bamboo fibers are about 2.9 mm long and 8 μm wide. Wall fiber thickness is 8.5 μm, and the length/width ratio is 165. White bamboo culms are composed of 54% cellulose, 22% lignin, and 19% pentose.

Fresh and dry weight: A typical size for a culm of white bamboo would be a diameter of 8 cm, height 14 m, fresh weight 27.5 kg, and dry weight 14.6 kg (Wood Mechanical and Chemical Properties Department 1978-1979).

Growth features

Culm base growth

The growth of white bamboo proceeds from cells at the base of culm. The culm base also stores essential nutrients and starch reserves to supply aboveground expansion and growth of culms. The culm base is relatively short and appears like part of the culm that is underground. Buds from the culm base develop into new base, shoot and culm. Roots proliferate from around the culm base.

Growth is initiated from the base (underground) of the mother culm in the spring. In the first growth phase, the base develops horizontally for a short distance then turns vertically at the beginning of the rainy season to form a bamboo shoot and culm. The culms develop as clumps, commonly with 10 to 30 culms per clump.

Shoot and culm growth

The growth of shoot is concentrated at the beginning of the rainy season (June and July in Northern Vietnam), when culms expand to 70% of their final height and diameter. The season of shoot elongation and the number of culms per clump decline as white bamboo culms get old. About one-third to half of the initiated shoots can mature into full size culms. The other shoots die or may be collected for food (Tran Nguyen Giang, Luu Pham Hoanh 1977).

The height growth of new shoots is slow for about 20 days, averaging only about 10 cm/day. From 20-40 days after initiation, shoots accelerate to growth rates of 20-30 cm/day, sometimes reaching maximum rates of 60-70 cm/day. Height growth slows after about 45 days, until the culm is fully formed and height growth stops by about day 55. Interestingly, height growth is more rapid at night (about 3 times faster) than during the day.

As a monocot, the growth in diameter of white bamboo is different from the growth of trees. White bamboo only grows in height, with no secondary growth leading to increased diameter through the growing season. Culms taper very little from the base to near the top. The highest diameter of the white bamboo internodes is at the 20-30% of the height from the base. From this point, the internodes diameter does not decrease to the base but to the top. Diameter at breast height of white bamboo is 10-12 cm.

The distance between internodes (internodes length) is shortest near the base. The internodes in the 20 to 60% of the total of internodes (from the base) have the highest internodes length. The average internodes length of white bamboo is 20-30 cm.

In trees, the diameter of stems tapers with increasing height, as the physical stress on the stem declines with height into the canopy. The same stresses are accommodated in white bamboo by changes in the thickness of the internode wall rather than tapering of the culms. White bamboo planted in fertile soil at age 5 has internode wall thickness of 2.4 cm with the internodes near the base and 0.1 cm with the internodes near the top. Internode wall thickness is thinner (about 75-91%) in white bamboo growing in shade than in open areas.

White bamboo starts to develop branches above the 10^{th} node from the base, with most branches developing above the 20^{th} node. One node usually has one main branch and several auxiliary braches. Main branch may reach several meter length. Branches comprise only a small amount of the total biomass. All leaves are on branches, not on the culm. There are primary and secondary branches (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

Ecological and physiological characteristics of white bamboo

In general, white bamboo is shade intolerant but it can tolerate shade as low as 0.4 (40%) of full sunlight. In shoot elongation period, white bamboo does not require much light, and high light intensity can actually retard shoot growth. White bamboo can be mixed with timber trees, especially with legume trees, to form 2-layer forest: timber tree with the canopy cover from 30-40% (70-100 trees/ha), with a second layer of white bamboo with canopy cover of 70-80%. Mixed forests provide a sufficient light intensity for bamboo shoot growth and also increase microclimate humidity, protect shoots from strong wind, and may supply more nitrogen for white bamboo (though this expectation may warrant more experimentation) (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

White bamboo grows best on moist sites that are not waterlogged. White bamboo has a relatively high requirement for nutrients, especially nitrogen and potassium (total nitrogen content $\geq$ 0.25%, K_2O available $\geq$ 10mg/kg soil). Interestingly, the need for phosphate appears to be low. Unlike trees, all bamboo tissues are high in silica, and some plantations show growth responses to applications of silica (Nguyen Ngoc Binh 1976-1980).

White bamboo requires a warm, moist climate, with mean temperatures of 22-23° C and annual ranges from 6 to 35°C. Rainfall ranges from about 1600-1800 mm/year, and distinct rainy and dry seasons are characteristic (though seasonality in rainfall may or may not be important). (Do Dinh Sam at el. 2000). Humidity averages 85%, highest more than 90%, and lowest 70% (Do Nhu Chien 2000).

White bamboo grows well at elevations less than 300 m in Vietnam, on slopes up to 20°. Growth of white bamboo declines sharply at higher elevations and on steeper slopes, and shoots and culms break easily in high winds. The best growth of white bamboo occurs on clayey loam soils, those are deep and well drained. White bamboo does not grow well on sandy soils, highly eroded sites, or soils with frequent flooding or high salinity (Nguyen Ngoc Binh 1976-1980).

Products and economic value

White bamboo is commonly used in construction, including houses, fences, bridges, and rafts. It is also used for making agricultural tools, for weaving, for making chopsticks, and even toothpicks (Photo 1.2.1). Many handicraft products are made from various parts of white bamboo. Young shoots provide a healthy food that can be eaten fresh or dry. Young leaves are fed to livestock.

With the development of modern processing technology, white bamboo raw material can be processed into high value-added products like bamboo mats, flooring boards, and furniture (Photo 1.2.2). The long fibers of white bamboo yield a valuable pulp for making paper. Culms, bases and leftover parts of white bamboo can be used to produce charcoal and active charcoal. The fluid extracted from bamboo culms, bamboo leaves, and charcoal product processing can be used in making cosmetic and medicinal products. As mentioned above, white bamboo is also valuable for watershed protection (widely used, for example, in Thanh Hoa province). White bamboo is one of the species used to help people in the hilly and mountainous areas to eliminate starvation, reduce poverty and gain wealth (Photo 1.2.3). In mature white bamboo plantations (from 8 years old onwards), people can harvest about 1250 culms/year/ha, yielding $860 US, plus $94 from shoot production, for a gross income of $954. Accounting for labor costs leaves a net income of about $904 US/ha/year. One household with 6-8 ha mature white bamboo can earn $5,424.00 to $7,232.00 US per year, while the average income of farmer in Vietnam is only $380 US/farmer (about $1,900 US/household/year) (Nguyen Ngoc Binh, Pham Duc Tuan 2007). In addition, with the development of technology the value of products that can be made from white bamboo is increasing and people are deriving more benefits.

Planting techniques

Material for planting

Because of the need for plantlets to establish new plantation, scientists have studied and applied advanced methods to propagate white bamboo. So far four basic approaches are used for establishing new planting of white bamboo.

Propagate white bamboo from stump-base. This is a traditional way to propagate white bamboo.

The standard: People select "medium" white bamboo that is 8 to 12 months old, grows well and is not affected by disease to propagate. Culms are cut, leaving only some internodes next to the base (about 50-60 cm long). The stump-bases are removed from the bamboo clump with caution not to break the buds. The root around the base is shortened then the stump- bases are transported to the site and planted as soon as possible.

Disadvantage: This method of propagation cannot supply a great number of bamboo stump-bases for plantation in large area. The survivor rate is low if the weather is not favorable. The stump-bases are heavy and bulky, and expensive to transport.

Propagate from stump sprout (chet).

The standard: Strong bamboo plants, 1 to 2 years-old, and not affected by disease are selected to propagate.

The culms are removed close to the ground. After a short period, the buds on the base grow up to form new shoots (with bases and culms called "chet" in Vietnamese). Each mother bamboo can produce new bamboo shoots that are small because the lack of nutrients from the mother bamboo. After 8 to 12 months, new bamboos are separated from the mother's base and transported to planting site.

Advantage: This method gives more bamboo plantlets than propagating from stump and base because from one base can provide 2-3 new bamboo plantlets. New bamboo plantlets are also lighter than the mother stump and base so they cost less to transport.

Disadvantage: They are still insufficient in quantity for planting large areas.

Propagate by culms. This method was studied by Forest Science Institute of Vietnam and applied in white bamboo plantation in Ngoc Lac district, Thanh Hoa province since 1976-1977 (Tran Nguyen Giang and Luu Pham Hoanh 1977).

The standard for white bamboo plantlets: Age: 5 to 6 months old. There is a new generation of fully developed bamboos (have leaves and pass shoot period). Healthy bamboo plants 12 to 18 months old (diameter 6-8 cm) are chosen. If the culm has branches, one node is cut with 2 parts of internodes in both sides. The top of the branches are removed, only 3 internodes close to the base of branches are kept, and all leaves are removed. The buds on the branch's bases (the bottom of the branch that connects to the culm) must be protected carefully. If the culm has only buds, one of internodes with 2 nodes that have at least one bud is cut. The cuttings are put in a root stimulating solution 2.4.5T (2.4.5 tri chlorophenoxy acetic acid), 30 mg/litter for 10-12 hours. These cuttings are cultivated in the nursery for 5 to 6 months and shielded from the sun with the shade 50%. The shield is 1 to 1.5 m high to make it is easy for tending. The soil is watered, weeded, and gently turned over regularly.

Advantage: The number of bamboo plantlets is much higher than that in stump-base and stump sprout.

Disadvantage: Often planted by bare-root so the dead plantlet rate is high when the weather is not favorable. Transportation costs are still high.

Propagate from branch.

The standard: Healthy culms are chosen after 12 to 18 months, using only culms with several branches and no flowers. The branches are 3 to 10 months old. If branches are older than 10 months the old branches are cut, the branch bases with buds are left for the new branches. Branch diameter is at least 0.8 cm. There are two methods to propagate white bamboo from branches:

Layering

The culm is cut 2/3 of its diameter in a position about 50-70 cm from the base, then partly cut the opposite side. The culm is laid down apart from the clump. Two rows of branches in the culm should be parallel.

Only 1/3 of branches are used on the base side for layering because the branches on the top are so small. The top of the branch is cut by sharp knife, leave 3 internodes, about 30-40 cm long. Leaves on the top of the culm are kept for photosynthesis, supplying nutrients and water for layered branches.

The branch base is cut 4/5 from top down by small, sharp saw, leaving 1/5 uncut. This is done carefully so as not to damage the buds on the branch base. Small root and branches around the branch base should be cut.

The branch base is covered by 250-300 grams mixture of mud in pond and straw with the ratio 2:1. This mixture should be in moist condition. If the mixture is wet, it will make buds rotten. Otherwise, it will extend the rooting period.

The mixture is wrapped by plastic sheet with 20-25 cm wide, 30-40 cm long then tied both bottom and top tightly to maintain moisture. After 20 days, the branch base is examined for the presence of newly formed roots. If there are a lot of root with light yellow color the branch should be cut and brought to the nursery for cultivating. (In favorable weather the branch can root in 15 days, otherwise it may need 25 to 30 days).

Cultivating branches in the nursery

For long distance transportation, branches need to be dipped in a mixture of mud and completely decomposed manure after removing plastic covers. Nursery areas need to be flat, and near a water source, with loose soil and good drainage. Nursery soil is basally fertilized by manure and nitrogen, phosphate, and potassium. The area is plowed deep and raked carefully to make beds. The space for branches in the bed is 25 cm x 40 cm or 25 cm x 30 cm. The branches are planted at an angle (60^0 to the bed) and buds on the branch on two sides of the bed. The soil around the branch base is compacted.

The sun shield is made for the cultivated branches with 50% shade. The shield is 1.2 to 1.5 meters high. The beds are watered regularly to ensure the suitable moisture for branches. The surface soil is weeded, broken gently, and applied additional completely decomposed manure. Pest and disease need to be controlled, especially foliage insects.

The amount of water should be decreased over time, for the 1st 10 days, white bamboo need to be watered once a day with the amount of 10 liters per square meter. In the next 10 days, 4 to 5 days one time, 10 liters per square meter. Then 10 to 20 days one time, also 10 liters per square meter.

After 6 to 8 months in the nursery (when having shoot and leaves) the branches are transported to the sites for planting.

Transplanting

The branches from 3 to 10 months old on the 12 to 16 months old culms in dark green color with diameter bigger than 1 cm with bases are selected. The base is cut closely to the culm. The top is removed, only 3-4 internodes with the length about 35-40 cm are kept. The branch bases are put in the root stimulating solution 2.4.5T (30 mg/liter) for 8-10 hours right after cutting. After that the bases are put in the moist sand or sawdust in 20-25 days then stored in the open and cool place. The branches are observed regularly and the well developed root and bud ones are picked out, brought to nursery for cultivating. Branches are cultivated in the nursery for about 6-8 months until shoot goes out and has leaves. Shade is 50% and the shield is 1.2-1.5 m high (Le Quang Lien 1999).

Advantage: The number of the bamboo plantlets from a bamboo culm is high, and can meet the requirement for white bamboo plantations in a large area. The survival rate is high because branch bases are usually containerized, and the costs of labor and transportation are low. In the first 5 years, the growth of white bamboo plantation from the culm is the best then from the base-stump, stump sprout, and the last is from branches. From the eighth year onward, there is no significant difference in growth between plantations from different materials (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

White bamboo planting techniques

Site selection. White bamboo needs fertile soil, relatively rich in humus, nitrogen, and potassium. Soils are best suited with heavy textures (high clay), high porosity, good drainage, and moist almost around the year.

Site preparation. Sites commonly used for white bamboo plantations are in human-impacted natural forests or low-volume secondary forests. Planting white bamboo follows the cutting of all the vegetation (though sometimes leguminous trees are retained, but not more than 100 well-distributed trees/ha). Various experiments have shown that planting holes should be 60 x 60 x 40 cm (length x width x depth). When digging the holes the surface soil (0-10 cm) should be set aside separately. White bamboo need to be basally fertilized by completely decomposed manure with 5-10 kg/hole. The amount of manure should be increased if the soil is poor. The holes should be dug a month ahead the planting season. The hole is filled to almost full; the surface soil is on the top. The soil should not be compacted.

Density. The space between bamboos is about 4 m, between rows is about 10 m, giving 200 to 300 bamboo plants/ha. Bamboos are planted staggered, with one row in the middle of the two other bamboos in the row next to it).

Planting season. The best time for planting white bamboo (in northern Vietnam) is in March because of sustained, light rains that keep soils moist White bamboo can also be planted in fall (August or September), but the bamboo will shoot the following year.

Planting materials. The most popular materials for white bamboo plantation are from culms or branches. Plantlets developed from culms are 5 to 6 months old. There is one fully developed generation of shoot (with leaves). Plantlets have healthy and mature roots (roots have brown color). Plantlets developed from branches are 6 to 8 months old and have at least one shoot (with leaves). Plantlets should have healthy and mature roots (roots have brown color).

Planting techniques. The containerized plantlets should be used in planting white bamboo plantation. A part of the top of the plantlet is cut by a sharp knife; 50-60 cm long is left uncut. The holes with dimension 60 x 60 x 40 cm are dug one month ahead the planting time then filled up by manure and surface soil then dug about 30 cm deep one month latter for planting. The plastic cover of the container is removed; the plantlet is put in the center of the hole. The plantlet container is filled over by fine grained soil. The soil around the plantlet container is compacted then covered by 10-12 cm layer of soil. The holes should be covered by litter or dry leaves to keep the soil moist. After planting, the hole should be a little hollow. In the high rainfall area, the soil cover the hole should be higher than that around the hole to protect the bamboo from waterlogged.

Tending

Tending work is applied from 3 to 4 years onward. In 1st year: tending 3-4 times, 2nd year: tending 2 times, 3rd and 4th years: tending once a year. The creepers, bushes are cut, the depressing weeds are removed. Hoe and mound around white bamboo clump in an area of 1 m diameter. The soil is hoed 10-15 cm deep and white bamboo bases are covered by litter or dry leaves. In infertile soils, more manure and nitrogen, potassium, and phosphate are needed.

Cleaning

After planting 4-5 years the white bamboo plantations need to be cleanly cut. All old culms (older than 4 to 5 years) are removed, and broken, topless, damaged culms are cut. Residues should be shred and properly arranged or removed from the plantation.

Disease control

The most dangerous insect for the white bamboo shoot is the weevil (*Cyrtrachelus longimanus Fab).* Weevils can damage 50-60 % of the total shoot in one year (Photo 3.1.1). Insecticide Bi 58 is used to control weevils, with applications of 1:120 concentration sprayed at a rate of about 10 mL for each bamboo shoot. Mature weevils can also be caught and killed by hand. Weevils have a habit of pretending to die to evade natural enemies. If the bamboo culms are shaken, weevils will pretend to die then fall down. This work can be done in the morning or afternoon, the time for the mature weevils to leave eggs on the young shoots. Pupae and mature weevils in the soil can be killed by using hoe to turn up the soil around the white bamboo clump with the diameter 1 m and the depth 20-25 cm to change the ecological conditions or make it easy for natural enemies to find and kill weevils (Ngo Quang De 1994).

The most popular and destructive disease is witch-broom. This disease is caused by a fungus species *Balansia take.* If a clump is infected by witch-broom disease, all infected culms must be cut and removed from the plantation then burned. Fungicide is applied on the infected bases immediately (Photo 3.1.2).

Currently, there is a new disease that makes white bamboo culms small and die then leaves purple stripes on the culms (Photo 1.3.3). This disease is easy to spread and damage many bamboo culms. So far, there has been not any effective control method for this disease.

White bamboo harvesting

White bamboo plantations are harvested with a "culm-by-culm" selection felling system. The felling cycle is 2-4 years and the cutting intensity is at 1/4 to 2/3 of the standing stock in term of existing culms. The first harvesting occurs after 3 years. The exploitation of bamboo shoots for foodstuff processing could be done at the end of the bamboo shoot growing season and when the new regrowth of bamboo reach the removed ones each year (Ministry of Forestry of Vietnam 1993).

After planting 6 years, salvage logging should be done for the white bamboo plantation. From 7th year onward bamboo plantations give stable and regular yield and white bamboo culm in these plantations can be harvested annually, about 1250 culms per ha in average (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

Experiments with 3 levels of felling intensity: *high intensity felling* (cut all white bamboo culms that are older than 1 year); *medium intensity felling* (cut all culms that are older than 2 years); and *low intensity felling* (cut all the culms that are older than 3 years) have shown that medium intensity felling works best, giving the greatest number of regenerating culms. Diameters and heights are also relatively high after applying this method. The annual yield is from 800 to 1200 culms/ha, comprising 25-30% total culms in the plantation (Tran Nguyen Giang 1997).

The felling season is in the dry season, the off season for white bamboo culm growth (from November this year to February next year in northern Vietnam). Felling rotation is 1, 2, or 3 years. When cutting the culms the cutting position should be as low as possible because high leftover stumps can inhibit young bamboo culms growth. All branches and tops of the cutting bamboo should be removed from the white bamboo clumps. White bamboo plantations need to be cleaned and fertilized after felling (Ngo Quang De 1994).

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FIGURES

Photo 1.1 White bamboo morphological features

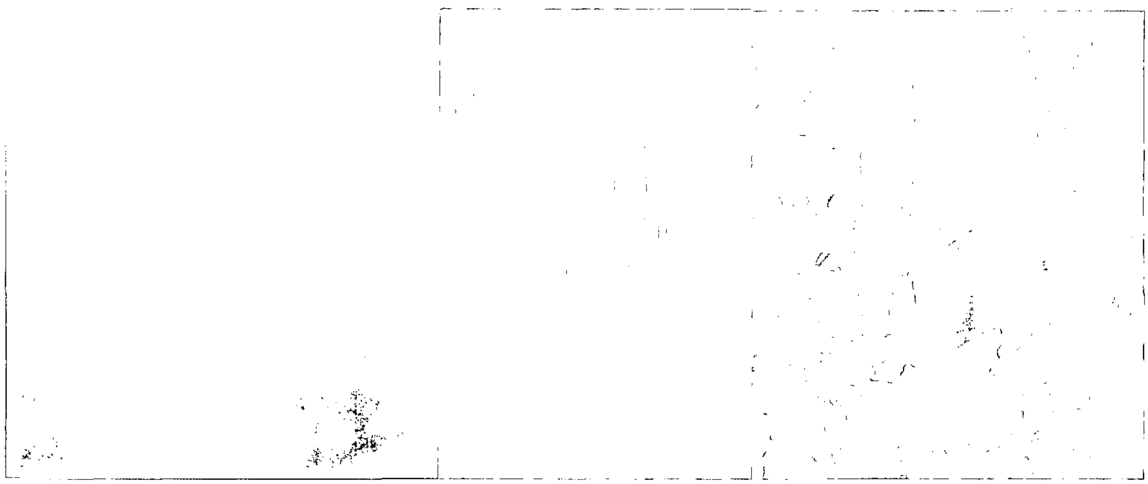

Photo by Truong Le

1.1.1 White bamboo plantation, clump, and shoot

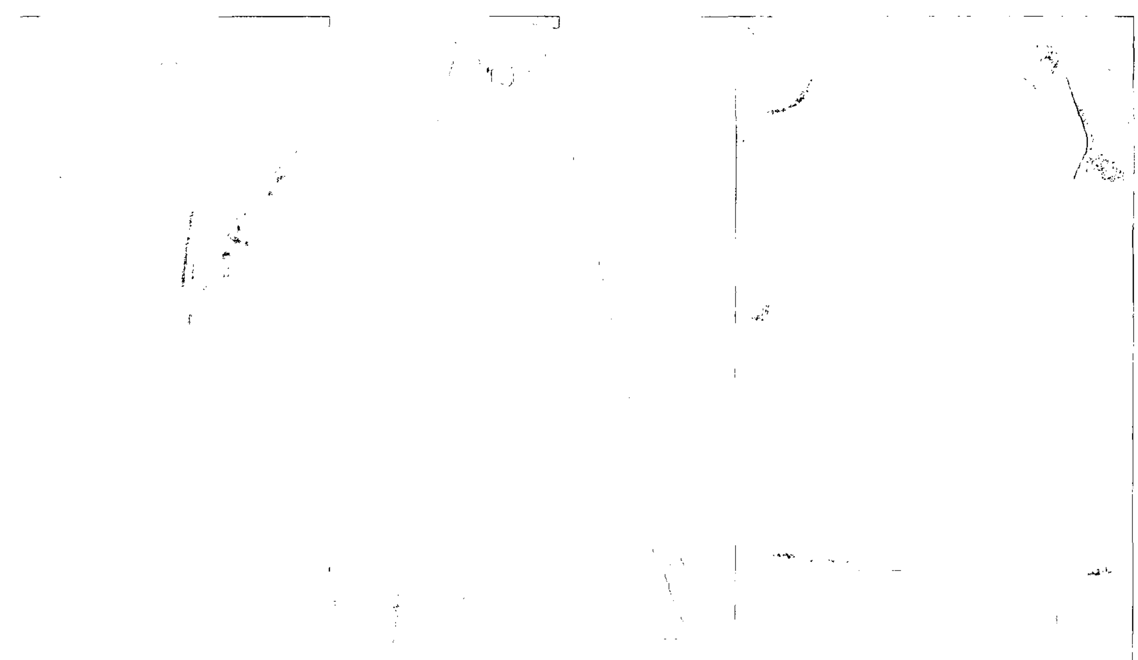

Photo by Son Thanh Le

1.1.2 White bamboo leaves and sheath (up side and down side)

Photo1.2 White bamboo uses

Photo by Truong Le

1.2.1 White bamboo house and white bamboo class room

Photo by Truong Le

1.2.2 White bamboo rod and bamboo mat making

Photo by Truong Le

1.2.3 White bamboo culms and one way of transportation

1.3 White bamboo affected by disease and management

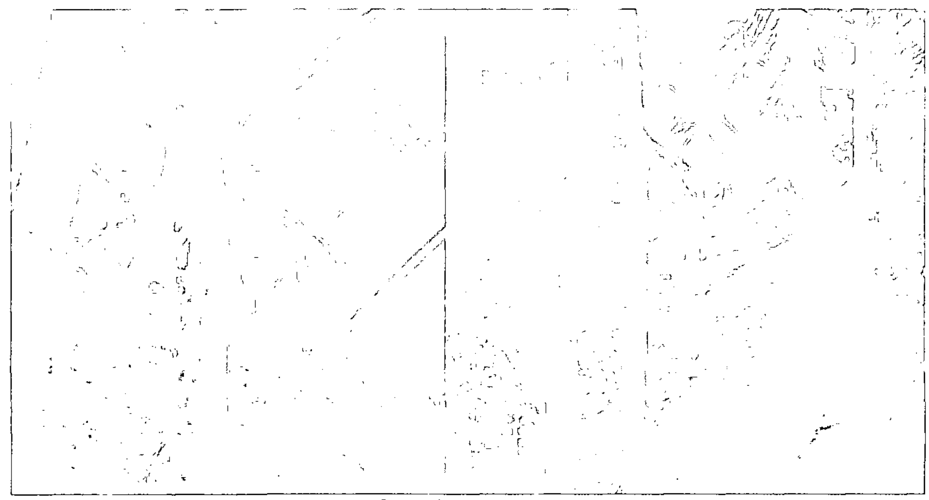

Photo by Truong Le

1.3.1 White bamboo affected by weevil

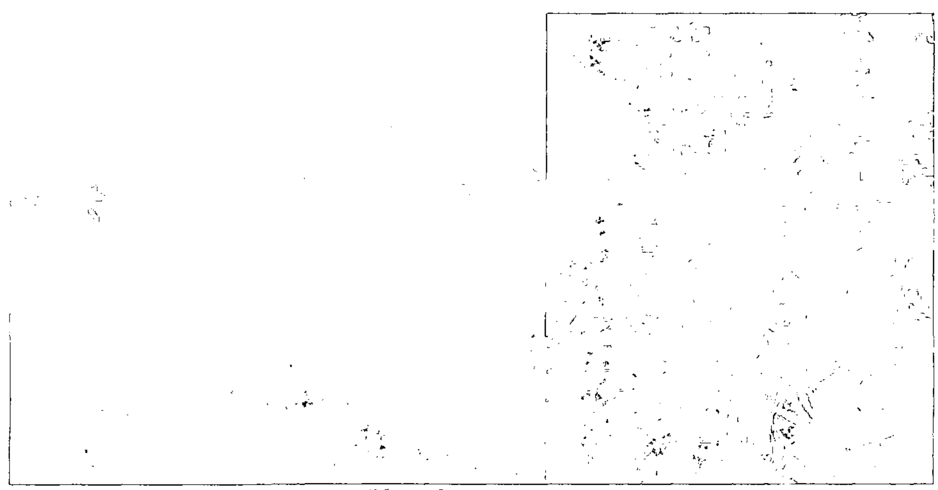

Photo by Truong Le

1.3.2. White bamboo affected by witch-broom

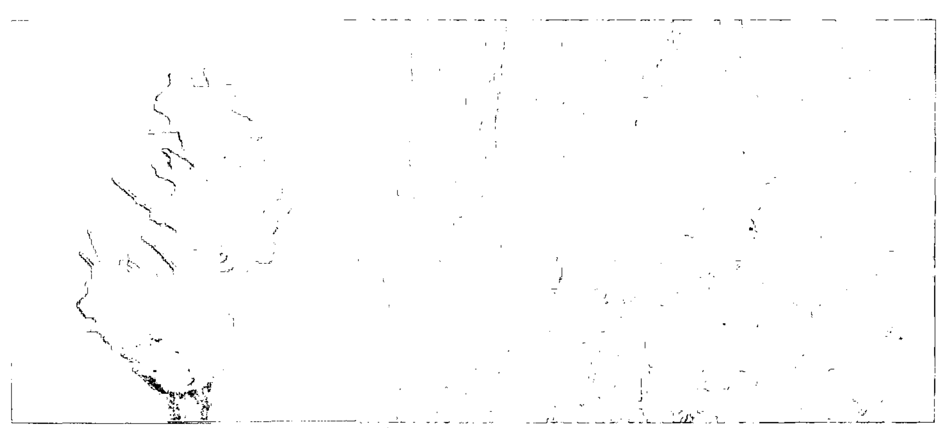

Photo by Truong Le

1.3.3. White bamboo affected by purple strips and management

Chapter 2

THE GROWTH OF WHITE BAMBOO IN RELATION TO TOPOGRAPHIC POSITION AND MANAGEMENT INTENSITY

Abstract: Topographical position and management intensity may influence white bamboo growth. I tested the hypotheses that white bamboo planted on footslopes grows better than white bamboo planted on hilltops, that different management intensities have various effects on bamboo growth, and that there is a difference in light use efficiency of white bamboo on different topographical position and management intensity. The diameter at breast height (DBH), height, total culm volume, culm wall volume, culm dry mass, and number of economic valuable culms collected in 29 plots in three areas (Cau Hai-Phu Tho, Ngoc Lac-Thanh Hoa, and Luong Son-Hoa Binh) were used in testing the hypotheses. Topographic position had strong effects on white bamboo growth in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa but not in Luong Son- Hoa Binh. The differences between white bamboo grown on footslopes and hilltops were 42% in total culm volume in 3-year-and-younger, 13% in DBH, 8% in culm height in Cau Hai-Phu Tho. In Ngoc Lac-Thanh Hoa white bamboo planted on footslopes had 29% larger DBH, 39% greater height than that on the hilltops. The number of economically valuable culms of footslope white bamboo also higher than that of white bamboo on hilltop in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa.

Management intensity had significant effect on total culm volume in Cau Hai-Phu Tho (in both all-age and 3-year-and-younger calculations) and in Ngoc Lac-Thanh Hoa (in 3-year-and-younger calculation), on culm wall volume in Cau Hai-Phu Tho and Ngoc

Lac-Thanh Hoa, on dry culm mass in Cau Hai-Phu Tho (in both calculation methods), and in DBH and height in Luong Son-Hoa Binh. In all three areas white bamboo in pure intensive management always had greatest growth features.

Topographic position had significant effect on culm volume light use efficiency in Cau Hai-Phu Tho, culm DBH and height light use efficiencies in Ngoc Lac-Thanh Hoa, and number of economically valuable culm light use efficiency in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa. Management intensity had significant effect on culm DBH light use efficiency in Cau Hai-Phu Tho and Luong Son-Hoa Binh, on culm height light use efficiency in Luong Son-Hoa Binh, on culm volume, culm wall volume, and dry culm mass light use efficiencies in Cau Hai-Phu Tho.

Keywords: topographic position, footslope, hilltop, management intensity, pure intensive, growth indicators, DBH, height, total culm volume, culm wall volume, culm dry mass, number of economic valuable culm, light use efficiency.

Introduction

Topographic position and management intensity strongly influence bamboo growth. White bamboo grows best in humid, tropical climates, in full sun on relatively flat sites with well-drained soils of high nutrient supply. White bamboo's preferred soils are laterite and black limestone (Li Dezhu, Chris Stapleton 2006). The appropriate soil for planting white bamboo is the soil that has porosity of the surface layer (0-10 cm) from 53-68%, clay from light to heavy, surface infiltration rate $\geq$ 5 mm/minute, depth > 30 cm, pH (H_2O): 4.8-5.9, pH (KCl): 4.2-5.0, soil organic matter $\geq$ 3.5%, total nitrogen $\geq$ 0.25%, K_2O available $\geq$ 10 mg/100g (Nguyen Ngoc Binh 1976-1980).

Management intensity also affects growth of bamboo in general, and white bamboo in particular. The internode lengths of white bamboo planted in three modes: slash and burn, clear cutting plantation, and strip plantation are 23.2 cm, 27.1 cm and 29.2 cm, respectively. The means of internodes diameter are 3.0 cm, 5.0 cm, and 5.1 cm for white bamboo planted 4 years in these lands (Ngo Quang De 1994).

High-intensity harvesting (culms 2 years or older are cut, only culms 1 years old are left, cutting rotation is 2 years) increases the number of shoots in a bamboo plantation, but the shoots remain smaller. Low harvesting intensity (culms from 4 years or older are cut, culms 1, 2 and 3 years old are left) has fewer, but larger shoots. Medium harvesting intensity (culms from 3 years or older are cut, culms 1 and 2 years old are left, cutting rotation of 2 years) is the most appropriate for white bamboo plantation management because under this harvesting intensity white bamboo have more shoots (about 80% of high harvesting intensity), and the shoots are big and tall (Tran Nguyen Giang 1977).

Research on permanent plots in 5 years (1976-1990) with a considerable number of soil samples showed that in pure plantations of white bamboo, soil porosity, field capacity, moisture, pH, organic matter, total nitrogen, K_2O, and clay content decline. For example, clay content declined from 73.5% in first year to 66.8% in fifth year, in soil depth 0-10 cm. These changes in site factors strongly reduce white bamboo growth, especially in already-poor sites. Mixing white bamboo with trees *(Erythrophloeum fordii, Pelthophorum tonkinensis, Ormosia henryi, Ormosia pinnata)* with low density (70-100 trees/ha) helps slow down the destruction of soil physical properties and maintain soil nutrients and soil moisture via increasing humus content by decomposing litter from trees. In addition, mixing with trees can reduce disease and wind damage for white bamboo shoots, hence improving culm quality (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

White bamboo mixed with broad leaf trees in Phu Tho province, Vietnam is the ideal way for white bamboo plantation in degraded hill soil because broad leaf trees can improve soil properties under a white bamboo plantation canopy. Research on four treatments of white bamboo mixed with different broad leaf trees and one control pure white bamboo in 7 years (1995-2000) in Cau Hai-Phu Tho indicated that nutrients in soil under white bamboo mixed with *Acacia mangium* plantations were much higher than under pure plantations of white bamboo. The ratios of soil organic matter, available nitrogen, phosphate, and potassium between mixed and pure white bamboo plantations in 0-20 cm soil depth were 1.6, 1.5, 1.4, and 2.1 respectively (Nguyen Truong Thanh 2002).

White bamboo mixed with timber plantation grows better than that in pure white bamboo plantations. A study on white bamboo growth in white bamboo mixed with nitrogen-fixing *Acacia mangium* and in white bamboo planted under degraded forest canopy showed that white bamboo planted under *Acacia mangium* and degraded forest (with tree canopy cover from 0.3 to 0.5) grew better than in bamboo monocultures. Soil is in better condition and biodiversity is higher than in the mono culture (Le Xuan Truong 2002).

Intensive cultivation of bamboo can more than double bamboo growth. In China intensively managed stands of moso bamboo *(Phyllostachys pubescens)* had higher, more stable growth than stands managed with low intensity. The intensive management moso bamboo plantation gave 20-40 Mg culm $ha^{-1}yr^{-1}$, 5-10 Mg shoot $ha^{-1}yr^{-1}$, while these values in extensive management were only 5 Mg culm $ha^{-1}yr^{-1}$ and less than 1 Mg $ha^{-1}yr^{-1}$ (Zhou Fangchun 2002)

This chapter explores the hypothesis that white bamboo planted on footslope grows better than white bamboo planted on hilltops, and different management intensities have various effects on bamboo growth. The objectives of this study were to elucidate the impact of topographical position and management intensity on white bamboo growth, as determined by DBH, height, volume, mass, commercial quality of culms and light use efficiency in three areas in Vietnam with extensive plantations of white bamboo. These objectives addressed three questions:

1. Is there any difference in growth of white bamboo planted on different topographic positions?
2. Does intensive management increase white bamboo growth?
3. Is there any difference in light use efficiency of white bamboo on different topographic positions and across management intensities?

Through this study I want to make general inferences about the growth of white bamboo under different topographic positions and management intensities. Moreover, this study may provide useful information for sustainable management of white bamboo plantations, increasing commercial value of white bamboo culms, controlling risks of disease and other natural factors, and maintaining soil fertility.

Materials and method

Site description

White bamboo plantations were planted by seedlings propagated from culm or branch in 1994-1995 in 3 areas: Cau Hai, Phu Tho at $21^0 33'25"$ N and $105^0 11'21"$ E; Luong Son, Hoa Binh at $20^0 54'09"$ N and $105^0 28'33"$ E; and Ngoc Lac, Thanh Hoa at $20^0 05'27"$ N and $105^0 22'25"$ E (Figure 2.2).

In Cau Hai, Phu Tho white bamboo plantations were at 33-90 m elevation, slope $\leq 25^0$, with a mean annual temperature of 22.9^0 C, and average annual rainfall of 1590 mm. There are 5-6 rainy months, 2-3 dry months, and 2 drought months in a year. The soils are Ferralsols (Oxisols in US or Feralits in Vietnam soil taxonomy system) red or yellow developed on gneiss or mica schist, thick or medium layers.

In Luong Son, Hoa Binh white bamboo plantations were at 62-183 m elevation, slope $\leq 35^0$, with a mean annual temperature of 23.6^0 C, and average annual rainfall of 1500-2000 mm. The rainy season is from April to October, the dry season from November to March next year, and there is no drought month. The soils are red or brownish yellow Ferralsols developed on limestone, reddish yellow Ferralsols on metamorphic rock, light yellow Ferralsols on sandstone, and brownish Ferralsols on alluvium.

In Ngoc Lac, Thanh Hoa white bamboo plantations were at 54-91 m elevation, slope $\leq 25^0$, mean annual temperature of 23.1^0 C, and average annual rainfall of 1864 mm. There are 6 rainy months, from May to October, and no drought month. Humidity is 85% in annual average. The soils are reddish yellow Ferralsols on shale and metamorphic rock, light yellow Ferralsols on sandstone, and brownish Ferralsols on alluvium. Soil textures are light silt, medium silt and clay.

All white bamboo plantations in three areas were planted on the hilly or mountainous lands that were covered by forest in the past. In most of the sites, the soils still have a thick layer, high porosity, and some may have small trees or degraded forest vegetation cover. In all three areas, bamboo plantations were examined on hilltop and toeslope positions, and 3 management intensities were examined for each topographic position.

Pure bamboo extensive cultivation: Little or no fertilizer was applied. People planted white bamboo with a density the same as in intensive cultivation then harvested bamboo culm and shoot. No special techniques were applied. White bamboo harvesting intensity depended on market need. If market demand was high, a large number of white bamboo culms would be cut, otherwise the culms would be left (uncut) on site.

Pure bamboo intensive cultivation: Advanced techniques and fertilizers were applied. The fertile sites with a thick soil layer, high porosity and moist, rich in nutrient and clay content, were chosen. The sites were prepared by cutting and burning vegetation cover in the dry season. White bamboo was planted with a density of 200-300 bamboos/ha. White bamboo was basal fertilized at a rate of 15-30 kg manure/bamboo and fertilized with 0.5 kg N+P+K/bamboo annually, with regular tending and weeding. Bamboo culms over 3 years old were harvested but at least 15 culms per clump were left.

Timber mixed plantation: White bamboo was mixed with nitrogen-fixing trees *(Acacia mangium)*, using advanced techniques and fertilizers. White bamboo density was 200 bamboos/ha and initial timber tree density was 500 trees/ha and tree density to 200-250 trees/ha after 5-6 years. Fertilizer, tending and weeding were applied as needed. White bamboo was harvested as in the pure intensive cultivation mode.

Experimental design and growth measurements

In this study twenty nine 20 x 20 m temporary plots were set up in three areas: Cau Hai-Phu Tho, Luong Son-Hoa Binh, and Ngoc Lac-Thanh Hoa with two levels of topographic position hilltop and fooslope; and three levels of management: pure-intensive, pure-extensive, and mixed with *Acacia mangium* (Table 2.1).

Plot position and elevation were determined by GPS. . The number of clumps in each 400 m^2 plot and number of culms in each clump were counted. All culms inside plots were identified with respect to age, measured for diameter and height, and rated for overall vigor. Culm age was determined by an experienced observer based on culm color, secondary branch generation, and sound.

White bamboo culm volume was estimated by the equation:

$$V_t = 4.93 \times 10^{-5} \times D^{1.65179} \times H^{1.326} \qquad (1)$$

Culm wall volume was estimated by the equation:

$$V_w = 7.18 \times 10^{-5} \times D^{0.880578} \times H^{1.5276} \qquad (2)$$

Dry culm mass was estimated by the equation:

$$M_d = 0.6345 + 0.4415 \times M_f \qquad (3)$$

$$(M_f = 0.105377 \times D^{1.04218 \times} H^{1.25298}) \qquad (4)$$

Vt: culm volume; D: culm breast height diameter; H: culm height; V_w*: culm wall volume;* M_d*: dry culm mass;* M_f*: fresh culm mass.* (Do Nhu Chien 2000).

Values were calculated for each culm and summed for total plot. The volume (or mass) per ha or the yield was extrapolated to a hectare basis.

The number of economically valuable culms per ha (N_e, straight, disease-free culms > 8 cm dbh, > 7 m height) was counted for each treatment (Nguyen Truong Thanh 2002).

Acacia mangium cover (%) was estimated by multiplying average crown areas in the 400 m^2 plots, then dividing by 400. Average crown area = Square average crown diameter * $\Pi/4$.

Light interception was measured during clear days using 2 quantum meters (Apogee Instruments, Inc., model LQS-QM), one inside the plot and one in an open area. Light intensity was measured at 100 spots per plot, evenly spaced along 5 parallel transects. Absorbed photosynthetically active radiation was determined as the difference between values measured under the canopy and full-light measurements outside the canopy. I calculated the mean for light intensity in plot and open area; light interception by the bamboo (and any trees in the plot) was the difference between full light in the clear area and the light measured under the canopy. Light use efficiency of each white bamboo growth indicator in each plot was indicated by dividing the mean growth indicator of 3-years-and-younger culms by mean light interception of that plot.

Statistical analysis

The impacts of site topography and management intensity on growth of white bamboo culms were evaluated with independent samples t-test and one-way ANOVA (SAS version 9.0) for breast height diameter (DBH), height (H), total culm volume (V_t), culm wall volume (V_w), dry culm mass (M_d), and number of culms with high economic value (N_e). Total culm volume, culm wall volume, dry culm mass, and number of economic culm were analyzed in two different categories: all-age and age-3-and-younger calculations.

Each of the growth features in each levels of topographic position or management intensity was tested for differences among sites. If there is no significant interaction, the effects of the factors are consistent and the population response can be characterized simply. Where topographic position or management intensity showed a significant interaction with site, the data needed to be analyzed separately for each site.

The means of white bamboo growth in two populations, footslope (topo1) and hilltop (topo2) were compared by using paired independent samples t-test. The means of growth indicators in 3 management intensity levels (pure-extensive (mana1), pure-intensive (mana2), and mixed timber (mana3) white bamboo plantations) were compared by using a one-way ANOVA model. All the statistic models were tested with the significance level at 5%.

Results and discussions

When testing the growth features among different sites, most of the growth features were significant different in three areas (Table 2.2) so growth data was analyzed in separate site.

The effect of topographical position on white bamboo growth

In Cau Hai-Phu Tho

White bamboo culms planted on footslopes were bigger than culms planted on the hilltops. White bamboo grown on footslopes had a DBH 8.9 cm on average, while hilltop DBH was 7.9 cm. The difference of average white bamboo DBH between footslope and hilltop was 1.0 cm (13%), (Fig. 2.3).

Height was strongly affected by topographical position. Height responded similarly to DBH growth. Average heights of white bamboo planted on two topographic positions differed significantly. White bamboo culm heights were 15.2 m and 14.1 m on footslopes and hilltops, respectively. The average height of white bamboo planted on footslopes was 1.1 m (8%) higher than that of white bamboo planted on hilltops (Fig. 2.3), (Table 2.3). Total culm volume was 148.3 m^3/ha for the footslope sites, which were higher than the hilltop plantations, with an average of 104.2 m^3/ha (($P_r = 0.03$) in age-3-and-younger calculation (Fig. 2.3). Topographic position did not affect total culm volume in all-age but in 3-year-and-younger calculations.

Culm wall volume and dry culm mass did not differ significantly between topographic positions. The number of culms that were large enough to have economic value was almost twice as high on footslope plots (2000 culms/ha) as on the hilltop plots (1175 culms/ha). The same pattern was evident for the younger class of culms (1600 culms/ha footslope, 1000 culms/ha hilltop, Fig.2.3). White bamboo planted on footslopes had much higher economic value than that on the tophills. High moisture and cation exchange capacity of footslope sites supported white bamboo growth and protected white bamboo culms that could increase economic white bamboo culms value (Table 2.6).

In Ngoc Lac-Thanh Hoa

White bamboo grown on footslopes had a DBH 7.9 cm, on average, while hilltop DBH was 6.1 cm. The difference of average white bamboo DBH between footslope and hilltop was 1.8 cm (29%), (Fig. 2.4).

Similar to DBH, height was strongly affected by topographical position. Average heights of white bamboo planted on two topographic positions differed significantly. White bamboo culm heights were 11.1 m and 8.0 m on footslopes and hilltops, respectively. The average height of white bamboo planted on footslopes was 3.1 m (39%) higher than that of white bamboo planted on hilltops (Fig. 2.4), (Table 2.4). Number of economically valuable culms on the footslope sites were 1250 culms/ha and 1050 culms/ha for all-age and 3-year-and-younger, respectively; which were higher than the hilltop plantations, 275 culms/ha and 250 culms/ha for all-age and 3-year-and-younger calculations, respectively ($P_r < 0.01$) (Fig. 2.4). Topographic position did not affect total culm volume, culm wall volume, and dry culm mass in both all-age and 3-year-and-younger calculations.

The protrusive in soil moisture, porosity, soil pH_{KCl}, soil organic matter, labile nitrogen content, and cation exchange capacity in footslopes to compared with hilltops may explain for the difference in white bamboo growth in two these topographic positions (Table 2.6).

In Luong Son-Hoa Binh

There was no significant difference in white bamboo growth in two topographic positions in Luong Son-Hoa Binh. The topographic positions did not differ much in soil properties, so this may explain the lack of a topographic effect on white bamboo growth (Table 2.6).

Topographic position had strong effects on white bamboo growth in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa but not in Luong Son- Hoa Binh. The significant differences were in total culm volume in 3-year-and-younger in Cau Hai-Phu Tho, DBH and height in Ngoc Lac-Thanh Hoa, and number of economically valuable culms in both calculations in two areas. There were changes in soil properties in topographic positions relate to white bamboo growth differences.

White bamboo planted on footslopes typically grows better than that on the hilltops. Diameter at breast height of white bamboo on footslopes was 10% lager than that on hill top (Pham Thi Quyen 2003). Culm volume and culm wall volume are the accumulations of white bamboo growth under specific planting site conditions, so white bamboo planted on footslope positions had greater volume than that at the hilltop.

The lack of significance in culm wall volume and dry culm mass may have resulted from differences in cutting intensity, such that the number of culm left in an area unit sites inhomogeneous. The number of economic culm per ha, the true economic value of white bamboo plantation, was substantially different between the two positions in both all-age and 3-year-and-younger calculations.

The effect of management intensity on white bamboo growth

In Cau Hai- Phu Tho

The pure intensive management treatment provided larger total culm volume (199.9 m^3/ha) than either the Acacia-mixture (94.1 m^3/ha) or extensive management treatments (187.3 m^3/ha) in all-age calculation. In 3-year-and-younger, all treatments differed in total culm volume with the largest culm volume in the intensive treatment (161.8 m^3/ha), followed by extensive management (127.4 m^3/ha) and acacia-mixture (92.2 m^3/ha). Culm wall volume in all age calculation were highest in pure intensive (94.0 m^3/ha) and lowest in the Acacia-mixture (42.7 m^3/ha). In 3 years and younger, average culm wall volume of white bamboo were highest in the pure intensive (71.2 m^3/ha) and lowest in Acacia-mixture (41.8 m^3/ha). Dry culm mass also highest in pure intensive management (43.9 Mg/ha and 34.7 Mg/ha in all-age and 3-year-and-younger calculations, respectively) and the lowest were in Acacia mixture (Table 2.8) (Fig. 2.5)

White bamboo breast height diameter, height, and number of economically valuable culms did not differ significantly among three management intensities.

In Ngoc Lac-Thanh Hoa

The pure intensive management treatment provided higher total culm volume (111.3 m^3/ha) than either the Acacia-mixture (72.3 m^3/ha) or extensive management treatments (39.9 m^3/ha) in 3-year-and-younger but not all age calculation. Culm wall volume in all-age calculation were highest in pure extensive managements (68.3 m^3/ha) and lowest in pure extensive management (29.3 m^3/ha). For the 3 years and younger calculation, average culm wall volume of white bamboo was highest in pure intensive 57.3 m^3/ha and lowest was in pure extensive (20.9 m^3/ha). The differences were significant among the three management modes ($P = 0.05$ and 0.04 for all-age and 3-year-and-younger calculations, respectively) (Table 2.9). Different management modes had various effects on white bamboo growth. The effects of management intensity were significant for culm volume, culm wall volume but not for DBH, height, dry culm mass, and number of economically valuable culms (Fig. 2.6).

White bamboo pure plantation under intensive management had highest, white bamboo in pure extensive plantations had lowest, and white bamboo in acacia mixture had medium culm volume and culm wall volume in all three management modes.

In Luong Son-Hoa Binh

The pure intensive management treatment provided larger culm diameters (9.5 cm) than the extensive management treatments (8.4 cm), a 13% difference. Average white bamboo culm height in pure intensive plantations was 14.5 m, higher than that in pure extensive (13.1 m, 11%) (Table 2.10, Fig. 2.7).

The other growth features, culm volume, culm wall volume, dry culm mass, and number of economically valuable culms did not showed the significant differences in both all-age and 3-year-and-younger calculations.

In all three sites, management intensity had significant effect on total culm volume in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa (only in 3-year-and-younger calculation), on culm wall volume in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa, on dry culm mass in Cau Hai-Phu Tho, and in DBH and height in Luong Son-Hoa Binh.

White bamboo pure plantation under intensive management had largest culms in all three management modes. Bamboo culms in pure intensive management had average total culm volume, culm wall volume, and dry culm mass higher than that in bamboo mixed with *Acacia mangium* and in pure extensive plantation. This result was counter to an earlier study that compared white bamboo growth of five 7-year old plantations (one pure white bamboo and four mixed with broad-leaf trees) in Cau Hai-Phu Tho. In that study white bamboo mixed with *Acacia mangium* had DBH 5% higher than that of pure white bamboo plantation (6.85 and 7.2 cm in pure plantation and Acacia-mixture, respectively) (Nguyen Truong Thanh 2002). There might be a competition in resources that favor for white bamboo height growth in this period. The current *Acacia mangium* cover in mixed bamboo plantation ranged from 59 to 64%, averaged 61% (Table 2.4). This cover of *Acacia mangium* was probably too high for good growth of white bamboo. The best tree coverage for white bamboo growth was 0.3 (30%). White bamboo growth declined when tree cover increased beyond 0.6 (60%) (Le Van Ninh 2001).

The differences in number of economic value culms were not significant in three management intensities. This did not correspond with a previous study on white bamboo mixed with trees in Cau Hai-Phu Tho, which showed that the number of economically valuable culms in white bamboo plantations mixed with *Acacia mangium* was the highest and significantly different from that of the pure white bamboo plantations (Nguyen Truong Thanh 2002). This difference might be explained at the young age (6 year-old) *Acacia mangium* supported well for white bamboo planted on degraded soil but at the old age (13-14 year-old) it could not. The high coverage of *Acaca mangium* crown might inhibit white bamboo growth (Le Van Ninh 2001).

The effect of topographic position and management intensity on light use efficiency

In Cau Hai-Phu Tho

In all tested light use efficiencies, only culm volume and number of economic culm showed the significant effects of light use efficiencies between topographical positions. Culm volume of white bamboo on the footslope had 0.42 m^3/light use efficiency unit higher than that on the hilltop (a 37% difference). Similarly, white bamboo planted on the footslope had number of economic culm approximately 6 culms/light interception units (56%) higher than that in white bamboo planted on hilltop. It means that with the same light interception, white bamboo planted on the footslope had more economic culms than that on the hilltop (Table 2.12, Fig. 2.8).

Management intensity had more effects on light use efficiency of white bamboo growth than topographic position did. DBH light use efficiency was highest in Acacia-mixture and lowest in pure extensive plantations. Culm volume light use efficiency was lowest in Acacia-mixture (1.01 $m^{3/}$/LI) and highest in pure intensive plantations (1.69 m^3/LI). The pure intensive white bamboo also had highest culm wall volume and dry culm mass light use efficiencies in three management intensities. These differences were significant (Table 2.15, Fig. 2.10).

In Ngoc Lac-Thanh Hoa

Culm DBH, culm height, and number of economically valuable culm light use efficiencies were significantly different in two topographic positions. DBH light use efficiency of footslope was 25% higher than that in hilltop. This value in culm height light use efficiency was 34%. The number of economically valuable culm light use efficiency was strongly affected by topographic position. The number of economically valuable culm light use efficiency of footslope plantations was 3 times higher than that in hilltop (Table 2.13, Fig. 2.9). But in this area, management intensity did not show a significant difference in all growth light use efficiencies (Table 2.16).

In Luong Son-Hoa Binh

Topographic position did not significantly affect light use efficiency of white bamboo growth (Table 2.14). Culm DBH and culm height light use efficiencies were significantly different between two different management modes. DBH light use efficiency in intensive management was 24% higher than that in extensive management. Culm height light use efficiency also was a 23% difference between two management intensities (Table 2.17, Fig. 2.11).

The effect of topographic position and management intensity on white bamboo growth light use efficiencies was various in different sites. In three areas, topographic position had significant effect on culm volume light use efficiency in Cau Hai-Phu Tho, culm DBH and height light use efficiencies in Ngoc Lac-Thanh Hoa, and number of economically valuable culm light use efficiency in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa sites. Management intensity had significant effect on culm DBH light use efficiency in Cau Hai-Phu Tho and Luong Son-Hoa Binh, on culm height light use efficiency in Luong Son-Hoa Binh, on culm volume, culm wall volume, and dry culm mass light use efficiencies in Cau Hai-Phu Tho.

Footslope and intensive management that had fertile soils had higher light use efficiency than hilltop and other management intensities. This was similar to another study that taken on ryegrass. According to that study plant dry matter was significantly higher ($P < 0.05$) under both sufficient water and N supply. The adverse effect of insufficient water and N supply to plants decreased both the individual leaf area as well as the whole canopy leaf area index (M. Akmal and M. J. J. Janssens 2004).

In conclusion, topographic position had strong effects on white bamboo growth in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa but not in Luong Son- Hoa Binh. The significant differences were in total culm volume in 3-year-and-younger in Cau Hai-Phu Tho, DBH and height in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa, and number of economically valuable culms in both all-age and 3-year-and-younger calculations in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa.

Management intensity had significant effect on total culm volume in Cau Hai-Phu Tho (in both all-age and 3-year-and-younger calculations) and in Ngoc Lac-Thanh Hoa (in 3-year-and-younger calculation), on culm wall volume in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa, on dry culm mass in Cau Hai-Phu Tho (in both calculation methods), and in DBH and height in Luong Son-Hoa Binh.

The effect of topographic position and management intensity on white bamboo growth light use efficiencies was various in different sites. Topographic position significantly affected culm volume light use efficiency in Cau Hai-Phu Tho, culm DBH and height light use efficiencies in Ngoc Lac-Thanh Hoa, and number of economically valuable culm light use efficiency in both Cau Hai-Phu Tho and Ngoc Lac- Thanh Hoa. Management intensity had a significant effect on culm DBH light use efficiency in Cau Hai-Phu Tho and Luong Son-Hoa Binh, on culm height light use efficiency in Luong Son-Hoa Binh, on culm volume, culm wall volume, and dry culm mass light use efficiencies in Cau Hai-Phu Tho.

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Tables and Figures

Table 2.1 Experiment design of the study

Area	Topographic position	Management Intensity		
		Mixed	Pure- Intensive	Pure- extensive
Cau Hai	Top	2	2	2
	Foothill	2	2	2
Luong Son	Top	0	2	2
	Foothill	0	2	2
Ngoc Lac	Top	2	1	2
	Foothill	2	1	1

Table 2.2 Results of testing differences in white bamboo growth among Cau Hai, Ngoc Lac, and Luong Son

Growth		**P value > F**				
		Topographic position		**Management intensity**		
		Footslope	Hilltop	Extensive	Intensive	Mixed
DBH		**<0.01**	**<0.01**	**<0.01**	**0.02**	**0.03**
Height		**<0.01**	**<0.01**	**<0.01**	**0.01**	**<0.01**
Culm volume	All	**0.01**	**<0.01**	**<0.01**	0.14	0.60
	≤ 3	**0.02**	0.07	**<0.01**	**0.02**	0.43
Wall volume	All	**<0.01**	**0.01**	**<0.01**	0.23	0.74
	≤ 3	0.055	0.18	**<0.01**	**<0.01**	0.55
Dry mass	All	**0.02**	**0.01**	**<0.01**	0.16	0.96
	≤ 3	**0.03**	0.19	**<0.01**	**<0.01**	0.82
Ne	All	**0.03**	**<0.01**	**<0.01**	0.30	0.37
	≤ 3	0.055	**<0.01**	**0.02**	0.11	0.23

Table 2.3 Analysis results of topographic position in Cau Hai-Phu Tho

Sources		Means			t- test (one-sided)			Equality of Variance	
		Footslope	Hilltop	Differ.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm)	All	***8.9***	***7.9***	***1.0***	***10***	***3.79***	***<0.01***	1.57	0.63
Height (m)	All	***15.2***	***14.1***	***1.1***	***10***	***3.30***	***<0.01***	1.04	0.96
Culm vol. (m^3/ha)	All	186.4	134.5	51.9	10	1.58	0.07	1.22	0.83
	≤ 3 yrs	***148.3***	***104.2***	***44.1***	***10***	***2.21***	***0.03***	2.01	0.46
Culm wall vol.(m^3/ha)	All	85.5	67.2	18.3	10	1.12	0.14	1.48	0.68
	≤ 3 yrs	68.1	51.2	16.9	10	1.75	0.06	2.11	0.43
Dry culm mass (Mg/ha)	All	38.864	30.912	7.952	10	1.07	0.15	1.34	0.65
	≤ 3 yrs	30.894	23.551	7.343	10	1.68	0.06	2.21	0.40
N of eco. culm (culms/ha)	All	***2000***	***1175***	***825***	***10***	***2.91***	***<0.01***	1.03	0.98
	≤ 3 yrs	***1600***	***1000***	***600***	***10***	***3.19***	***<0.01***	3.02	0.25

Table 2.4 Analysis results of topographic position in Ngoc Lac-Thanh Hoa

Sources		Means			t- test (one-sided)			Equality of Variance	
		Footslope	Hilltop	Differ.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm)	All	***7.9***	***6.1***	***1.8***	*7*	***4.13***	***<0.01***	1.72	0.68
Height (m)	All	***11.1***	***8.0***	***3.1***	*7*	***2.95***	***0.02***	2.95	0.33
Culm vol. (m^3/ha)	All	104.6	65.6	39.0	7	1.57	0.08	1.89	0.54
	≤ 3 yrs	89.5	54.7	34.8	7	1.64	0.07	1.17	0.85
Culm wall vol.(m^3/ha)	All	48.8	36.8	12.0	7	0.91	0.18	1.08	0.90
	≤ 3 yrs	41.7	30.3	11.4	7	0.98	0.18	1.42	0.80
Dry culm mass (Mg/ha)	All	24.034	18.498	5.536	7	1.09	0.15	1.78	0.58
	≤ 3 yrs	20.516	14.902	5.614	7	1.31	0.11	1.14	0.86
N of eco. culm (culms/ha)	All	***1250***	***275***	***975***	*7*	***3.38***	***<0.01***	7.14	0.09
	≤ 3 yrs	***1050***	***250***	***800***	*7*	***3.65***	***<0.01***	3.99	0.21

Table 2.5 Analysis results of topographic position in Luong Son-Hoa Binh

Sources		Means			t- test (one-sided)			Equality of Variance	
		Footslope	Hilltop	Differ.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm)	All	9.1	8.8	0.3	6	0.81	0.22	1.08	0.95
Height (m)	All	14.1	13.5	0.6	6	1.05	0.16	1.64	0.69
Culm vol. (m^3/ha)	All	241.1	202.7	38.4	6	1.19	0.14	11.24	0.07
	≤ 3 yrs	102.6	94.2	8.4	6	0.5	0.32	1.31	0.83
Culm wall vol.(m^3/ha)	All	106.3	92.4	13.9	6	0.93	0.19	4.39	0.26
	≤ 3 yrs	46.2	44.8	1.4	6	0.17	0.43	1.48	0.75
Dry culm mass (Mg/ha)	All	49.250	43.267	5.983	6	0.86	0.21	4.11	0.27
	≤ 3 yrs	21.159	20.798	361	6	0.10	0.46	1.61	0.70
N of eco. culm (culms/ha)	All	3925	2450	1475	3.14	1.27	0.14	**43.46**	**0.01**
	≤ 3 yrs	1175	1025	150	6	0.66	0.26	1.91	0.61

Table 2.6 Soil property in different topographic positions

Area	Topo	Moist. %	Den.	Nat. W	Poro. %	SiO2 %	pH KCl	OM %	Total			Labile			CEC
									N	P2O5	K2O	N	P2O5	K20	
Cau Hai	Top	20.94	2.54	1.19	51.10	66.45	3.72	2.10	0.14	0.09	0.12	10.09	1.57	3.70	9.51
	Foot	23.57	2.39	1.15	48.33	60.70	3.73	2.08	0.15	0.15	0.11	11.23	1.35	3.67	10.74
Ngoc Lac	Top	15.18	2.51	1.20	50.20	41.19	3.15	1.81	0.13	0.08	0.38	8.62	1.42	2.78	9.23
	Foot	19.67	2.54	1.26	54.68	39.93	3.34	2.01	0.14	0.14	0.45	9.36	1.35	3.09	10.47
Luong Son	Top	22.48	2.40	1.16	52.24	60.52	3.68	2.19	0.15	0.08	0.89	9.61	1.25	3.71	11.15
	Foot	20.76	2.30	1.10	55.96	64.03	3.62	2.25	0.15	0.09	0.89	9.10	1.65	3.78	11.69

Table 2.7 Light interception in different white bamboo plots

Cau Hai-Phu Tho		Ngoc Lac-Thanh Hoa		Luong Son-Hoa Binh	
Plot	**LI (%)**	**Plot**	**LI (%)**	**Plot**	**LI (%)**
1	85.8	1	95.7	1	94.5
2	94.3	2	96.4	2	90.4
3	83.6	3	92.9	3	89.8
4	93.8	4	96.1	4	88.1
5	93.5	5	84.9	5	77.8
6	97.5	6	88.6	6	80.2
7	95.5	7	88.0	7	93.0
8	96.1	8	99.2	8	93.0
9	90.5	9	95.1		
10	96.5				
11	93.8				
12	95.5				

Table 2.8 Analysis results of management intensity in Cau Hai-Phu Tho

Sources		Means					Comparison of LSM (least square means) significant at 0.05 level		
		DF	Pure Ext. (1)	Pure Int. (2)	Mixed (3)	$P_r > F$	(1)- (2)	(2)-(3)	(1)-(3)
DBH (cm)	All	2	7.9	8.5	8.8	0.22	0	0	0
Height (m)	All	2	14.4	14.8	14.7	0.80	0	0	0
Culm vol. (m^3/ha)	***All***	***2***	***187.3***	***199.9***	***94.1***	**<0.01**	0	*	*
	≤ 3 yrs	***2***	***124.7***	***161.8***	***92.2***	***0.03***	0	*	0
Culm wall vol.(m^3/ha)	***All***	***2***	***92.4***	***94.0***	***42.7***	**<0.01**	0	*	*
	≤ 3 yrs	***2***	***60.9***	***71.2***	***41.8***	**<0.01**	0	*	0
Dry culm mass (Mg/ha)	***All***	***2***	***42.274***	***43.855***	***19.534***	**<0.01**	0	*	*
	≤ 3 yrs	***2***	***27.891***	***34.711***	***19.138***	**<0.01**	0	*	*
N of eco. culm (culms/ha)	All	2	1700	2025	1050	0.07	0	*	0
	≤ 3 yrs	2	1200	1625	1025	0.13	0	0	0

Table 2.9 Analysis results of management intensity in Ngoc Lac_Thanh Hoa

Sources		Means					Comparison of LSM (least square means) significant at 0.05 level		
		DF	Pure Ext. (1)	Pure Int. (2)	Mixed (3)	$P_r > F$	(1)- (2)	(2)-(3)	(1)-(3)
DBH (cm)	All	2	6.1	7.5	7.2	0.28	0	0	0
Height (m)	All	2	7.6	11.2	9.9	0.17	0	0	0
Culm vol. (m^3/ha)	All	2	53.4	134.1	79.5	0.06	*	0	0
	≤ 3 yrs	***2***	***39.9***	***111.3***	***72.3***	**0.05**	*	0	0
Culm wall vol.(m^3/ha)	All	***2***	***29.3***	***68.3***	***38.7***	**0.05**	*	*	0
	≤ 3 yrs	***2***	***20.9***	***57.3***	***35.2***	**0.04**	*	0	0
Dry culm mass (Mg/ha)	All	2	16.480	29.940	19.826	0.14	0	0	0
	≤ 3 yrs	2	11.933	24.243	18.072	0.11	*	0	0
N of eco. culm (culms/ha)	All	2	250	1300	750	0.23	0	0	0
	≤ 3 yrs	2	225	1050	650	0.23	0	0	0

Table 2.10 Analysis results of management intensity in Luong Son-Hoa Binh

Sources		Means			t- test (one-sided)			Equality of Variance	
		Pure Ext.	Pure Int.	Differ.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm)	All	***8.4***	***9.5***	***-1.1***	***6***	***-5.93***	***<0.01***	1.59	0.71
Height (m)	All	***13.1***	***14.5***	***-1.4***	***6***	***-4.16***	***<0.01***	3.81	0.30
Culm vol. (m^3/ha)	All	224.1	219.7	4.4	6	0.12	0.90	2.09	0.56
	≤ 3 yrs	102.0	94.8	7.2	6	0.42	0.68	1.80	0.64
Culm wall vol.(m^3/ha)	All	103.0	95.6	7.4	6	0.47	0.65	2.01	0.58
	≤ 3 yrs	48.6	42.3	6.3	6	0.83	0.43	2.49	0.47
Dry culm mass (Mg/ha)	All	48.564	43.953	4.611	6	0.64	0.54	2.34	0.50
	≤ 3 yrs	22.736	19.221	3.515	6	1.05	0.33	2.81	0.42
N of eco. culm (culms/ha)	All	2825	3525	700	6	-0.56	0.59	9.76	0.09
	≤ 3 yrs	1225	1000	225	6	1.03	0.34	2.68	0.44

Table 2.11 *Acacia mangium* crown cover in Acacia mixture

Plot	Number of trees	Average cover (%)	DBH (cm)	Height (m)
CH 1	19	***64***	13.8	14.1
CH 2	13	60	15.4	13.4
CH 3	14	63	14.7	13.2
CH 4	10	61	17.4	17.8
NL 5	13	***59***	16.8	14.2
NL 6	14	61	19.4	15.7
NL 8	14	60	17.6	14.4
NL 9	15	60	17.7	14.2
Average		61		

Table 2.12 Analysis results of light use efficiency in different topographic positions in Cau Hai-Phu Tho

Sources	Means			t- test (one-sided)			Equality of Variance	
	Footslope	Hilltop	Diff.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm/LI)	0.094	0.087	0.007	10	1.61	0.07	3.49	0.19
Height (m/LI)	0.159	0.156	0.003	10	0.67	0.26	2.82	0.28
Culm volume (m^3/LI)	***1.55***	***1.13***	***0.42***	***10***	***2.18***	***0.03***	1.95	0.48
Wall volume (m^3/LI)	0.71	0.56	0.15	10	1.68	0.06	2.01	0.46
Dry mass (kg/LI)	323.8	255.7	68.1	10	1.61	0.07	2.12	0.42
N_E (culm/LI)	***16.75***	***10.75***	***6.0***	***10***	***3.17***	***<0.01***	3.07	0.24

Table 2.13 Analysis results of light use efficiency in different topographic positions in Ngoc Lac-Thanh Hoa

Sources	Means			t- test (one-sided)			Equality of Variance	
	Footslope	Hilltop	Diff.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm/LI)	***0.084***	***0.067***	***0.017***	*7*	***4.62***	***<0.01***	2.45	0.48
Height (m/LI)	***0.118***	***0.088***	***0.030***	*7*	***2.55***	***0.02***	5.12	0.14
Culm volume (m^3/LI)	0.95	0.60	0.35	7	1.54	0.08	1.40	0.73
Wall volume (m^3/LI)	0.44	0.33	0.11	7	0.91	0.20	1.15	0.94
Dry mass (kg/LI)	218.2	163.7	54.5	7	1.12	0.15	1.30	0.78
N_E (culm/LI)	***11.0***	***2.75***	***8.25***	*7*	***3.64***	***<0.01***	4.15	0.20

Table 2.14 Analysis results of light use efficiency in different topographic positions in Luong Son-Hoa Binh

Sources	Means			t- test (one-sided)			Equality of Variance	
	Footslope	Hilltop	Diff.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm/LI)	0.105	0.100	0.005	6	0.61	0.28	1.52	0.74
Height (m/LI)	0.161	0.153	0.008	6	0.62	0.28	1.22	0.87
Culm volume (m^3/LI)	1.17	1.06	0.11	6	0.62	0.28	2.23	0.53
Wall volume (m^3/LI)	0.53	0.50	0.03	6	0.30	0.39	1.01	0.93
Dry mass (kg/LI)	241.5	233.1	8.4	6	0.22	0.41	1.00	0.99
N_E (culm/LI)	13.25	11.5	1.75	6	0.75	0.24	2.05	0.57

Table 2.15 Analysis results of light use efficiency in different management intensities in Cau Hai-Phu Tho

Sources	Means					Comparison of LSM (least square means) significant at 0.05 level		
	DF	Pure Ext. (1)	Pure Int. (2)	Mixed. (3)	$P_r > F$	(1)-(2)	(2)-(3)	(1)-(3)
DBH (cm/LI)	2	***0.084***	***0.088***	***0.098***	**0.02**	0	*	*
Height (m/LI)	2	0.153	0.155	0.165	0.11	0	0	0
Culm volume (m^3/LI)	2	***1.33***	***1.69***	***1.01***	**0.03**	0	*	0
Wall volume (m^3/LI)	2	***0.65***	***0.79***	***0.46***	**<0.01**	0	*	*
Dry mass (kg/LI)	2	***295.7***	***362.1***	***211.3***	**<0.01**	0	*	*
N_E (culm/LI)	2	12.75	17	11.25	0.15	0	0	0

Table 2.16 Analysis results of light use efficiency in different management intensities in Ngoc Lac-Thanh Hoa

Sources	Means					Comparison of LSM (least square means) significant at 0.05 level		
	DF	Pure Ext. (1)	Pure Int. (2)	Mixed. (3)	$P_r > F$	(1)-(2)	(2)-(3)	(1)-(3)
DBH (cm/LI)	2	0.065	0.078	0.079	0.20	0	0	0
Height (m/LI)	2	0.082	0.117	0.107	0.22	0	0	0
Culm volume (m^3/LI)	2	0.43	1.16	0.79	0.07	*	0	0
Wall volume (m^3/LI)	2	0.23	0.59	0.39	0.07	*	0	0
Dry mass (kg/LI)	2	130.1	252.5	199.1	0.18	0	0	0
N_E (culm/LI)	2	2.5	11.0	7.0	0.23	0	0	0

Table 2.17 Analysis results of light use efficiency in different management intensity in Luong Son-Hoa Binh

Sources	Means			t- test (one-sided)			Equality of Variance	
	Ext.	Int.	Dif.	DF	t- value	$P_r > F$	F value	$P_r > F$
DBH (cm/LI)	***0.091***	***0.113***	***-0.022***	***6***	***-4.52***	***<0.01***	4.71	0.24
Height (m/LI)	***0.141***	***0.173***	***-0.032***	***6***	***-5.56***	***<0.01***	2.66	0.44
Culm volume (m^3/LI)	1.09	1.13	-0.04	6	-0.19	0.42	1.27	0.84
Wall volume (m^3/LI)	0.52	0.50	0.02	6	0.20	0.42	1.69	0.67
Dry mass (kg/LI)	244.6	229.9	14.7	6	0.39	0.35	1.78	0.64
N_E (culm/LI)	13.0	11.75	1.25	6	0.47	0.32	1.58	0.71

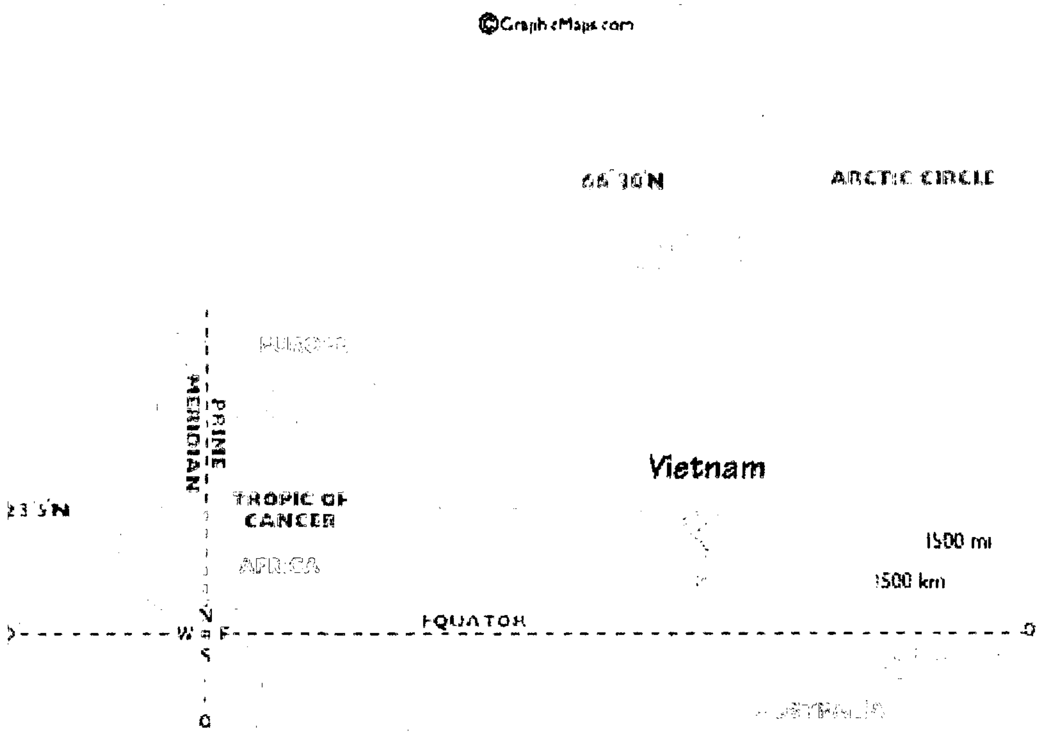


Figure 2.1 Vietnam in Asia

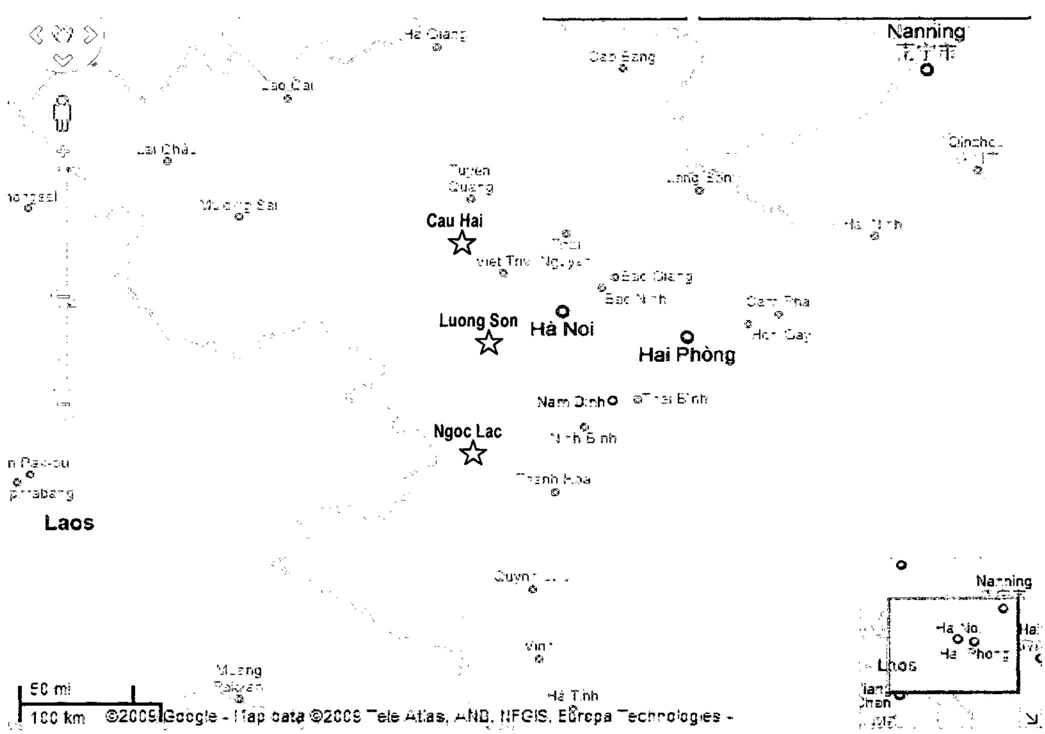
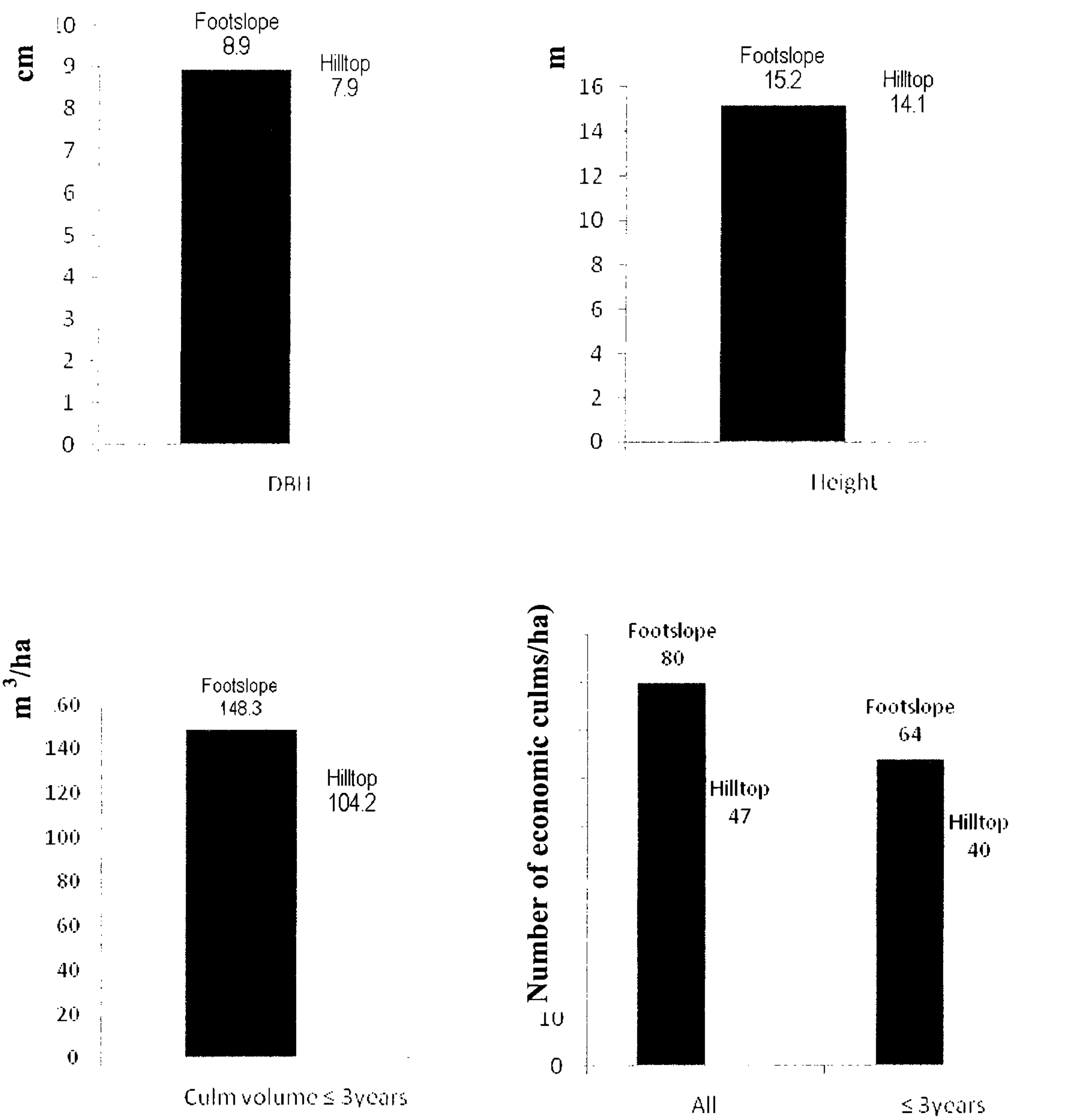
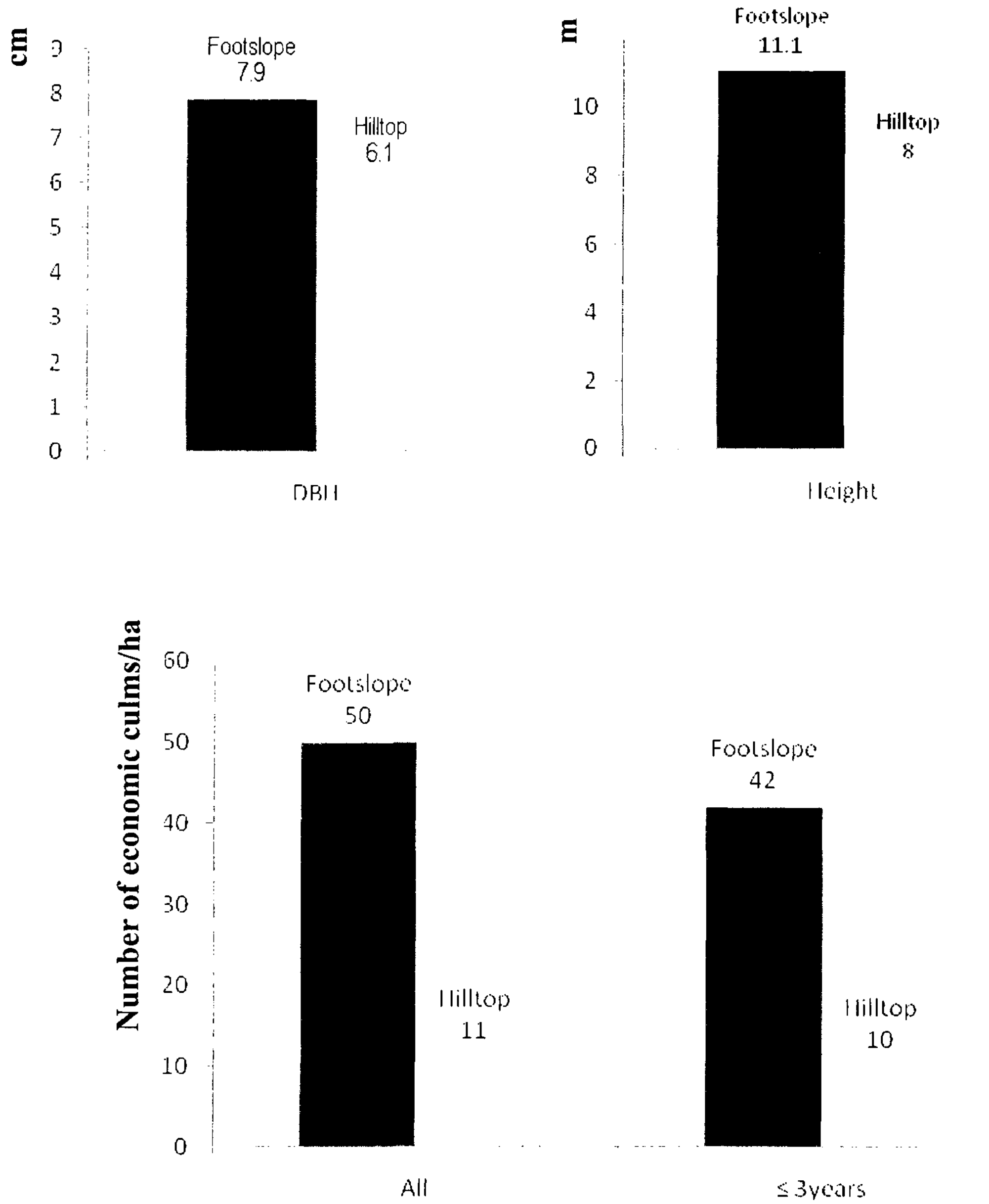


Figure 2.2 Studying areas of research



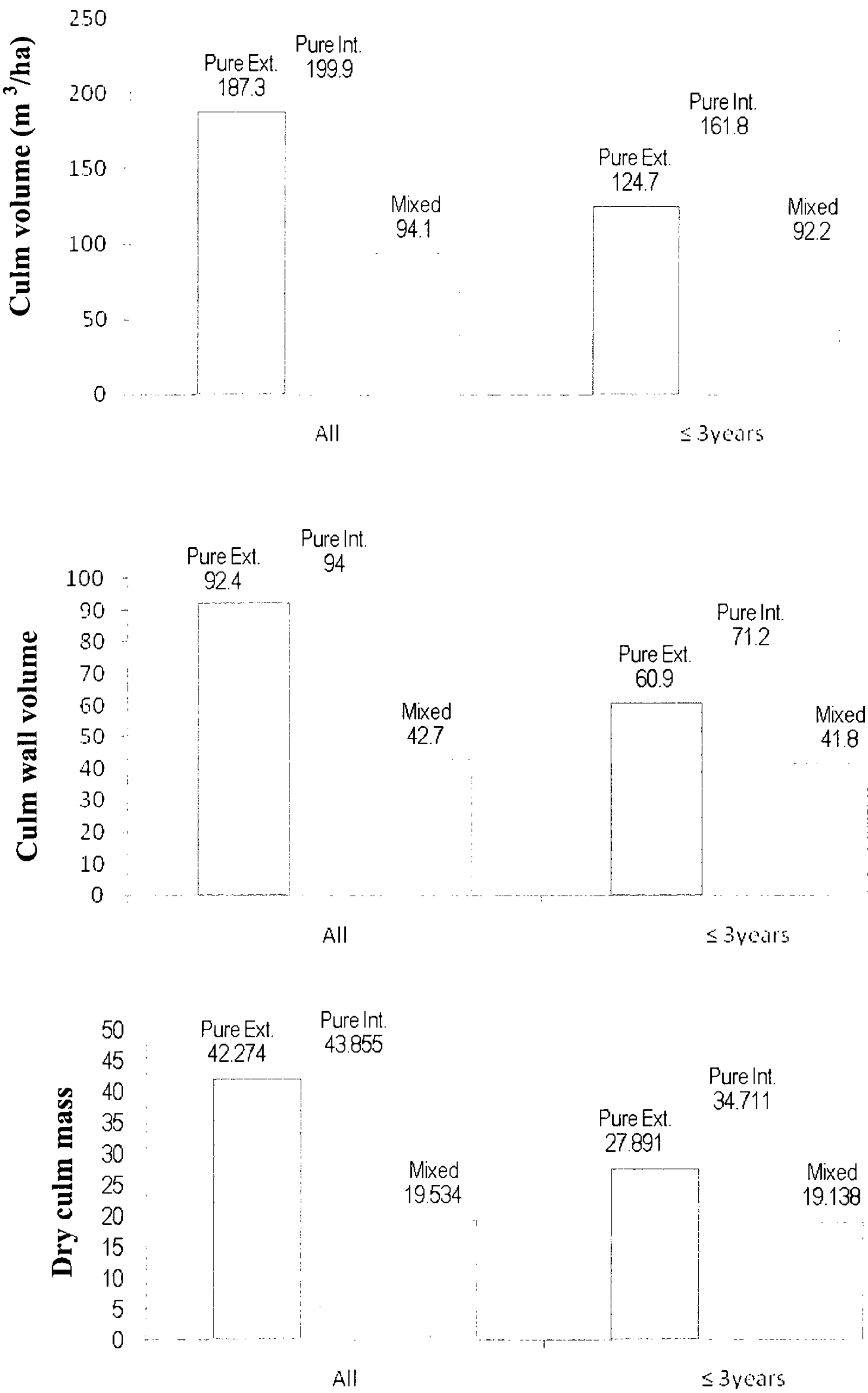
All of the differences were significant at 0.05 level

Figure 2.3 White bamboo growth in different topographic positions in Cau Hai-Phu Tho



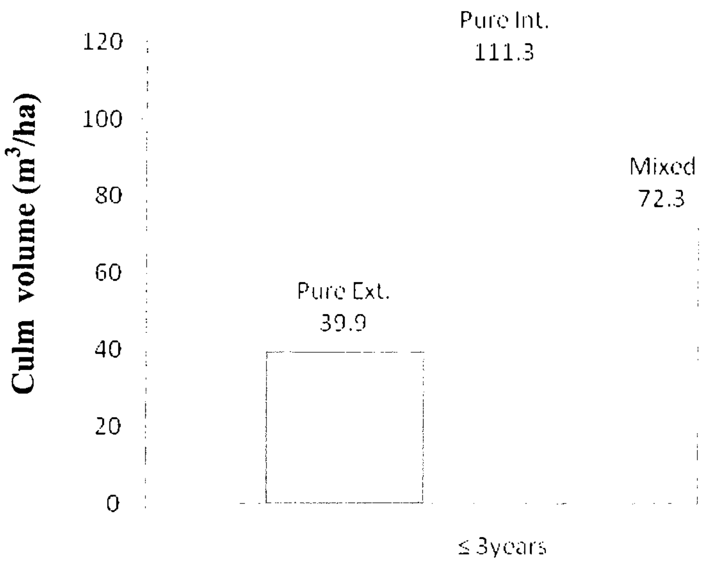
All of the differences were significant at 0.05 level

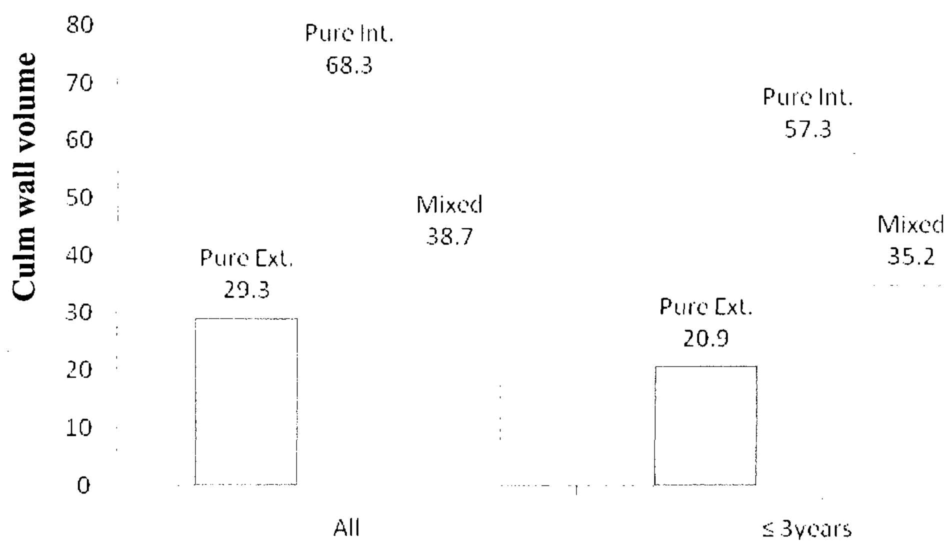
Figure 2.4 White bamboo growth in different topographic positions in Ngoc Lac-Thanh Hoa



All of the differences were significant at 0.05 level

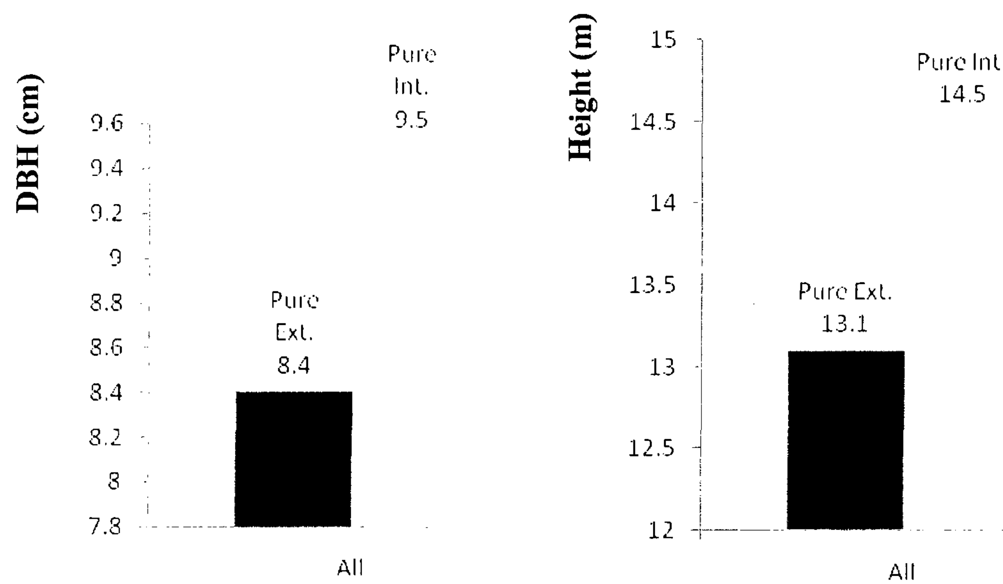
Figure 2.5 White bamboo growth in different management modes in Cau Hai- Phu Tho





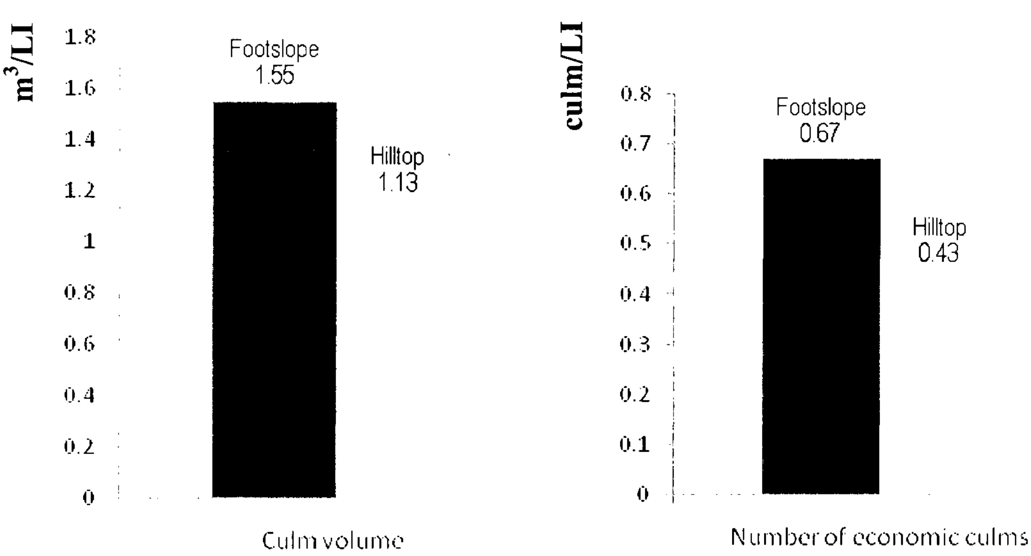
All of the differences were significant at 0.05 level

Figure 2.6 White bamboo growth in different management modes in Ngoc Lac-Thanh Hoa



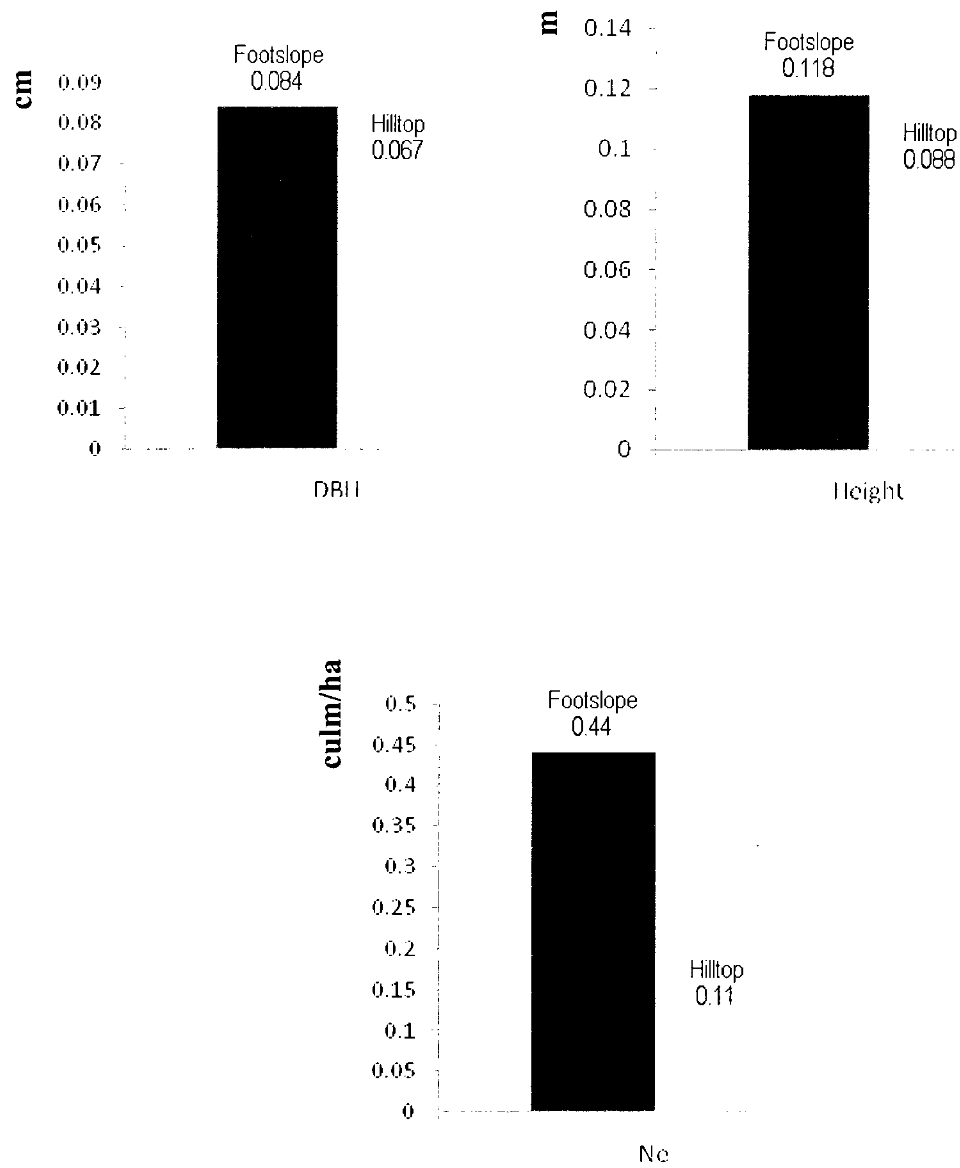
All of the differences were significant at 0.05 level

Figure 2.7 White bamboo growth in different management modes in Luong Son-Hoa Binh



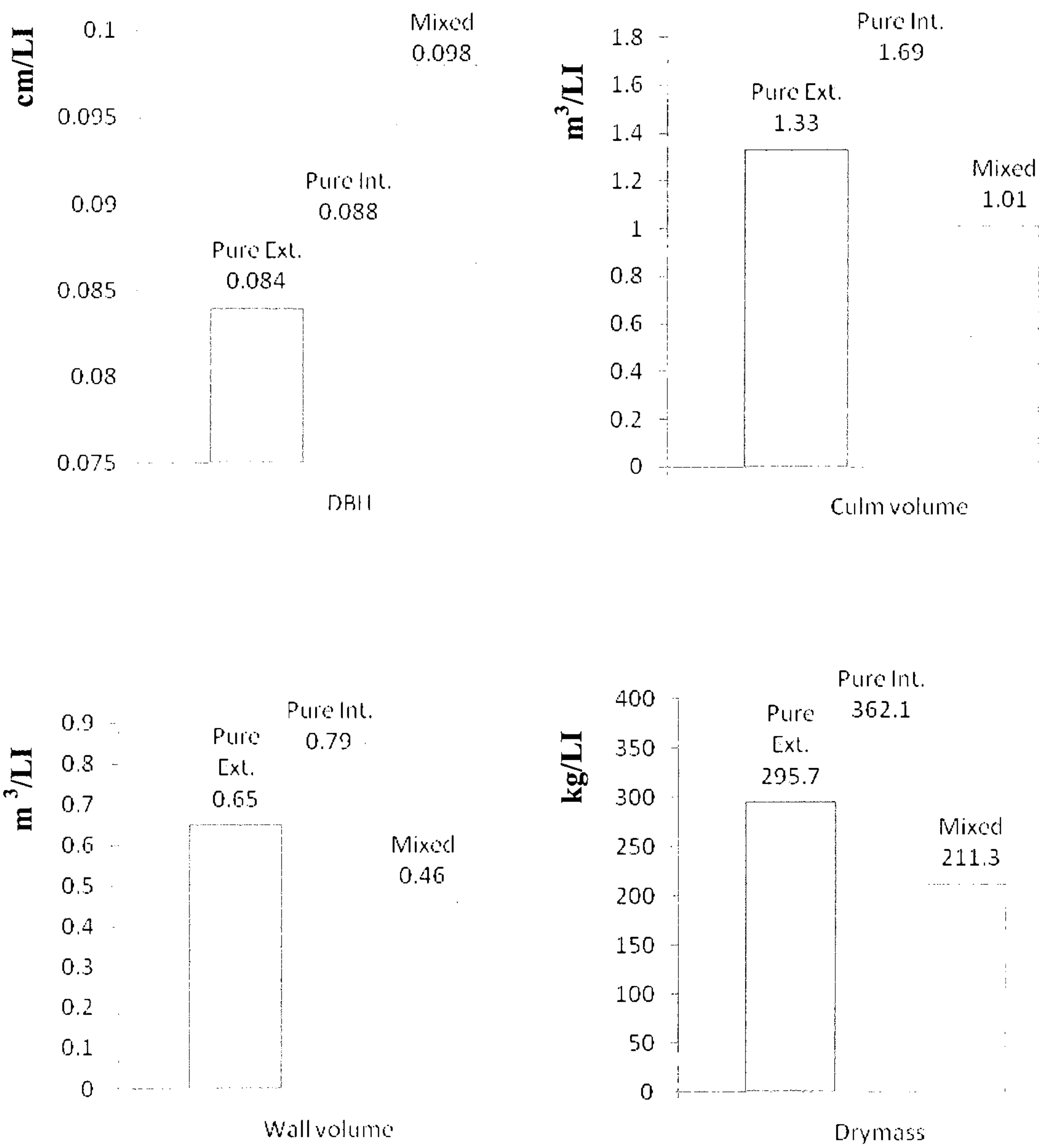
All of the differences were significant at 0.05 level

Figure 2.8 White bamboo light use efficiency in different topographic positions in Cau Hai-Phu Tho



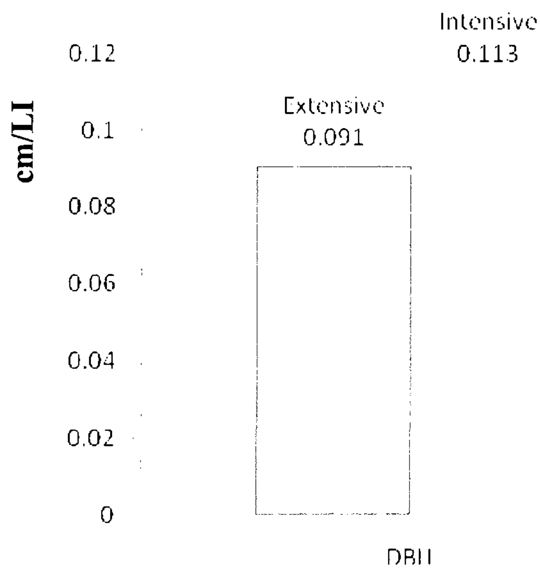
All of the differences were significant at 0.05 level

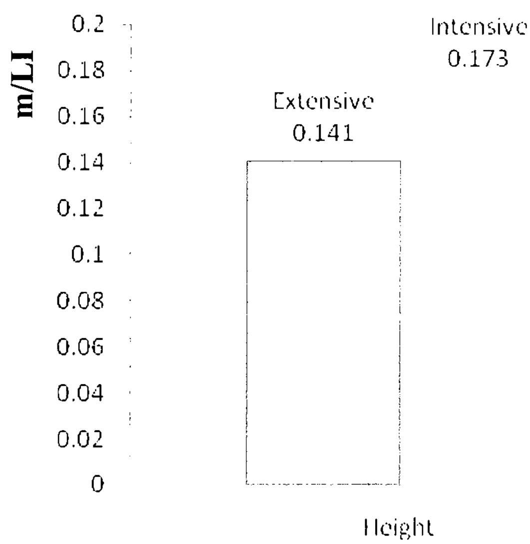
Figure 2.9 White bamboo light use efficiency in different topographic positions in Ngoc Lac-Thanh Hoa



All of the differences were significant at 0.05 level

Figure 2.10 White bamboo light use efficiency in different management modes in Cau Hai-Phu Tho





All of the differences were significant at 0.05 level

Figure 2.11 White bamboo light use efficiency in different management modes in Luong Son-Hoa Binh

Chapter 3

THE EFFECTS OF ECOLOGICAL FACTORS AND FERTILIZERS ON WHITE BAMBOO GROWTH

Abstract: White bamboo growth is affected by ecological factors. I tested total culm volume, culm wall volume, dry culm mass, and number of economic valuable culm collected in 29 plots in three areas (Cau Hai-Phu Tho, Ngoc Lac-Thanh Hoa, and Luong Son-Hoa Binh, Vietnam) in relation to soil features (moisture, density, bulk density, porosity, pH, organic matter, silica, total and available content of nitrogen, potassium, and phosphorus). Total culm volume correlated well with soil moisture. Culm wall volume correlated very well with dry culm mass, and both related moderately well to soil pH. The number of economically valuable culms correlated moderately with soil pH and cation exchange capacity. Fertilization with N, P, K, or N+P+K in 12 plots in Cau Hai tended to show increased growth with additions of N, K, or N+P+K, but the differences were not significant for the first growing season. Light interception and light use efficiency showed the weak regression with white bamboo growth and most of the relationship were not significant. Non-bamboo vegetation may reflect in determining the light interception that caused these effects.

Keywords: white bamboo growth, ecological factors, fertilizer, soil pH, soil moisture, cation exchange capacity, light interception, light use efficiency, non-bamboo.

Introduction

White bamboo growth is strongly affected by ecological factors. Living organisms and their abiotic environments are inseparably interrelated and interact upon each other (Odum 1983), and the growth of white bamboo reflects the relationship between white bamboo and the surrounding environment. Bamboo grows best on soil with high porosity, good moistures and drainage, high clay, organic matter, total nitrogen, potassium, and calcium contents (Koichiro Ueda 1960), typically yielding twice as much biomass as poorer sites (Nguyen Van Dao 2003). This general insight needs to be developed with quantitative details for use in understanding variations in bamboo growth across landscapes.

Forest production depends on trees obtaining resources from the environment and using these resources to fix atmospheric CO_2 into biomass (Binkley at el. 2004). Knowledge of canopy light interception and absorption is fundamental for understanding many aspects of crop growth and productivity, and for crop modeling (Rosati at el. 2001).

White bamboo is relatively intolerant of shade, doing best with at least 60% of full sunlight (although not much light is required during the period of rapid shoot elongation). White bamboo is a moisture-loving plant that cannot tolerate waterlogged soils.

White bamboo diameter growth has strong, directly proportional regression to soil organic matter, total nitrogen, K_2O available content in surface soil layer but not to P_2O_5 available (Nguyen Ngoc Binh 1976-1980). The available K_2O content in soil has very strong correlation with white bamboo growth (Le Quang Lien 1990).

White bamboo planted on infertile soil or in old plantations needs fertilizer application to sustain culm growth and improve culm quality (Nguyen Ngoc Binh, Pham Duc Tuan 2007). For example, fertilization with nitrogen, phosphate and potassium (0.5 kg N+P+K/clump) increased culm diameter by 39% and height by 12% (Pham Thi Quyen 2003).

This chapter explores the hypothesis that growth of white bamboo correlates with ecological conditions, and that the range in ecological conditions includes some sites that are nutrient limited as evidenced by experimental response to fertilization so fertilized white bamboo grows faster than unfertilized one. I also examined patterns in light interception, and the efficiency of bamboo growth per unit of light interception in relation to ecological conditions and fertilization. The ecological factors included soil moisture, soil density, soil bulk density, soil porosity, total silica (SiO_2) content, pH, organic matter concentration, total and available nitrogen, phosphorus, potassium, and cation exchange capacity. The measures of white bamboo growth were DBH, height, volume of all culms, culm wall, dry culm mass and number of economic valuable culms (culm that has DBH $\geq$ 8 cm, H $\geq$ 7 m, straight, and not infected by disease). These measurements were evaluated in terms of culms less than three years old to homogenize the age patterns of white bamboo culm in different sites. .

The objectives of this study were to elucidate the patterns between ecological factors and white bamboo growth, to indentify nutrient limitation, and examine the role of light interception and light use efficiency in explaining growth patterns. These objectives were met by answering the following questions for three locations in Vietnam:

1. Which ecological factors correlate strongly with growth of white bamboo?

2. Is bamboo growth limited by nutrient deficiencies, as evidenced by response to fertilizer application?

3. How does the growth of bamboo relate to the capture of light and the efficiency of light use?

Through this study I want to make general inferences on the correlations between ecological factors and white bamboo growth indicators and the effects of fertilizers on white bamboo growth. Results from this study can be useful information in cultivating white bamboo, maintaining soil productivity and sustainable white bamboo plantation management.

Materials and method

Site description

White bamboo plantations were planted by seedlings propagated from culm or branch in 1994-1995 in 3 areas: Cau Hai, Phu Tho at $21^0 33'25''$ N and $105^0 11'21''$ E; Luong Son, Hoa Binh at $20^0 54'09''$ N and $105^0 28'33''$ E; and Ngoc Lac, Thanh Hoa at $20^0 05'27''$ N and $105^0 22'25''$ E (Fig. 3.2).

In Cau Hai-Phu Tho white bamboo plantations were at 33-90 m elevation, slope $\leq 25^0$, with a mean annual temperature of 22.9^0 C, and average annual rainfall of 1600 mm. The rainy season lasts for 5-6 rainy months, with 2-3 dry months, and 2 very dry months per year. The soils are red or yellow Ferralsols (Oxisols in US or Feralits in Vietnam soil taxonomy system) (FAO 1992) developed on gneiss or mica schist, with thick or medium horizons.

In Luong Son-Hoa Binh white bamboo plantations were at 62-183 m elevation, slope $\leq 35^0$, with a mean annual temperature of 23.6^0 C, and average annual rainfall of 1500-2000 mm. Rainy season from April to October, dry season from November to March next year, and there is no drought month. The soils are red or brownish yellow Ferralsols developed on limestone, reddish yellow Ferralsols on the metamorphic rock, light yellow Ferralsols on sandstone, and brownish Ferralsols on the alluvium.

In Ngoc Lac-Thanh Hoa white bamboo plantations were at 54-91 m elevation, slope $\leq 25^0$, mean annual temperature of 23.1^0 C, and average annual rainfall of 1900 mm. Six rainy months, from May to October are followed by lower rainfall periods with no pronounced drought. Humidity averages about 85% throughout the year. The soils are reddish yellow Ferralsols on shale and metamorphic rocks, light yellow Ferralsols on sandstone, and brownish Ferralsols on alluvium. Soil textures are light silt, medium silt and clay.

All white bamboo plantations in three areas were planted on hilly or low mountainous lands that were once covered by forest. Most of the sites still had thick layers of soil with high porosity and good fertility.

Experimental design

I established twenty nine 20 x 20 m temporary plots across a range of locations, topographic positions, and management intensities. The design used three areas (Cau Hai, Ngoc Lac, and Luong Son), two topography positions (hilltop and footslope), and three management schemes (pure bamboo with low-intensity management, pure bamboo with intensive management, and bamboo mixed with nitrogen-fixing Acacia trees, Table 3.1).

Soil samples in the depth of 0-30 cm were collected with soil corer in twenty five spots set up evenly in 5 parallel transects in each plot. Twenty five soil cores in each plot were mixed carefully to form one soil sample then put in plastic bags, marked, and transported to the lab for analyzing. One profile was dug in the central of each plot for general descriptive purposes.

Nutrient limitation was tested in 12 plots in Cau Hai, Phu Tho. Five clumps were selected in each plot, with similar, average culm diameter, height, and vigor. In five selected clumps one was fertilized with ammonium nitrate (NH_4NO_3), one with superphosphate ($Ca(H_2PO_4)_2$), one with potassium chloride (KCl), one with N+P+K (10:3:5), and the last one was not fertilized (control clump). The rates of application were: 106 g/clump N, 140 g/clump P, and 210 g/clump K. Four culms age from 1 to 2 years old in fertilized and control clumps were marked by paint and remeasured one year later.

Light interception was measured by using 2 quantum meters that were manufactured by Apogee Instruments, Inc., model LQS-QM, one inside plot and one in the open area. In each plot set up 100 spots evenly in 5 parallel transects. Absorbed photosynthetically active radiation was determined as the difference between values measured under the canopy and full-light measurements outside the canopy.

Growth measurements and ecological factors estimation

All measurements were taken inside a 20 x 20m plot (400 m^2). GPS was used to indicate plot position, and elevation. The number of clumps in each plot was counted, as well as the number of culms in each clump. All culms interior-plot culms were identified by age, measured for diameter and height, and rated for overall vigor. Culm age was determined by an experienced observer based on culm color, secondary branch generation, and sound.

Four measures of growth were determined for each plot: total culm volume, culm wall volume, dry culm mass, and number of economically valuable culms, all extrapolated to a hectare basis. Total culm volume is the total volume of all white bamboo culms. Culm wall volume is the true volume (omitting interior air space) that is useful for making paper, bamboo mat, bamboo poly wood. Dry culm mass (weight of after drying) is the popular way to estimate white bamboo yield. The number of economically valuable culms (N_e) is the number of culms big enough for construction or for other commercial purposes (straight, disease-free, culms $\geq$ 8 cm dbh, $\geq$ 7 m height; Nguyen Truong Thanh 2002). White bamboo culm volume was estimated by the equation:

$$V_t = 4.93 \times 10^{-5} \times D^{1.65179} \times H^{1.326} \qquad (1)$$

Culm wall volume was estimated by the equation:

$$V_w = 7.18 \times 10^{-5} \times D^{0.880578} \times H^{1.5276} \qquad (2)$$

Dry culm mass was estimated by the equation:

$$M_d = 0.6345 + 0.4415 \times M_f \qquad (3)$$

$$(M_f = 0.105377 \times D^{1.04218 \times} H^{1.25298})$$

Vt: culm volume; D: culm breast height diameter; H: culm height; V_w*: culm wall volume;* M_d*: dry culm mass;* M_f*:fresh culm mass* . (Do Nhu Chien 2000).

Values were calculated for each culm and summed for the total plot and extrapolated to a hectare basis.

Soil samples were analyzed by Soil Analyzing Division, National Institute of Agricultural Planning and Projection, Ministry of Agriculture and Rural Development of Vietnam. Soil moisture was estimated by comparing soil sample weight before and after drying in oven. Soil bulk density was estimated by dividing dry soil bulk density core weight by its volume. Soil density was estimated by Pycnometer method. Porosity was identified by gravity method. Dilute Hydrofluoric Acid Extraction was used to estimate soil SiO_2 content. Solution of KCl 0.1 mol/L and pH-meter were used to identify soil pH_{KCl}. The content of organic carbon was estimated with the Tiurin method (similar to Walkley-Black wet oxidation method). Potassium dichromate ($K_2(Cr_2O_7)$) was used in excess to determine organic carbon with the present of sulfuric acid (H_2SO_4); the remaining dichromate was identified by iron sulfate ($FeSO_4$). Total nitrogen was estimated with Kjeldahl method, and available nitrogen was estimated with Tiurin and KoonvA methods. In KoonVa method sulfuric acid with the concentration of 0.5 mol/L was used to extract labile nitrogen, determined colorimetrically (at 262-400 nm). Color comparison and Oniani methods were used to estimate total and available phosphate contents respectively. In Oniani method, available phosphorus was extracted by sulfuric acid 0.1 mol/L with the soil/acid ratio of 0.04, followed by colorimetry using molybdate ammonium solution with zinc chloride (deoxidized substance). Flame spectrum analysis was used to estimate both total and available potassium contents. The intensity of light emission at potassium-specific wavelengths was measured by emission spectroscopy. Cation exchange capacity was estimated with ammonium acetate method, a procedure using ammonium acetate as an extractant. Total silica content was dissolved by the combination of three condensed acids: hydrochloric acid, nitric acid, and sulfuric acid with ratio 2:1:4 then extracted by organic gelatin.

The response of bamboo growth to fertilization was estimated by measuring all marked culms and their 1 year old culms for 4 fertilized and control clumps in each plot in total 12 experimented plots. The protrusive value of growth of average 1 year old culms and average marked culms (the parent culms) compared to these values in control clumps was the respond of white bamboo for each fertilizer in each plot.

Statistical analysis

The ecological characteristics of the 29 sites were correlated with measures of bamboo size, growth and value using stepwise forward multiple regressions. The difference of white bamboo growth in fertilized and controlled clumps was examined by using 1-tail independent samples t-test, SAS 9.0 program with the significant at 0.05 level.

Results and discussion

Influence of ecological factors on white bamboo growth

Among the 14 ecological factors examined, soil moisture had the strongest relationship with total white bamboo culm volume (r^2= 0.31, P_r< 0.01) (Table 3.2). Two others ecological factors, pH_{KCl} and SiO_2 had r^2= 0.29 and 0.19 respectively in correlation matrix (Table 3.3), but did not add significantly to the prediction of culm volume beyond soil moisture alone (Equation 1). Other measures of ecological factors (soil density, soil bulk density, soil porosity, soil pH, soil organic matter, total and available nitrogen, potassium, phosphate, and cation exchange capacity) showed no pattern with total culm volume. The volume of white bamboo culm walls also correlated moderately well with soil pH (R^2= 0.27, P_r< 0.01). The soil moisture had r^2= 0.27 in the correlation matrix (Table 3.3) but did not appear in the culm wall volume regression equation (Equation 2). The other ecological factors had medium or weak regression with culm wall volume.

Soil pH correlated best with dry culm mass (R^2= 0.26, P_r< 0.01, Table 3.2), followed closely by soil moisture (r^2= 0.23) but soil moisture did not showed up in the regression equations because it correlated well with soil pH (r^2= 0.31, Table 3.3).

White bamboo plantations with high numbers of economically valuable culms provide high incomes for farmers. Soil pH and cation exchange capacity had relatively strong regression with number of economic valuable culm (R^2= 0.43, P_r= 0.03, Table 3.2). Soil moisture, soil SiO_2 content, and soil available K content had medium correlation with number of economic valuable culm (r^2= 0.25, 0.21, and 0.16 respectively, Table 3.3) but were not present in the multiple regression equation. The remaining ecological factors showed medium or weak regression with number of economic valuable culm.

Soil moisture is one of the most important factors to white bamboo growth. In shoot phase moisture needs for shoot growth because water occupies most of white bamboo shoot mass. This is the most important phase for white bamboo to form its culm diameter and height. Bamboo shoot grows well in the moist soil or at night because of high relative humidity (Ngo Quang De 1994). As white bamboo plants get older, a good supply of water helps the plant obtain nutrients in the soil and transport them to the leaves for photosynthesis, and then transport photosynthate from leaves to other parts of white bamboo. If there is not enough moisture and nutrient, shoot will die (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

Soil pH is one of the important soil chemical patterns to white bamboo growth. Soil pH can determine soil solution properties that control soil nutrients, root, microbiology activities and plant metabolism. White bamboo grows well on slightly acidic soils (pH= 5-6.5), and variations in soil pH from 4 to 6 generally show no influence on white bamboo growth. Soil pH_{KCl} below 4 is stressful for white bamboo growth (Nguyen Ngoc Binh 2001), so the range in soil pH_{KCl} in my study (from 2.62 to 3.87, table 3.6) led to good correlation with white bamboo growth. Soil pH influenced total culm volume, culm wall volume, fresh and dry culm mass, and number of economic valuable culm.

Soil cation exchange capacity is determined by the amount of clay and humus present in the soil, as well as soil pH. These two colloidal substances are essentially the cation warehouse or reservoir of the soil. Sandy soils with very little organic matter (OM) have a low CEC, but heavy clay soils with high levels of OM have a much greater capacity to hold cations (*http://www.norganics.com/cec.pdf*). The soil with high cation exchange capacity can hold more nutrient cations than that of low cation exchange capacity. This is important to white bamboo because it grows in sub-tropical and tropical regions, those have high leaching rate. White bamboo needs high clay content soil (Nguyen Ngoc Binh, Pham Duc Tuan 2007). In fertile soil white bamboo grows well, has big culm diameter and culm height, then increases number of economic valuable culm.

The effect of fertilizer on white bamboo growth

White bamboo growing on fertile soils has bigger, taller culms as well as higher survival of shoots compared with bamboo on infertile soils. White bamboo has high requirements for mineral nutrients, especially nitrogen and potassium. Nitrogen application increased growth more than other fertilizer treatments, increasing growth by about three-fold over the control. However, great variation in growth among culms and clumps resulted in a non-significance of all fertilization treatments (Table 3.4). When using SAS program to test the different effects of fertilizers on white bamboo growth it showed that only white bamboo fertilized with nitrogen had culm volume, culm wall volume, and dry culm mass increments significant difference from the others (P_r= 0.05, 0.03, and 0.05 respectively). All of the other fertilizers did not have significant effects on white bamboo growth (Table 3.5)

The increased rate of total culm growth in response to N fertilization was 11.5 m^3/ha per year, and culm wall volume growth increased by 5.3 m^3/ha per year. Dry culm mass increments one year was 1839 kg extrapolated for one ha. The number of economic valuable culm increased 208 culms/ha per year (Table 3.4).

The second-most effective fertilizers were Potassium and NPK. These fertilizers increased total culm volume 12.0 and 4.0 m^3/ha/, wall culm volume 4.6 and 3.4 m^3/ha, dry culm mass 1479 and 1438 kg/ha, and number of economic culm 104 and 139 culm per ha per year, respectively (Table 3.4).

The least effective fertilizer was phosphate. Total culm volume may have declined 2.1 m^3 and culm wall volume increment was only 1.13 m^3 per ha per year, although these were not significantly less than the controls. Dry culm mass increments declined 183 kg per ha. Number of economic valuable culms only increased 17 culms per ha per year (Table 3.4).

However, the differences in growth increment among white bamboo fertilization experiments were not significant. There were no reliable differences in growth of white bamboo to the fertilization treatments excepted nitrogen on culm volume, culm wall volume, and dry culm mass. White bamboo fertilized with Nitrogen, Potassium and NPK showed the increment in total culm volume, culm wall volume, dry culm mass, and number of economically valuable culms. Phosphate did not affect much on these growth indicators. White bamboo had high demand on Nitrogen, Phosphate, Potassium, especially Nitrogen and Potassium. In other words, white bamboo needs fertile, high nutrient content soils (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

In the short period (two years) and at young age (two years after planted) fertilization did not significantly affect white bamboo growth (Le Quang Lien 1990). In this study white bamboo plantations were in 14-15 years old but the duration of fertilization was only one year so it may make the difference not significant. In Ngoc Lac white bamboo fertilized with NPK in continuous years had greater average DBH and height than non-fertilized white bamboo. Average DBHs were 10.4 and 10.1 cm in fertilized footslope and hilltop plantations, 38% and 40% bigger than controlled plantations (7.5 and 7.2 cm on footslope and hilltop respectively). Fertilized white bamboo also had culm height 12% greater than controlled ones in both topographic positions (14.0 and 13.9 m in fertilized footslope and hilltop plantations to compare with 12.5 and 12.4 in controlled footslope and hilltop plantations respectively (Pham Thi

Quyen 2003). Another reason that might affect the significance effect of fertilizers was the sample size. In this study, because of the limit in time, labor, and finance only 4 culms in clump in 12 plots in one area were selected for applying each of fertilizer so the sample size was too small for a high variation in growth of white bamboo culm. These results could be used as the reference for on-going studies on the effects of fertilizers on white bamboo growth.

The effect of light interception and light use efficiency on white bamboo growth

Light interception related weakly with total culm volume, culm wall volume, dry culm mass, and number of economic valuable culm, but the slopes of the relationships were high. The regression equations predicted that increasing light interception by 10%, for example, would increase culm volume by 27.0 m^3/ha, culm wall volume by 13.4 m^3/ha, culm mass by 5750 kg more dry culm mass, and economically valuable culms by 303/ha (Figure 3.1). The regressions between light interceptions and culm volume, culm wall volume, dry mass, and number of economic valuable were R^2= 0.12, 0.14, 0.14, and 0.09 respectively with the correlative powers were 0.06, 0.04, 0.04, and 0.10 (Table 3.7)

The regressions between total culm volume, culm wall volume, dry culm mass, and number of economic valuable culm and light use efficiencies were very weak and not significant. R^2 was highest in culm wall volume and number of economic valuable culm-light use efficiency equations (R^2= 0.06, P_r= 0.19 and 0.29), lowest in total culm volume-light use efficiency equation (R^2= 0.05, P_r= 0.25) (Table 3.8).

Plant growth typically correlates strongly light interception. The high variation around this trend for white bamboo may be real, or it may reflect a strong (and variable) effect of non-bamboo vegetation in determining the light interception that occurred in my stands.

Ecological factors had various effects on white bamboo growth indicators. Soil moisture had strong relationship with total culm volume but not with other tested ecological factors. Soil pH correlated well with culm wall volume, the other ecological measures had medium or weak regression with this growth feature. The number of economically valuable culms had relatively strong relationships with soil pH and cation exchange capacity and medium correlation with soil moisture, soil silicate, and soil available potassium contents. Nitrogen was the most effective fertilizer in the fertilization experiment. White bamboo fertilized with nitrogen had culm volume, culm wall volume, and dry culm mass increment significant difference from that with other fertilizers. Potassium and NPK were the seconds, and the least was phosphorus. But most of the effects were not significant for the first growing season so it is necessary to observe white bamboo growth in these fertilized plots in following years. Light interception had weak and light interception efficiency had so weak relationship with white bamboo growth features (total culm volume, culm wall volume, dry culm mass, and number of economic value culm) and most of these regressions were not significant. This may caused by non-bamboo vegetation in determining the light interception in white bamboo stands. In following research, there should be other method to determine the light interception that can eliminate non-bamboo vegetation effects.

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Table and figures

Table3.1: Experiment design of the study

Area	Site productivity	Management Intensity		
		Mixed	Pure- Intensive	Pure- extensive
Cau Hai	Top	2	2	2
	Foothill	2	2	2
Luong Son	Top	0	2	2
	Foothill	0	2	2
Ngoc Lac	Top	2	1	2
	Foothill	2	1	1

Table 3.2 Regression results of white bamboo culm volume, culm wall volume, dry culm mass, number of economic culm and ecological factors

N_o	Equation	$P_r > F$	R^2
1	$CV = -15.6 + 5.69\ SM$	*< 0.01*	0.31
2	$CWV = -54.92 + 29.03\ pH$	*< 0.01*	0.27
3	$DM = -19{,}983 + 11{,}944\ pH$	*< 0.01*	0.26
4	$N_E = -3{,}136 + 771.89\ pH + 136.58\ CEC$	*0.03*	0.43

CV: Culm volume (m^3 per ha)

CWV: Culm wall volume (m^3 per ha)

DM: Dry culm mass (kg per ha)

N_E: Number of economic culm per ha

SM: Soil moisture

pH: Soil pH

CEC: Cation exchange capacity

Table 3.3 Correlation matrix

	Vol All	Vol wall	D. mass	Ne	Moist	Den.	Bulk Den.	Poro.	SiO_2	pH KCl	OM	Tt N	Tt P_2O_5	Tt K_2O	Avail. N	Avail. P_2O_5	Avail. K_2O	CEC
Vol. All	1.00																	
Vol.	0.98	1.00																
D.mass	0.98	0.99	1.00															
Ne	0.90	0.84	0.84	1.00														
Moist	**0.56**	**0.52**	**0.48**	**0.50**	1.00													
Density	-0.21	-0.11	-0.09	-0.26	-0.23	1.00												
Bulk den.	**-0.31**	**-0.31**	-0.22	-0.24	-0.27	0.46	1.00											
Porosity	-0.13	-0.15	-0.19	-0.01	0.00	-0.12	-0.26	1.00										
SiO_2	**0.43**	**0.40**	**0.42**	**0.46**	0.37	-0.09	-0.08	-0.14	1.00									
pH KCl	**0.54**	**0.52**	**0.51**	**0.56**	**0.56**	-0.13	-0.11	0.04	0.56	1.00								
OM	0.21	0.15	0.11	**0.35**	0.36	-0.56	-0.23	0.26	0.32	0.24	1.00							
Tt. N	0.26	0.20	0.16	0.35	0.53	-0.40	-0.18	0.35	0.27	0.27	0.69	1.00						
Tt. P_2O_5	0.26	0.21	0.22	0.26	0.40	0.05	0.14	0.11	-0.05	-0.05	-0.01	0.03	1.00					
Tt. K_2O	-0.26	**-0.31**	-0.29	-0.13	-0.01	-0.30	-0.14	0.31	0.00	-0.02	0.19	0.17	-0.27	1.00				
Av. N	0.29	0.29	0.27	0.29	0.19	0.08	0.06	-0.47	0.30	0.37	-0.08	-0.03	-0.12	-0.28	1.00			
Av. P_2O_5	-0.06	-0.06	-0.08	-0.12	0.12	-0.12	-0.10	-0.11	0.04	0.13	0.16	-0.31	-0.02	0.10	0.10	1.00		
Av. K_2O	**0.38**	**0.35**	**0.31**	**0.40**	0.59	-0.42	-0.32	0.17	0.49	0.55	0.72	0.67	-0.07	0.00	0.12	0.02	1.00	
CEC	**0.35**	0.28	0.24	**0.42**	0.42	-0.50	-0.48	0.36	0.11	0.16	0.40	0.44	0.20	0.41	0.15	-0.02	0.30	1.00

Table 3.4 White bamboo cuml volume, culm wall volume, dry mass, and number of economic valuable culm increment response to fertilization treatments

No	Pattern	Fertilizer	$\Delta_{Treatment}$ (per culm)	$\Delta_{Control}$ (per culm)	$\Delta_i = \Delta_{Tr} - \Delta_{Co}$ (per culm)	Δ per ha (Δ_ix1250)
1	Culm volume increment (m^3/yr)	Nitrogen	0.0104	0.0012	0.0092	11.50
		Potassium	0.0108	0.0012	0.0096	12.00
		Phosphate	-0.0005	0.0012	-0.0017	-2.13
		NPK	0.0044	0.0012	0.0032	4.00
2	Culm wall volume increment (m^3/yr)	Nitrogen	0.0039	-0.0003	0.0042	5.25
		Potassium	0.0034	-0.0003	0.0037	4.63
		Phosphate	0.0006	-0.0003	0.0009	1.13
		NPK	0.0024	-0.0003	0.0027	3.38
3	Dry culm mass increment (kg/yr)	Nitrogen	1.6778	0.2069	1.4709	1839
		Potassium	1.3901	0.2069	1.1832	1479
		Phosphate	0.0603	0.2069	-0.1466	-183
		NPK	1.3571	0.2069	1.1502	1438
4	N_e increment (culm/yr)	Nitrogen	0.125	-0.0417	0.1667	208
		Potassium	0.0417	-0.0417	0.0834	104
		Phosphate	-0.0278	-0.0417	0.0139	17
		NPK	0.0694	-0.0417	0.1111	139

Table 3.5 White bamboo increment comparison

No	Content	Fertilizer	Treatment mean	Control mean	F value	P_r
1	Culm volume increment (m^3*yr*ha^{-1})	***Nitrogen***	***12.96***	***1.47***	***2.80***	***0.05***
		Potassium	13.56	1.47	1.17	0.15
		Phosphate	1.47	-0.59	0.08	0.39
		NPK	5.44	1.47	0.15	0.35
2	Culm wall volume increment (m^3*yr*ha^{-1})	***Nitrogen***	***4.92***	***- 0.39***	***5.66***	***0.02***
		Potassium	4.31	-0.39	1.43	0.13
		Phosphate	0.80	-0.39	0.19	0.34
		NPK	3.05	-0.39	0.89	0.18
3	Dry culm mass increment (kg*yr*ha^{-1})	***Nitrogen***	***2097***	***259***	***3.04***	***0.05***
		Potassium	1738	259	0.75	0.20
		Phosphate	259	175	0.02	0.45
		NPK	1696	259	0.68	0.21
4	N_e increment (culm*yr*ha^{-1})	Nitrogen	156	-52	0.89	0.18
		Potassium	52	-52	0.17	0.35
		Phosphate	-35	-52	0.01	0.47
		NPK	87	-52	0.25	0.31

Table 3.6: Soil properties of white bamboo plantations

Plot No	Moist %	Density	Bulk Density	Porosity %	SiO2%	pH KCl	OM%	Total (%)			Available (mg/100g)			CEC (ld/L)
								N	P2O5	K2O	N	P2O5	K2O	
CH01	22.20	2.57	1.26	52.25	58.68	3.64	2.06	0.15	0.09	0.25	8.96	1.40	3.19	9.09
CH02	28.17	2.40	1.24	53.69	60.45	3.67	2.18	0.16	0.25	0.05	9.94	1.40	3.76	12.17
CH03	24.05	2.54	1.22	51.07	68.41	3.79	2.02	0.15	0.10	0.03	10.40	1.20	4.18	9.46
CH04	20.08	2.25	1.16	50.92	50.79	3.64	2.44	0.16	0.08	0.05	10.90	1.30	4.25	10.03
CH05	18.64	2.53	1.35	45.94	68.29	3.62	2.46	0.14	0.09	0.04	10.19	2.30	3.74	9.24
CH06	27.65	2.48	1.13	50.51	69.68	3.73	2.05	0.14	0.21	0.08	8.19	1.40	3.80	9.34
CH07	20.32	2.50	1.25	40.59	70.01	3.82	1.80	0.13	0.09	0.03	19.02	1.50	3.12	11.16
CH08	20.86	2.52	1.16	50.57	68.23	3.59	2.17	0.15	0.08	0.14	10.31	1.40	4.78	9.37
CH09	19.06	2.56	1.12	50.11	67.13	3.87	1.99	0.13	0.08	0.09	10.40	1.90	3.01	7.47
CH10	23.82	2.27	1.16	40.73	56.41	3.72	1.92	0.14	0.12	0.18	9.77	1.10	3.47	9.98
CH11	21.40	2.43	0.99	53.56	56.85	3.82	2.09	0.14	0.12	0.24	9.56	1.40	3.63	11.75
CH12	20.82	2.51	1.02	56.68	67.97	3.81	1.93	0.14	0.10	0.18	10.27	1.20	3.32	12.43
Average	***22.26***	***2.46***	***1.17***	***49.72***	***63.58***	***3.73***	***2.09***	***0.14***	***0.12***	***0.11***	***10.66***	***1.46***	***3.69***	***10.12***
NL01	20.12	2.52	1.24	54.75	40.25	3.63	2.12	0.16	0.08	0.36	10.44	1.00	3.46	10.41
NL02	18.99	2.56	1.05	54.36	29.41	3.25	1.86	0.14	0.09	0.05	9.40	1.40	3.14	10.17
NL03	14.14	2.54	1.08	47.97	38.01	2.62	1.85	0.12	0.06	0.37	9.01	1.50	2.84	9.52
NL04	15.76	2.55	1.31	55.21	39.91	2.82	1.83	0.13	0.19	0.35	8.30	1.40	2.31	9.95
NL05	14.71	2.52	1.27	42.32	48.85	2.72	1.85	0.13	0.09	0.54	7.79	1.20	2.21	9.38
NL06	24.21	2.51	1.23	53.00	39.56	3.55	2.05	0.14	0.11	0.52	9.49	1.60	3.58	10.46
NL07	15.65	2.48	1.37	52.15	45.17	3.81	1.71	0.13	0.07	0.45	8.76	1.40	2.99	8.35
NL08	18.58	2.59	1.28	55.76	40.01	3.35	2.05	0.14	0.19	0.58	9.19	1.40	3.00	11.03
NL09	12.40	2.46	1.23	54.21	44.50	3.35	1.76	0.12	0.08	0.48	8.12	1.60	2.74	8.75
Average	***17.17***	***2.53***	***1.23***	***52.19***	***40.63***	***3.23***	***1.90***	***0.13***	***0.11***	***0.41***	***8.94***	***1.39***	***2.92***	***9.78***
LS01	19.38	2.49	1.22	50.46	68.75	3.68	2.04	0.14	0.07	1.06	9.57	1.30	3.51	10.55
LS02	20.39	2.45	1.16	53.27	67.07	3.67	2.18	0.15	0.07	0.90	10.07	1.40	3.69	11.11
LS03	26.73	2.26	1.08	49.95	54.03	3.62	2.33	0.16	0.09	0.98	10.73	1.70	3.93	11.84
LS04	26.30	2.17	0.99	54.43	54.84	3.83	2.21	0.14	0.10	1.10	9.53	2.70	3.80	12.72
LS05	19.18	2.24	1.12	54.45	52.98	3.70	2.35	0.14	0.09	0.67	8.46	1.00	3.84	11.54
LS06	18.20	2.12	1.07	60.50	65.91	3.16	2.45	0.17	0.08	0.66	7.83	1.10	3.97	11.94
LS07	24.65	2.63	1.21	54.09	66.33	3.72	2.02	0.16	0.07	0.85	9.68	1.00	3.55	10.68
LS08	18.17	2.46	1.17	55.64	68.28	3.83	2.16	0.14	0.10	0.91	8.96	1.40	3.65	10.98
Average	***21.63***	***2.35***	***1.13***	***54.10***	***62.27***	***3.65***	***2.22***	***0.15***	***0.08***	***0.89***	***9.35***	***1.45***	***3.74***	***11.42***

Table 3.7 Regression results of total culm volume, culm wall volume, dry culm mass, number of economic valuable culm and light interception

N_o	Equation	$P_r > F$	R^2
1	CV = -146.94 + 2.7 LI	0.06	0.12
2	CWV = -75.24 + 1.34 LI	***0.04***	0.14
3	DM = -30,279.7 + 574.87 LI	***0.04***	0.14
4	N_e = -1,752.8 + 30.265 LI	0.10	0.09

Table 3.8 Regression results of total culm volume, culm wall volume, dry culm mass, number of economic valuable culm and light interception efficiency

N_o	Equation	$P_r > F$	R^2
1	CV = -0.525 + 0.0177 CV/LI	0.25	0.05
2	CWV = -0.318 + 0.0092 CWV/LI	0.19	0.06
3	DM = -96.02 + 3.70 DM/LI	0.21	0.06
4	N_e = -7.85 + 0.206 N_e /LI	0.29	0.06

CV: Culm volume (m^3 per ha)

CWV: Culm wall volume (m^3 per ha)

DM: Dry culm mass (kg per ha)

N_E: Number of economic culm per ha

LI: Light interception (%)

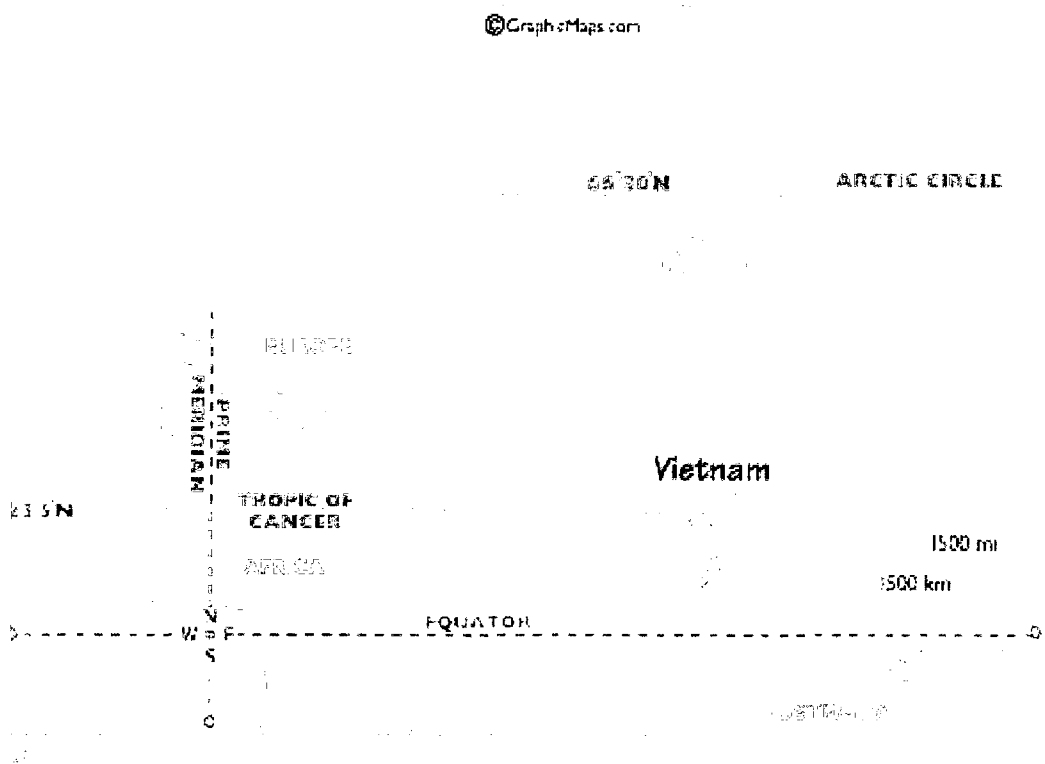

Figure 3.1 Vietnam in Asia

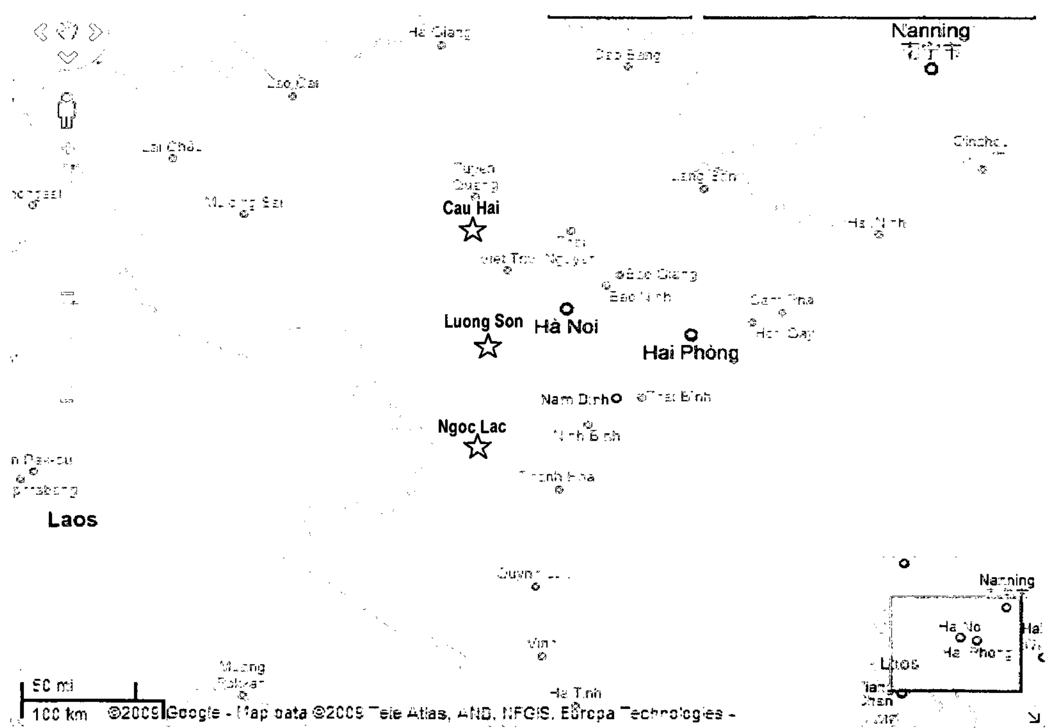

Figure 3.2 Studying areas of research

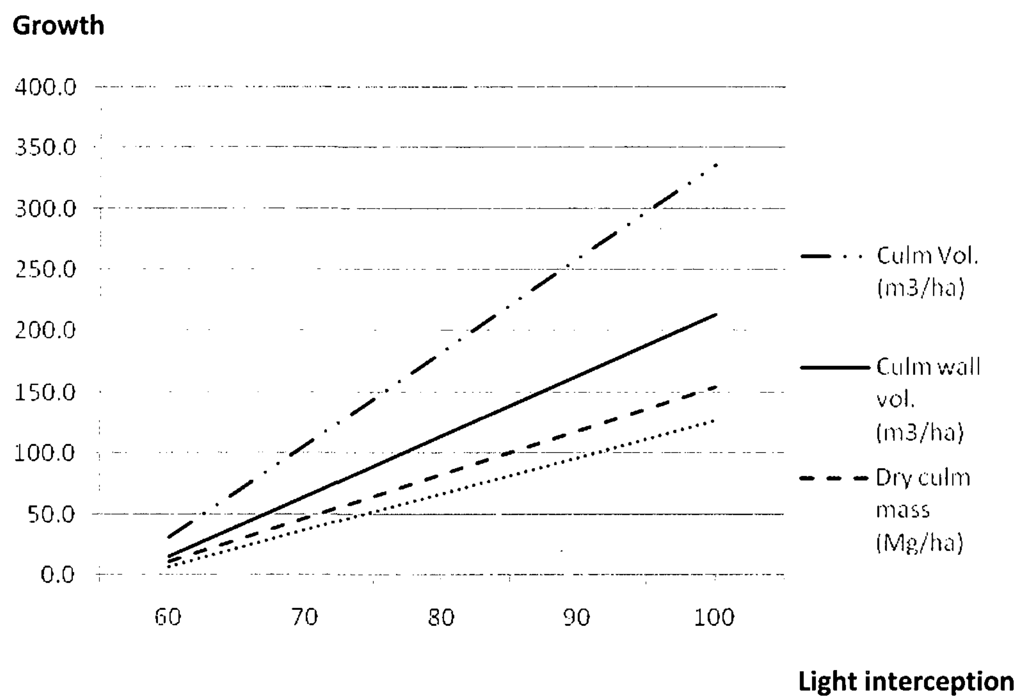

Figure 3.3 Regression results of total culm volume, culm wall volume, dry culm mass, number of economic valuable culm and light interception

Chapter 4

CONCLUSIONS ANS MANAGEMENT RECOMMENDATIONS

Summary

White bamboo is a fast growing species distributed across southern China, Laos, Myanmar, northern Thailand, and northern Vietnam. In Vietnam white bamboo is very well known and widely used in rural areas. White bamboo plantations occupied over 80.000 ha by 2004 with 10-20% of the plantations for watershed protection and special uses, the rest for production (Forest Ranger of Vietnam, 2005).

White bamboo is used commonly in construction and making agricultural tools, household appliances, and handicraft products. White bamboo raw material can be processed into high value-added products like bamboo mats, flooring boards, and furniture. The long fibers of white bamboo yield a valuable pulp for making paper. Young shoots provide a healthy food and young leaves are fed to livestock. White bamboo can help people in the hilly and mountainous areas to eliminate starvation, reduce poverty and gain wealth. White bamboo propagation and cultivation technologies are easy enough for farmers to implement.

White bamboo growth varies in response to environmental factors (some related to topography) and management intensities. Topographical position had significant effects to white bamboo growth and these effects were various in different sites. Topographic position had strong effects on white bamboo growth in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa but not in Luong Son-Hoa Binh. The significant differences were in total culm volume in 3-year-and-younger in Cau Hai-Phu Tho, DBH and height in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa, and number of economically valuable culms in both all-age and 3-year-and-younger calculations in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa.

Management intensity affected total culm volume in Cau Hai-Phu Tho (in both all-age and 3-year-and-younger calculations) and in Ngoc Lac-Thanh Hoa (in 3-year-and-younger calculation), on culm wall volume in Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa, on dry culm mass in Cau Hai-Phu Tho (in both calculation methods), and in DBH and height in Luong Son-Hoa Binh.

The effect of topographic position and management intensity on white bamboo growth light use efficiencies differed among sites. Topographic position affected culm volume light use efficiency in Cau Hai-Phu Tho, DBH and height light use efficiencies in Ngoc Lac-Thanh Hoa, and number of economically valuable culm light use efficiency in both Cau Hai-Phu Tho and Ngoc Lac-Thanh Hoa. Management intensity had significant effect on culm DBH light use efficiency in Cau Hai-Phu Tho and Luong Son-Hoa Binh, on culm height light use efficiency in Luong Son-Hoa Binh, on culm volume, culm wall volume, and dry culm mass light use efficiencies in Cau Hai-Phu Tho.

White bamboo total culm volume had strong correlation with soil moisture. Soil pH also had strong correlation with total culm volume but did not show up in the regression equation. Culm wall volume had relatively strong regression with soil pH. Soil moisture had relatively strong correlation with culm wall volume but did not appear in the regression equation either. Both soil moisture and soil pH were important to white bamboo total culm volume and culm wall volume.

White bamboo dry culm mass, and number of valuable economic culms had relatively strong regression with soil pH. Soil pH affected on white bamboo culm growth thus determined white bamboo productivity. Number of economic valuable culm also had correlation with cation exchange capacity, one important feature of soil productivity.

Most of the fertilized bamboo showed higher increment in total culm volume, culm wall volume, fresh and dry mass, and number of economic valuable culm of white bamboo but only white bamboo fertilized with nitrogen showed the significant difference in total culm volume, culm wall volume, and dry culm mass. The other fertilization treatments did not significantly differ in one-year experiment. Nitrogen, potassium and N+P+K seemed to have more effect on white bamboo growth than phosphorus.

Suggestion for on-going study and future management of white bamboo

In this study there were not enough three management modes in all three areas because over mature *Acacia mangium* trees mixed with white bamboo were cut in Luong Son-Hoa Binh. In the ongoing study the mixed plantation should be open to the broadleaf mixed white bamboo plantations so we can test the impact of broadleaf trees on white bamboo growth.

In the correlation experiment, some vital ecological factors did not appear in the regression equations. This may cause by the variation of these factors, they are not significant enough to impact the growth of white bamboo. In future study we need to take care not only in the ecological factors themselves but also on their variation.

The fertilization experiments were implemented in clump units, so we could not identify light interception for each fertilized treatment. In ongoing study we need to measure light interception in fertilization experiments and estimate light interception efficiency for white bamboo in each fertilization treatment by enlarging fertilized plots (20 x 20 m) or identifying leaf area. The power of this study might improved by increasing number of fertilized culms and raising the number of experimented plots.

Long-term cultivation white bamboo without mixing with trees and fertilization (extensive cultivation) leads to declination in white bamboo growth. White bamboo products in these plantations were lower than that in intensive cultivation ones, both in yield and quality. To maintain productivity of these plantations we need to manage them sustainably.

The material leftover on a site after white bamboo harvest is mostly leaf matter. White bamboo leaves have low nutrient concentrations and high silica content, making decomposition difficult. Slow decomposition in pure extensive cultivation of white bamboo could decrease site productivity (Ngo Quang De 1994). White bamboo needs to be fertilized with ammonium nitrate 0.4 kg/clump or NPK (10:3:5)/clump annually. In the infertile soil, white bamboo should be fertilized with 15-30 kg manure/clump. In the first three years white bamboo can be mixed with agricultural crops, especially legume trees (Nguyen Ngoc Binh, Pham Duc Tuan 2007).

All of these studying results are the good references for white bamboo cultivation and management in Vietnam. Results from this study can be useful information in choosing planting site, managing white bamboo, maintaining soil productivity and sustainable white bamboo plantation management. White bamboo should be planted on footslope and be intensively managed. High coverage of *Acacia mangium* crown may inhibit white bamboo growth.