

Silvicultural performance of paper mulberry in Thailand

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ABSTRACT Paper mulberry plantations are needed in Thailand due to Thailand's high demand for paper manufacturing. In this paper, silvicultural systems were investigated to determine for attaining the optimum growth rate and yield. Paper mulberry from five sources (SS, UN, NN, RT and KZ) were planted in eight sites all over Thailand for a provenance trial, while two species (*Broussonetia papyrifera* and *B. kazinoki*) were planted at Wiang Sa district, Nan province for a species trial. Moreover, five spacings (1x1m, 2x1 m, 2x2 m, 2x4 m and 4x4 m) were used in RCBD (Randomized Complete Block Design) with three replicates in Wang Chin district, Phare Province for a spacing trial. Survival rate, growth rate, biomass and soil physical and chemical properties were recorded at every site. Paper mulberry can grow in various textures of soil as long as there is a good drainage. Soil fertility had a significant effect on growth and productivity. *B. papyrifera* had a higher biomass than *B. kazinoki* with the same growth rate. The number of trees (plant density) had an important effect on biomass. From these data, it is recommended that in paper mulberry plantation narrow spacing is used.

Key words: silvicultural performance, paper mulberry, provenance trial, species trial, spacing trial

INTRODUCTION

Paper mulberry bark has been used as the raw material to make a form of paper since AD 100 in China (Lewington, 1990). At that time, paper mulberry fibers were needed to write Buddhist scriptures. It is also known that people used handmade mulberry paper as currency (Xiao, 2001). At present, this traditional papermaking exists in many countries and has been developed on an industrial scale. Among the huge range of available materials for papermaking, the bark of paper mulberry (*Broussonetia papyrifera* and *B. kazinoki*) is the finest, because it produces a soft, strong paper with excellent texture (Kobayashi, 2001). With a rapid increase in demand for the bark of paper mulberry, large scale harvesting is being carried out with little or no proper management, resulting in the destruction of good growing areas. In an effort to try to correct the problem, paper manufacturers have themselves attempted to grow the tree, but to no avail. In Thailand, paper mulberry stands are distributed all over the country. Because they are mostly grown in protected areas, there are conflicts between villagers and foresters about paper mulberry harvesting. In this study, the growth of paper mulberry was investigated in terms of provenances and species. Growing conditions, such as site and spacing, were also examined to discover a combination that will provide a high and sustainable yield.

Of the four species of paper mulberry that were commonly used, *Broussonetia kaempferi*, *B. kursii*, *B. papyrifera* and *B. kazinoki*, the latter two species are still predominant to this day (Supapornhem, 1995). These two species are widely distributed in tropical areas, especially riverbanks and forests gaps, because these areas have an intermediate light intensity between open and closed sites, making it easy for pioneer and shade-tolerant species to survive (Hooker, 1885). Silvicultural research is needed in paper mulberry production to ensure the industry's sustainability to benefit growers and their communities. Much of silviculture is concerned with achieving the best match between species and planting site. Furthermore, for some species on some sites, addition of fertilizer is essential for satisfactory growth, as well as intensive management, such as weed control, pruning and thinning (Evans, 1992). The importance of finding a suitable growing site before planting will directly affect the final product, as reported by Richard (1985) that the major harvest product is affected by the availability of light, water and nutrients. A good provenance provides more yield and growth and therefore, the species chosen should first be adapted to the site's climate, soil and biotic environment (Anderson, 1950). Therefore, provenance and species trials were incorporated into this study. The success of a paper mulberry plantation will not only

increase the amount of raw material available for paper manufacturing, but can also help to decrease forest reliance and forest degradation. This study aims to find a production method for good quality paper mulberry by determining good varieties or clones at proper sites. Suitable silvicultural practice and appropriate management will decrease the harvesting of natural stands in conservation areas.

MATERIALS AND METHODS

Study sites

The study sites were divided into three parts for the three different experiments: provenance trial, species trial and spacing trial. These three factors are the important factors in a silvicultural system.

The experiment plots for the provenance trial were located in 8 provinces all over Thailand: Lampang and Phrae provinces in the northern part, Khon Kaen and Loei provinces in the northeastern part, Trat province in the eastern part, Kanchanaburi province in the west, Chachoengsao province in the center and Prachuap Khiri Khan province in the southern part of Thailand. The elevation of the study areas ranged between 5 to 470 m a.s.l. The lowest mean annual precipitation was 1,022 mm-lyr in Prachuap Khiri Khan, while the highest was 3,619 mm/yr in Trat (Table 1). The experimental design was RCBD (Randomized Complete Block Design) with 5 treatments (provenances: A, B, C, D and E) in 3 replicates. The size of each replication block was 10 x 20 m. Treatment A was Sukhothai provenance (SS), B was Udon Thani provenance (UN), C was Nan provenance (NN), D was Ratchaburi provenance (RT) and E was Kozo, imported from Japan (KZ; *B. Kazinoki*). SS, UN, NN and RT were selected from the plus trees of paper mulberry all over Thailand as David (1962) concluded in his study, the phenotype from an outstandingly good tree found in the wild population, has direct relationship to the quality of its genotype. SS and NN represented paper mulberry in the northern part, UN represented paper mulberry in the northeastern part, and RT represented paper mulberry in the western part of Thailand. KZ was paper mulberry collected from Japan, where hand-papermaking is very famous (Japanese Washi). Paper mulberry seedlings from five provenances were planted on all sites in May 1999. The spacing used in this experiment was 2x4 m of paper mulberry intercropped with three rows of pineapple (*Ananas comosus*). The sites were weeded 3 times in July, September and March. One-year old paper mulberry trees were harvested in early June 2000. Then, the coppices were harvested twice at 6 and 12 months after the first harvesting.

Soil samples were collected before and after planting in every site. From each site, both undisturbed and disturbed soil samples were collected. The undisturbed soil cores were collected from the soil profile surveying pits using 100 cc-soil cores at 0 and 20 cm depth for three phase analysis, bulk density and hydraulic conductivity measurement. For soil chemical characterization, soil samples were collected from each site (disturbed soil from three pits was mixed together and prepared as one sample/replicate) to analyze pH, EC, CEC, exchangeable cations (Ca, Mg, Na, K, Al and H), total carbon (T-C), total nitrogen (T-N), base saturation percentage (BS) and available phosphorus (Av. P). The pH value was measured with a pH meter using a soil solution ratio of 1:5 after shaking for 1 hour. Total carbon and nitrogen were determined using a dry combustion method with a NC-Analyzer (Sumigraph NC-80). Soil samples were extracted twice with 1 M-ammonium acetate at pH 7 (Peech, 1945; Pratt, 1965) and the exchangeable cations (Ca, Mg, Na and K) were determined by an atomic absorption spectrophotometer (AA). Al and H were extracted with 1 M KCl, then titrated with 0.01 M NaOH and 0.01 M HCl. Available phosphorus content was carried out using the Bray II method (Bray and Kurtz, 1945), where soil samples were extracted with an extracting solution (1 N NH_4F and 0.5 N HCl). Then, a color developing reagent was added and the available P was determined by absorbance measurement with a spectrophotometer at 710 nm. Soil texture was analyzed using the pipette method (Kilmer and Alexander, 1949; Day, 1965). In addition, the mortality rate was measured after planting, then total height (H) and diameter at soil surface (D_0) of paper mulberry trees were measured every four months. Data from all sites were combined and analyzed for differences in survival, growth and yield. ANOVA was used to test overall difference and further mean comparison was made using Tukey-Kramer HSD at 0.05 significance level.

Species trial

The success of plantations in the tropics depends on selecting the appropriate species for a site. Moreover, the timing of annual shoot growth differs with species, climate at the site and provenances (Laatsch, 1954; Evans, 1999;). Since the quality



Fig. 1. The location of study sites

Notes: Site codes (a): PR = Phrae, LP = Lampang, LO = Loei, KK = Khon Kean, CC = Chachoengsao, TR = Trat, KC = Kanchanaburi, PK = Prachuap Khiri Khan
Provenance codes (b): NN = Nan, SS = Sukhothai, UN = Udon Thani, RT = Ratchaburi,

Table 1. Topography, climate and soil type of the study sites

Sites	Latitude	Longitude	Elevation ^{1/} (m asl.)	Precipitation ^{1/} (mm./yr.)	Average temperature ^{1/} (°C)	Relative humidity ^{1/} (%)	Soil parent materials ^{2/}	Soil types ^{3/}
LP	20°35'600"N	57°53'50"E	300	1,153	25.8	74	Residuum and colluvium	Ultisols
PR	19°65'400"N	57°58'00"E	140	1,228	26.8	73.7	Residuum and colluvium	Ultisols
NN	20°66'250"N	69°27'00"E	260	1,279	26.7	76	Residuum	Ultisols
KK	17°90'150"N	24°03'50"E	200	1,188	27	63.8	Alluvium and river gravels	Ultisols
LO	19°53'350"N	81°19'00"E	470	1,215	25.9	63	Residuum	Ultisols
TR	13°71'850"N	25°14'00"E	100	3,919	27.3	82	Residuum	Ultisols
KC	16°48'950"N	44°38'00"E	170	1,765	26.5	83	Residuum	Inceptisols
CC	14°84'800"N	78°87'00"E	60	1,310	27.8	73.5	Residuum and colluvium	Entisols
PK	13°09'000"N	58°94'50"E	5	1,022	27.3	77.2	Alluvium deposits	Ultisols

Sources : 1/ Meteorological Department 2000

2/ Department of Land Development 1972

3/ USDA-NRCS 2000

of bast fiber of a Japanese species (*B. kazinoki*) is good, we compared its growth and yield to that of a native species (*B. papyrifera*). *B. papyrifera* and *B. kazinoki* have different growth forms. *B. kazinoki* has a shrubby form shooting out several stems as early as the first year after planting. Stems and branches of *B. kazinoki* were relatively thinner and softer than those of *B. papyrifera* and they often bend toward the ground. On the other hand, *B. papyrifera* maintains only one main stem before the first cutting and its shape is straight and relatively rigid (Tajima *et al.*, 2001). A study site was set in Wiang Sa district, Nan province. Two species of paper mulberry *Broussonetia papyrifera* (L.) vent and *B. kazinoki* Sieb (Paul and Sandra, 1991) were planted in a 0.16 ha (1,600 m²) plot each in August 1998. Due to site restriction, we could not make a replicate site. The spacing was 2x1 m and plant density was 800 plants/plot. Survival rate, growth rate (H and D₀) and biomass were recorded.

Spacing trial

The most appropriate initial spacing of plants has recently been the subject of much debate and should be guided by the objectives of the planting schemes and the nature of the site to be planted (Kerr, 1993). However, many planting schemes are governed by financial considerations and the constraints of grants available (Harmer and Kerr, 1995). Therefore, we selected the study site in Wang chin district, Phrae province, which is famous for paper mulberry bark production in Thailand. Sukhothai provenance (SS) was used in this experiment, because it is native to this area. Five spacings (treatments): 1x1 m, 1x2 m, 2x2 m, 2x4 m and 4x4 m were used in RCBD experiment with 3 replicates. Seedlings were planted in June 1999. Survival rate, growth (H and D₀) and biomass were measured after planting for 1, 4, 8 and 12 months, respectively.

RESULTS AND DISCUSSION

Site selection and provenance trial

The survival rate, growth rate and biomass of paper mulberry of eight sites varied among the sites and provenances, in agreement with Peter's (1996) hypothesis that the local distribution pattern of most species are limited by certain physical or biotic factors of the environment such as temperature, moisture, light, pH, soil quality, salinity and water current. Similarly, Assmann (1970) found that tree growth and branching were determined partly by its genome, but mostly by its interactions with the environment. In other words, the growth of such a tree was self-organized and its shape was an emergent property of the tree-environment system. After planting, the average survival rate of UN provenance was 72.5 %, higher than the other provenances of *B. papyrifera*, but less than KZ (*B. kazinoki*) (92.5 %), and NN was the lowest with 63.8 % (Table 2). Most of paper mulberry died in TR and KC, and our visual observation confirmed vigorous growth and competition with weeds; the average survival rate of paper mulberry was significantly lower in TR and KC than in other sites (38.6 and 39.8 %, respectively). Table 2 shows the survival rate and total biomass of one-year old paper mulberry in eight sites. The average total biomass of RT was the highest (825.0 kg/ha) among *B. papyrifera*, NN, SS, and UN, the average total biomass of which were 783.9 kg/ha, 723.3 kg/ha, and 667.2 kg/ha, respectively, while the average total biomass of KZ (*B. kazinoki*) was 1,147.7 kg/ha, much higher than all *B. papyrifera*. As far as the variation of total biomass of paper mulberry in different sites, average total biomass of KZ in PK was greatest with a yield of 2,353.8 kg/ha, followed by PR (1,915.0 kg/ha), KC (1,322.5 kg/ha), LP (1,316.3 kg/ha), respectively. On the other hand, the average total biomass of KZ in LO had the lowest yield of 410.0 kg/ha. The highest average total biomass of *B. papyrifera* (4 provenances) was recorded in PK (1,917.3 kg/ha), followed by KC (988.8 kg/ha), PR (834.4 kg/ha), and LP (704.4 kg/ha), respectively. The lowest average total biomass of paper mulberry (316.3 kg/ha) was recorded in CC.

Figure 2 shows the differences among sites in total height (H) and diameter at soil surface (D₀) of paper mulberry for different provenances. Growth rate (H and D₀) of KZ was higher than the others in almost every site during the first year, except at TR, LO and KC where D₀ were lower. In the second year after the first cutting, though total height of KZ was still higher, D₀ was very low in every site.

Naturally, paper mulberry is intolerant to environments with bad drainage soil or flooded land (Udomchoke *et al.*, 2001). Furthermore, paper mulberry is a light-demanding species and its seedling cannot compete with other faster growing weeds without help (Thammincha, 2001). Based on the former reason, there might have been some adverse effects for TR and KC provenances, which were collected in an area with high precipitation (3,919 and 1,765 mm/yr) and high humidity (82 and 83 %, respectively). Moreover, the mortality rate of paper mulberry seedlings might be due to light intensity and biotic factors

Table 2. The survival rate and total biomass of one-year paper mulberry of 5 provenances in 8 study sites

Sites/ provenances	NN		UN		RT		SS		KZ	
	SR	TB	SR	TB	SR	TB	SR	TB	SR	TB
PR	92.5 ^a	1,087.5 ^a	92.8 ^a	712.5 ^{ab}	82.8 ^{ab}	747.5 ^{ab}	95.3 ^b	790.0 ^a	98.8 ^c	1,915.0 ^b
LP	95.7	572.5 ^a	100.0	696.3 ^a	89.1	698.8 ^a	97.8	848.8 ^b	100.0	1,316.3 ^b
LO	73.9	537.5 ^b	80.4	295.0 ^{ab}	82.6	406.3 ^a	69.6	342.5 ^a	97.8	410.0 ^a
KK	47.8 ^a	713.8 ^{ab}	63.8 ^a	381.3 ^a	58.7 ^a	320.0 ^a	58.7 ^a	332.5 ^a	97.8 ^b	550.0 ^b
CC	82.6	187.5 ^a	89.4	291.3 ^a	93.5	387.5 ^a	84.8	405.0 ^b	100.0	542.5 ^b
TR	34.8 ^a	285.0 ^a	27.7 ^a	266.3 ^a	39.1 ^a	728.8 ^a	19.6 ^{ab}	122.5 ^{ab}	71.7 ^b	771.3 ^b
KC	21.3 ^a	1,191.3 ^a	38.8 ^a	978.8 ^a	23.8 ^a	648.8 ^{ab}	32.1 ^a	1,136.3 ^a	82.9 ^b	1,322.5 ^a
PK	97.8	1,696.3 ^a	87.2	1,716.3 ^a	91.3	2,662.5 ^b	95.7	1,808.8 ^a	93.5	2,353.8 ^b
Average	68.3	783.9	72.5	667.2	70.1	825.0	69.2	723.3	92.8	1,147.7

Note: SR = survival rate (%), TB = total biomass (kg/ha)
Superscript shows the result of Duncan test at 95% confidence level.

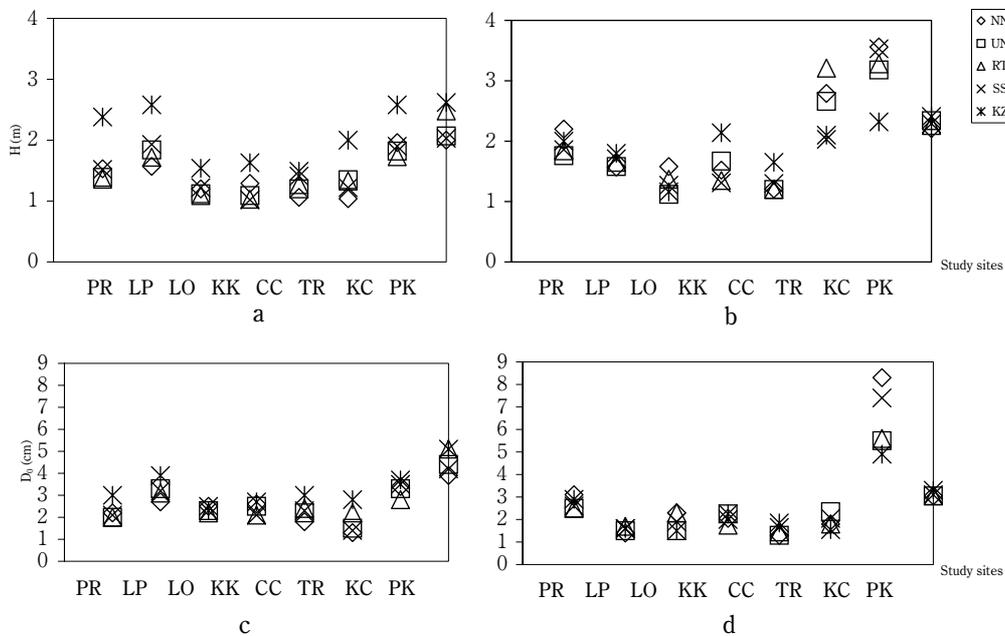


Fig. 2. Growth of paper mulberry, total height (H) of paper mulberry 1st year and 2nd year (a, b) and diameter at the soil surface (D₀) of paper mulberry 1st year and 2nd year (c, d)

Notes: Growth of paper mulberry (H and D₀) differed by varieties and sites significantly due to 2-way ANOVA analysis at 95 % confidence level in which $F > F_{0.05; 4, 28}$

such as fungal attack, pest and diseases. According to the growth rate, the appropriate sites to grow KZ were PR, KC and PK. Among different provenances of *B. papyrifera*, collected from 4 places in Thailand (NN, UN, RT, SS), total height of SS and UN were high in every site except at CC and PR. D₀ values were also bigger for SS and UN than other provenances. For NN, though the growth in total height and D₀ was low in the first year, its growth increased rapidly in the second year. Particularly, D₀ was higher than the others in almost every site. These results indicated that even though native species, SS, UN and NN, grew slower than KZ in the first year, in the long run, they may adapt to the environment better than KZ and therefore had higher growth rates.

Even though total biomass of paper mulberry was significantly affected by site and variety selection, it could not explain how much profit that the farmer receives. The main uses of paper mulberry, paper and Tapa cloth, are made of the inner bark of mulberry trees from Siam, Burma, Japan and the South Sea Islands (Dietrich, 1978). Therefore, the biomass of the

Table 3. The inner bark biomass of paper mulberry 5 provenances at 8 sites harvested in the 1st and 2nd year; (kg/ha)

Sites/ varieties	NN		UN		RT		SS		KZ		Average	
	1 st	2 nd										
PR	0.08	3.21	0.04	1.15	0.04	1.33	0.04	1.52	0.11	1.60	0.06	1.76
LP	0.03	0.37	0.04	0.36	0.04	0.45	0.05	0.39	0.07	0.47	0.05	0.41
LO	0.04	0.47	0.01	0.19	0.02	0.36	0.02	0.12	0.02	0.12	0.02	0.25
KK	0.05	0.45	0.02	0.52	0.02	0.34	0.02	0.33	0.03	0.57	0.03	0.44
CC	0.01	0.13	0.01	0.11	0.02	0.19	0.02	0.45	0.03	0.28	0.02	0.23
TR	0.02	0.70	0.01	1.84	0.05	0.65	0.01	0.60	0.04	0.39	0.03	0.83
KC	0.08	11.81	0.05	3.92	0.04	3.90	0.06	5.50	0.08	2.11	0.06	5.45
PK	0.13	1.24	0.10	1.23	0.17	1.21	0.09	1.34	0.14	1.32	0.12	1.27
Average	0.05	2.30	0.03	1.17	0.05	1.05	0.04	1.28	0.06	0.86	0.05	1.33

inner bark of paper mulberry indicates the potential profitability of each variety for the farmer. Table 3 compared the yield of inner bark of paper mulberry at the first and second year in different sites and provenances. Paper mulberry at the PK site provided the highest biomass of inner bark for every provenance: RT (171.3 kg/ha), KZ (137.5 kg/ha), NN (126.3 kg/ha), UN (95.0 kg/ha), and SS (92.5 kg/ha), followed by KC and PR (60.5 kg/ha). On the other hand, the biomass of paper mulberry inner bark at CC, TR, and LO were very low at 19.0 kg/ha, 25.8 kg/ha, and 23.0 kg/ha, respectively. As for the natural distribution of paper mulberry in Thailand, Phengklai and Khamsai (1985) reported that paper mulberry distributed along the riverbanks and the deciduous forest gaps in northern and northeastern Thailand, and it is rarely found in the southern part. Based on growth and biomass data, paper mulberry grown at PK, located in the southern part, had higher productivity for every provenance, so other factors, such as soil characteristic and soil fertility, were evaluated in this study. We collected both disturbed and undisturbed soil samples at two depths, 0 - 20 and 20 - 40 cm, in each experiment plot where the roots of paper mulberry were found. The soil texture and chemical properties are given in Tables 4, 5 and in Figures 3 and 4.

Soil physical properties

Soil texture is important for several reasons: it influences the penetration of plant roots, moisture storage capacity and establishes the rate of chemical reactions within the soil (Donald, 1976). Soil texture in study sites varied by site and the soils' parent materials. At LO, PR, KC, LP sites, soils consisting of clay 40-45 % higher than other sites, 30-37 % sand, 15-20 % silt and were classified as clay and clay loam (Table 4). Soils at TR and CC, located in the eastern and central part, consisted of 48 - 58 % sand, 23-37 % clay and 16-21 % silt and were classified as sandy clay and sandy clay loam, respectively. On the other hand, soils at the PK site near the seashore and the KK site with a parent material of alluvio-columium from sandstone consisting of more than 80 % sand were classified as loamy sand. Among the eight sites, the value of bulk density, porosity, hydraulic conductivity (K) and the percentage of solid phase in soils were not significantly different. The percentage of air phase was the highest for PK soil (32.7 and 36.2 % at 0 and 20 cm depth), followed by KC soil (23.5 and 21.7 % at 0 and 20 cm depth). On the other hand, the percentage of liquid phase was the lowest at PK (1.6 and 0.4 % at 0 and 20 cm depth), but it was the highest at KC (41.5 and 40.2 % at 0 and 20 cm depth).

Considering the total and inner bark biomass of paper mulberry, they were higher in PR, KC and PK with soil textures of clay, clay loam and sand, respectively. Thus, soil texture could not be the one of the most important factors affecting growth and yield of paper mulberry. Udomchoke *et al.* (2001) also found that a broad range of soils could support the growth of paper mulberry: sandy soils on high mountain, clayey soils in floodplain area, silty sand at the terrace terrain, sandy clay on rugged terrain of bare limestone, even sandy loam, loamy sand and sandy clay loam texture of hilly terrain areas. KC and LP soil had most balanced ratio of three phases. However, the analysis of variance (F-test) showed no significant differences among sites for all values of physical properties at 95 % confidence level ($\alpha = 0.05$).

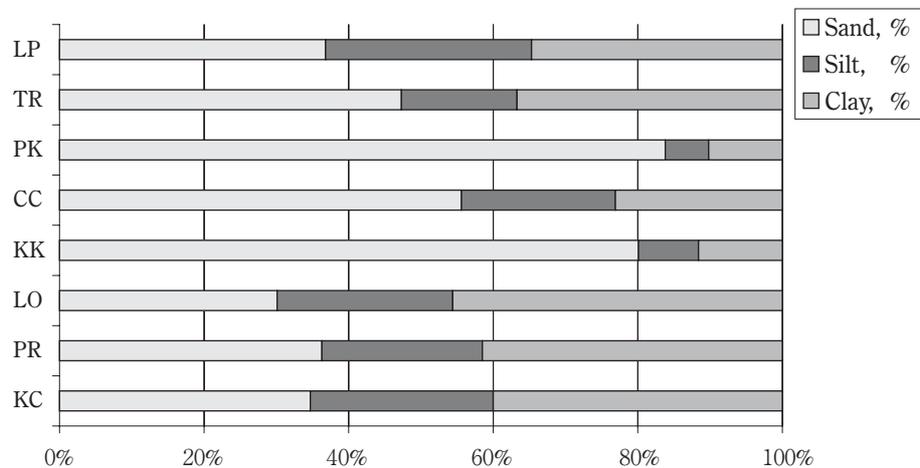
Soil chemical properties

Soil pH is very important when choosing a species for a new planting scheme (Moffatt and Buckley, 1995). Among the eight study sites, pH varied from 5.6 to 6.9 (acid to slightly acid soils). Soil organic matter was also considered a factor affecting

Table 4. The physical properties of soils at the provenance trial site

Sites	Depth (cm)	Air phase (%)	Liquid phase (%)	Solid phase (%)	Bulk density (g.cm ⁻³)	Porosity (%)	K (cm.sec ⁻¹)	Sand (%)	Silt (%)	Clay (%)	Soil texture
LP	0	11.4	23.5	65.1	1.642	34.9	10 ⁻⁴	36.8	28.5	34.7	CL
	20	13.4	23.7	63.0	1.619	37.1	10 ⁻³	56.0	16.8	27.1	SC
TR	0	19.2	32.0	48.9	1.270	51.2	10 ⁻²	47.3	16.0	36.7	SC
	20	8.2	33.1	58.8	1.424	41.3	10 ⁻²	51.0	10.8	38.2	LiC
PK	0	32.7	1.6	65.7	1.511	34.3	10 ⁻³	83.8	6.0	10.2	S
	20	36.2	0.4	63.4	1.484	36.6	10 ⁻³	90.3	4.0	5.8	LS
CC	0	17.9	16.2	66.0	1.555	34.0	10 ⁻³	55.6	21.3	23.1	SCL
	20	19.4	9.0	71.7	1.691	28.3	10 ⁻³	61.9	14.2	24.0	SCL
KK	0	32.1	7.2	60.7	1.586	39.3	10 ⁻³	80.1	8.3	11.6	LS
	20	19.7	14.3	66.1	1.733	34.0	10 ⁻⁴	81.8	4.4	13.8	LS
LO	0	19.1	26.3	54.6	1.500	45.4	10 ⁻²	30.1	24.3	45.6	LiC
	20	**	**	**	**	**	**	42.1	49.8	8.1	SiL
PR	0	2.9	31.4	65.7	1.656	34.3	10 ⁻⁶	36.3	22.2	41.5	LiC
	20	**	**	**	**	**	**	48.7	17.3	34.0	LiC
KC	0	23.5	41.5	35.1	0.919	64.9	10 ⁻²	24.7	25.3	40.0	CL
	20	21.7	40.2	38.2	1.026	61.8	10 ⁻³	7.8	9.0	83.3	HC

Remarks: S= Sand, LS= Loamy sand, SL= Sandy loam, SiL= Silt loam, SCL= Sandy clay loam, SiCL= Silty clay loam, CL= Clay Loam, SC= Sandy clay, LiC= Light clay, HC= Heavy clay, ** = no data

**Fig. 3. The percentage of sand, silt and clay in study sites**

growth and yield of paper mulberry. The high content of soil organic matter greatly contributes to their ability to supply plants with cation nutrients (Burton *et al.*, 1988). Figure 4 shows the variation of soil organic matter content in the eight sites. The organic matter content in the KC soil was the highest (6.6 %), while it was 2.5 - 3 % in LO, TR, LP and less than 2 % in KK, CC, PK and PR. The CEC value of soils is a general measure of plant nutrient availability and represents the total amount of cations that can be adsorbed by a kilogram of soil (Young, 1997). CEC varied between 4.9 - 24.5 cmol(+) kg⁻¹ in the surface soils (0-20 cm) and 3.6 - 19.9 cmol(+) kg⁻¹ in the subsurface soils (20-40 cm). CEC in the KC soils was the highest at both soil depths (24.5 and 19.9 cmol(+) kg⁻¹). Similarly, total carbon and total nitrogen content in the KC soil were the highest in both depths (49.83 and 28.05 g kg⁻¹ of total carbon and 3.52 and 2.47 g kg⁻¹ of total nitrogen). KC, PR, LP and LO soils had a large amount of exchangeable cations (Na, K, Ca, Mg), and PK soil showed an extremely high content of available phosphorus (P₂O₅) of 44.24 mg kg⁻¹. On the other hand, KK soil showed very poor chemical properties; it was lowest in the amount of total carbon, total nitrogen and exchangeable cations, as shown in Figure 4. The soil chemical properties are given in Table 5.

Based on the soil fertility, every site could be utilized for agriculture without serious effort, except KK which has extremely poor soil fertility and has coarse textured loamy sand. As mentioned before, total biomass of paper mulberry was the highest in PK. In this site, the values of CEC and total carbon and nitrogen were low, but those of exchangeable Ca and

Table 5. The chemical properties of soil at the provenance trial in 8 sites

Sites	Depth (cm)	pH (H ₂ O)	pH (KCl)	Δ pH	EC (mS/m)	T-C (g/kg)	T-N (g/kg)	C/N Ratio	CEC (cmol(+)/kg)	Exchangeable cation (cmol(+)/kg)						BS (%)	Av. P, P ₂ O ₅ (mg/kg)
										Na	K	Ca	Mg	Al	H		
KC	0-20	5.8	4.5	1.3	12.48	49.83	3.52	14.20	24.51	0.06	1.49	3.93	4.83	0.06	0.30	42.07	27.71
	20-40	5.1	4.0	1.0	7.50	28.05	2.47	11.40	19.86	0.03	0.18	0.41	0.60	2.14	0.31	6.17	6.85
PR	0-20	5.7	4.3	1.4	2.68	8.98	1.67	5.40	9.66	0.09	0.16	3.63	2.22	0.16	0.22	63.10	13.01
	20-40	5.6	4.2	1.5	4.80	9.99	1.65	6.00	9.30	0.10	0.15	3.13	1.22	0.24	0.22	49.40	8.46
KK	0-20	6.0	4.8	1.2	2.57	4.06	0.67	6.10	7.63	0.01	0.09	0.45	0.22	0.00	0.08	10.12	17.75
	20-40	5.8	4.5	1.4	1.90	1.93	0.79	2.40	3.65	0.02	0.07	0.15	0.21	0.04	0.21	12.45	12.11
CC	0-20	5.9	4.7	1.2	8.87	11.98	2.08	5.80	4.96	0.07	0.28	1.36	0.49	0.00	0.18	44.42	14.70
	20-40	5.2	4.1	1.1	4.09	6.13	1.22	5.00	4.36	0.05	0.10	0.64	0.25	0.59	0.21	23.94	9.02
PK	0-20	6.6	5.9	0.6	11.38	7.45	1.46	5.10	5.60	0.03	0.28	4.39	0.82	0.00	0.09	98.63	44.24
	20-40	7.0	6.1	0.9	4.81	4.94	3.37	1.50	4.87	0.03	0.18	3.37	0.70	0.00	0.07	87.57	9.01
TR	0-20	5.1	4.1	1.0	8.35	14.69	1.86	7.90	8.63	0.03	0.07	0.78	0.19	0.91	0.14	12.35	13.85
	20-40	5.3	4.2	1.1	1.58	8.39	1.38	6.10	8.73	0.07	0.09	1.08	0.18	0.58	0.25	16.32	4.65
LP	0-20	6.5	5.4	1.1	8.22	15.21	1.67	9.10	8.07	0.09	0.32	4.85	1.37	0.00	0.12	82.14	17.84
	20-40	6.5	5.1	1.4	10.69	13.19	1.45	9.10	8.38	0.11	0.20	3.99	1.68	0.00	0.12	71.38	13.51
LO	0-20	5.3	4.2	0.9	3.17	14.60	1.90	7.68	9.65	0.09	1.80	3.82	0.77	0.00	0.10	61.80	13.54
	20-40	5.1	4.0	1.1	3.02	8.76	1.41	6.21	9.87	0.10	0.15	3.06	0.65	0.06	0.11	54.70	9.03

Notes: T-C = total carbon, T-N = total nitrogen, BS = percentage of bases saturation

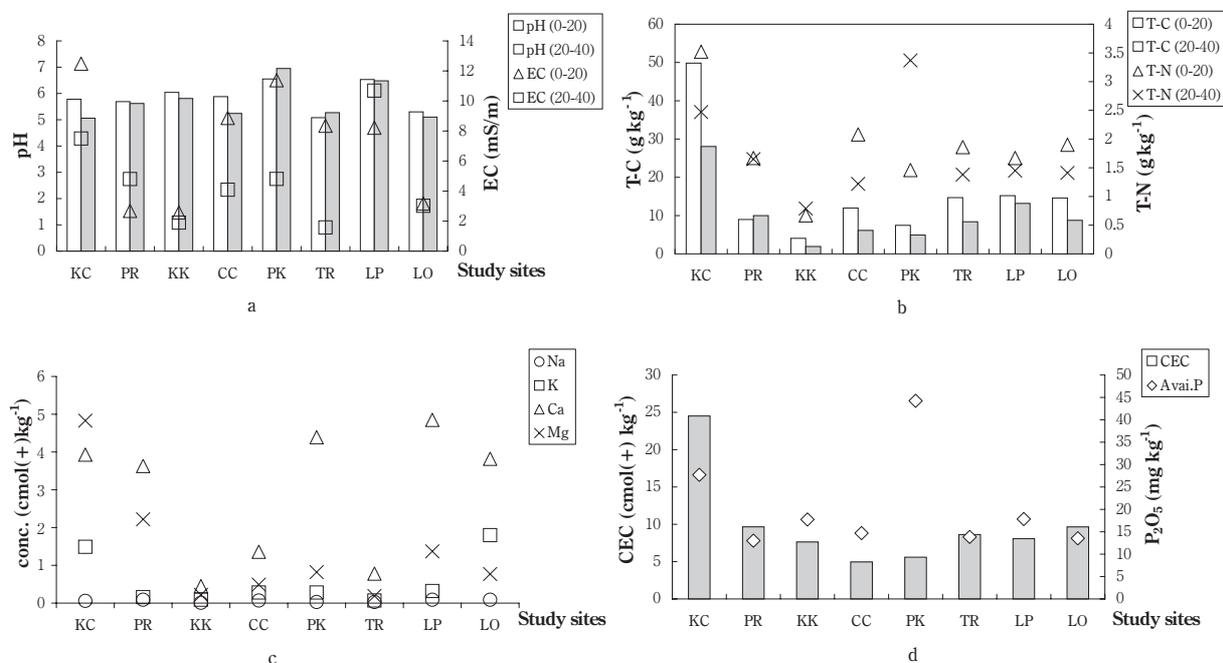


Fig. 4. The chemical soil properties; pH & EC (a), T-C & T-N (b), exchangeable bases (c), CEC and available P (d) in the 8 study sites

available phosphorus were moderately higher than the other sites. Growth and yield at KC were greater than at the other sites due to the higher fertility and good physical characteristics. PR and LP soils also provided satisfactory growth rates and yields. The growth rate and yield at LO, CC and TR was significantly low, even though the amount of total carbon and total nitrogen was not so low compared with other sites, but the content of available phosphorus and exchangeable cations (Na, K, Ca, Mg) were low. Besides, high content of exchangeable aluminum (Al) at TR might affect growth and yield of paper mulberry. As a result, soil organic matter and available P are only two of the many possible key factors of growth and yield of paper mulberry.

During two years of cultivation of paper mulberry, we harvested 25 trees of paper mulberry in each plot, separated leaves, branches, stem, inner bark and outer bark, and weighed all parts. Sub samples were dried to obtain the moisture content. The allometric equations was established to predict the yield of paper mulberry using the diameter at ground level (D_0) and total height (H). The most important part is the inner bark for paper manufacturing, and therefore, allometric

Table 6. Allometric equations for predicting inner bark biomass (W_i) of 5 provenances of paper mulberry for 1st and 2nd Year (N=25, W=biomass (g), D_0 =diameter at ground level (cm), H=total height (cm))

Provenances	1 st year		2 nd year	
	Equation	R ²	Equation	R ²
MC	$W_i = 0.0202(D_0^2 H)^{0.9607}$	0.9825	$W_i = 1.4591(D_0^2 H)^{1.081}$	0.9705
NS	$W_i = 0.0234(D_0^2 H)^{0.9117}$	0.9579	$W_i = 1.1487(D_0^2 H)^{1.015}$	0.9622
SP	$W_i = 0.0368(D_0^2 H)^{0.8842}$	0.9431	$W_i = 1.6351(D_0^2 H)^{0.9789}$	0.9129
SS	$W_i = 0.0239(D_0^2 H)^{0.9291}$	0.9459	$W_i = 1.4362(D_0^2 H)^{1.0009}$	0.9343
KZ	$W_i = 0.0145(D_0^2 H)^{0.9743}$	0.8526	$W_i = 1.5757(D_0^2 H)^{0.9643}$	0.8448

equations for predicting inner bark were made and are shown in Table 6.

Correlation between the growth of paper mulberry and environmental factors

Only a few studies have shown the relationship between the growth of paper mulberry and environmental factors. Most of these studies confirmed that paper mulberry could grow in a wide range of environments. Udomchoke *et al.* (2001) found that paper mulberry could grow in a broad range of soils and can grow even in high elevations, i.e. at 1,800 m a.s.l. in Thailand. However, cultivation of paper mulberry for paper manufacturing needs to attain better rates of growth and yield. Thus, the selection of suitable sites and environments should be considered when designing a paper mulberry plantation. Tajima *et al.* (2001) concluded that there was a relationship between paper mulberry growth performance and moisture regime, and that a phosphorus rich and neutral soil might yield higher total biomass. Our study showed that soil chemical properties affected growth and biomass of paper mulberry significantly. Margin (1958) recommended that the considerable uncertainties surrounding the recognition of productivity on the basis of soil characteristics and climate alone make it necessary to include the total plant yield for the assessment of site quality. Nevertheless, in agricultural site quality classification, a whole series of separate criteria based on edaphic and economic considerations is also used. However, site quality has been assessed until now solely on standing crop yields, and soil properties have been neglected. Among the correlations between growth of paper mulberry and soil environmental factors in Table 7, soil pH value at 0-40 cm depth was significantly correlated with basal diameter and biomass, amount of exchangeable potassium and total carbon content in 0-20 cm of soil depth showed significant correlations with height, basal diameter and biomass. Similarly, exchangeable Ca and K contents were highly correlated with height and biomass. Available phosphorus content also showed significant correlations with height, basal diameter and biomass of paper mulberry. Even though overall soil physical properties did not affect the growth and biomass, percentage of solid phase was significantly correlated with survival rate, and permeability in surface soils was negatively correlated with survival rate. Other soil properties, which were not shown in Table 7, had no correlation with survival rate and growth of paper mulberry. According to these correlations, multiple regression (stepwise method) was used to predict the survival rate, height, basal diameter, total biomass and inner bark biomass of paper mulberry in various sites base on soil properties. The predictive equations are as follows:

Survival rate	= 2.005 (Solid ₀) -39.293	R ² 0.973
Height	= 0.602 + 5.470 (K ₂₀) + 0.015 (P ₀)	0.808
Basal diameter	= 1.214 + 0.077 (P ₀)	0.817
Total biomass	= 53.633 (P ₀) - 351.962	0.949
Inner bark biomass	= 3.318 (P ₀) - 24.76	0.955

Note: Solid₀ = the percentage of solid phase at 0 cm depth

K₂₀ = an amount of K in soil at 20 cm depth

P₀ = an amount of P in soil at 0 cm depth

Species trial between *B. papyrifera* and *B. kazinoki* at Nan province

There were many different morphological characteristics between *B. papyrifera* and *B. kazinoki*. *B. papyrifera* is a 10-20 m tall tree, dioecious, has dark gray or green bark and is native to Thailand and the subtropical zone, while *B. kazinoki* is a shrub 2-4 m tall, monoecious, with branchlets obliquely spreading, and is native to China, Japan, Korea and Taiwan. The

Table 7. Correlation between growth of paper mulberry and environmental factors

Soil properties		0cm S.R.	Height	B.D.	Biomass	20 cm S.R.	Height	B.D.	Biomass	40 cm S.R.	Height	B.D.	Biomass	Average S.R.	Height	B.D.	Biomass
pH (H ₂ O)		0.622	0.504	0.807	0.704	0.561	0.518	0.718	0.773	0.499	0.450	0.702	0.757	0.581	0.514	0.773	0.789
pH (KCl)		0.502	0.567	0.864*	0.838*	0.465	0.619	0.817*	0.871*	0.308	0.638	0.864*	0.899*	0.430	0.619	0.859*	0.883*
T-C		-0.440	0.406	0.146	0.093	0.155	0.983**	0.908*	0.945**	-0.456	-0.174	-0.229	-0.224	-0.281	0.847*	0.622	0.613
Ex-K		-0.448	0.514	0.373	0.266	0.165	0.950**	0.756	0.753	0.028	0.046	-0.320	-0.242	-0.410	0.568	0.401	0.303
Ex-Ca		0.293	0.927**	0.743	0.742	0.624	0.582	0.444	0.560	0.413	0.645	0.610	0.757	0.489	0.839*	0.683	0.760
Ex-Ca/CEC		0.697	0.727	0.777	0.817*	0.666	0.644	0.675	0.763	0.467	0.640	0.800	0.872*	0.634		0.770	0.837*
Ex-Mg/CEC		0.343	0.645	0.393	0.348	0.836*	0.490	0.516	0.547	0.466	0.333	0.593	0.599	0.674	0.666	0.660	0.649
Ex-H		-0.285	0.240	-0.087	-0.157	-0.710	-0.355	-0.596	-0.644	-0.850*	-0.448	-0.422	-0.365	-0.866*	-0.282	-0.504	-0.524
BS		0.677	0.796	0.777	0.787	0.720	0.615	0.655	0.733	0.508	0.566	0.775	0.828*	0.681	0.708	0.786	0.835*
Av-P		0.170	0.863*	0.984**	0.985**	0.544	-0.200	0.164	0.023	0.086	0.189	0.516	0.370	0.262	0.758	0.973**	0.930**
Three phases	Air	-0.187	0.207	0.555	0.512												
	Liquid	-0.594	0.017	-0.399	-0.372												
	Solid	0.905*	-0.203	0.012	0.015												
Permeability		-0.917**	0.118	-0.154	-0.082												

Climatic factors		S.R.	Height	B.D.	Biomass
Precipitation	Avg.	-0.642	-0.377	-0.556	-0.432
	Max.	-0.678	-0.190	-0.453	-0.279
	Min.	-0.399	-0.013	-0.113	0.091
Air temp.	Avg.	0.393	-0.341	-0.100	-0.060
	Max.	0.519	0.130	-0.092	-0.053
	Min.	-0.344	-0.418	-0.070	-0.181
Humidity	Avg.	0.011	0.290	0.181	0.120
	Max.	0.393	0.724	0.340	0.415
	Min.	-0.622	0.328	0.595	0.484

Notes: * = greatly significant at $p < 0.05$, ** = highly significant at $p < 0.01$, B.D. = Basal Diameter, S.R. = Survival Rate

growth rate of both species planted in this study was not significantly different. The average diameter of *B. papyrifera* (DBH) and *B. kazinoki* (D_0) were 2.65 cm and 2.89 cm before harvesting. The average height of *B. papyrifera* in the 1st, 2nd and 3rd measurement were 0.40 m, 0.75 m, 3.27 m, respectively, while that of *B. kazinoki* were 0.53 m, 0.73 m, 3.17 m, respectively (Table 8). Total biomass of *B. kazinoki* (6,914.7 kg/ha) was higher than *B. papyrifera* (5,668.6 kg/ha) after one year, but results for the biomass of the inner bark (which is the most important part economically) showed a reverse trend. Inner bark yield of *B. papyrifera* was 327.1 kg/ha higher than *B. kazinoki* (308.5 kg/ha). Statistical analysis, however, showed no significance in the differences of growth and biomass of both species. According to the soil properties in Table 9, there are some differences between two experiment plots even though they were adjacent. Soil pH in the *B. papyrifera* plot was much lower than that in the *B. kazinoki* plot. Exchangeable Ca, base saturation percentage (BS) and available phosphorus were also different between the two plots. Available phosphorus (P) at both soil depths (0-20, 20-40 cm) in the *B. kazinoki* plot was much higher than that in the *B. papyrifera* plot. As for the tree growth rate and biomass, there were no significant differences except in stem biomass and the inner bark biomass of *B. papyrifera*, which were higher than those of *B. kazinoki*. It can be concluded then, that the difference in soil pH, BS, and available P might affect growth and total biomass of paper mulberry, but does not effect inner bark biomass, due to the higher inner bark biomass of *B. papyrifera* in soils which pH, BS and available P are low.

Spacing trial

In the 1 x 1 m plot, tree density was 10,000 trees/ha. The average D_0 in the 1x1 m, 1x2 m, 2x2 m, 2x4 m and 4x4 m plots were 2.6 cm, 2.6 cm, 3.2 cm, 4.1 cm, 4.9 cm, respectively in the 1st year, and 2.8 cm, 2.7 cm, 3.6 cm, 4.1 cm, 5.1 cm, respectively in the 2nd year. The survival rate of all spacing was high (over 80 %) in both years, and the average height was between 1.8 - 2.6 m. Planting density did not affect the survival rate of paper mulberry in these two years, as shown in Table

Table 8. Growth and biomass of two paper mulberry species (*B. papyrifera* and *B. kazinoki*) at Wiang Sa district, Nan province

Analysis topics	<i>B. papyrifera</i>	<i>B. kazinoki</i>
Number of plants/plot	800.00	800.00
Survival rate (%)	83.50	88.10
Average diameter (cm)		
3 rd measured (before harvesting)	2.65*	2.89**
Stem height (m)		
1 st average	0.40	0.53
2 nd average	0.75	0.73
3 rd average	3.27	3.17
Average growth rate	1.45	1.32
Biomass (kg/ha)		
Stem	2,343.30	3,447.20
Branch & twig	1,439.40	1,550.20
Leaf	1,351.60	1,391.40
Outer bark	207.20	217.40
Inner bark	327.10	308.50
Total biomass	5,668.60	6,914.70

Notes: * DBH, ** D₀**Table 9. The chemical properties of soil at the species trial plot, Nan province**

Sites	Soil Depth (cm)	pH (H ₂ O)	pH (KCl)	ΔpH	EC (mS/m)	T-C (g/kg)	T-N (g/kg)	C/N Ratio	CEC (cmol(+)/kg)	Exchangeable cation (cmol(+)/kg)						BS (%)	Av. P, P ₂ O ₅ (mg/kg)
										Na	K	Ca	Mg	Al	H		
PP	0-20	5.9	5.0	0.9	13.74	7.85	1.70	4.60	5.47	0.05	0.07	3.02	0.75	0.00	0.15	70.99	29.25
	20-40	6.2	4.9	1.3	5.17	6.11	1.65	3.70	8.46	0.07	0.07	3.10	0.98	0.00	0.11	49.94	11.53
KZ	0-20	6.3	7.5	0.7	29.90	6.62	1.76	3.80	5.40	0.06	0.14	21.62	1.87	0.00	0.05	438.77	57.23
	20-40	6.4	7.6	0.9	30.90	7.82	1.07	7.30	15.16	0.09	0.12	33.00	4.54	0.00	0.04	248.92	107.51

Notes: PP = soil properties in *B. papyrifera* plot, KZ = soil properties in *B. kazinoki* plot**Table 10. The survival rate and growth of paper mulberry (*B. papyrifera*) in different spacing at Wang chin district, Phrae province**

Spacings (m)	Plant density (trees/ha)	Survival rate (%)		Average D ₀ (cm)		Average Height (m)	
		1/	2/	1/	2/	1/	2/
1 x 1	10,000	99.1 ^{bc}	91.4 ^c	2.6 ^a	2.8 ^a	2.2 ^b	2.4 ^b
1 x 2	5,000	98.7 ^c	87.2 ^b	2.6 ^a	2.7 ^a	1.8 ^a	2.0 ^a
2 x 2	2,500	99.5 ^b	87.0 ^b	3.2 ^{bc}	3.6 ^{bc}	2.1 ^b	2.3 ^b
2 x 4	1,250	99.0 ^{bc}	82.3 ^a	4.1 ^b	4.1 ^b	2.2 ^b	2.3 ^b
4 x 4	625	100.0 ^c	91.7 ^c	4.9 ^c	5.1 ^c	2.4 ^c	2.6 ^c

Notes: 1/ the first year, 2/ the second year

Values within columns followed by superscript are significantly different (95 % confident level) (Duncan's test)

Table 11. Biomass of paper mulberry in different spacing at Wang chin district, Phrae province

Spacings (m)	Biomass (kg/ha)											
	Stem		Twig		Leaf		Inner bark		Outer bark		Total	
	1/	2/	1/	2/	1/	2/	1/	2/	1/	2/	1/	2/
1 x 1	2,068.8	2,556.2	731.2	900.0	918.8	1,131.2	219.0	269.0	156.0	194.0	3,975.0	4,918.8
1 x 2	837.5	975.0	293.8	343.8	375.0	437.5	87.5	100.0	65.2	68.8	1,612.5	1,868.8
2 x 2	731.2	1,050.0	256.2	368.8	325.0	456.2	75.0	106.0	56.2	81.2	1,406.2	2,025.0
2 x 4	643.8	693.8	225.0	243.8	281.2	300.0	68.8	68.8	50.0	56.2	1,250.0	1,337.5
4 x 4	506.2	600.0	175.0	206.2	218.8	256.2	50.0	65.2	43.8	50.0	1,612.5	1,162.5

Notes: 1/ the first year, 2/ the second year

10. There was also no effect on tree height. On the other hand, diameter at soil surface (D_0) varied with spacing; the growth rate in the narrow spacing was lower than that in the wide spacing due to higher competition for nutrients and light. At any given age, trees widely spaced are larger in diameter and have greater taper, thicker branches, and crowns that are both deeper and wider than trees in densely stocked stands (Eversole, 1955).

The total biomass was the biggest in the narrowest spacing (1x1 m), and was the smallest in the 2x4, 4x4 m spacing plot. Therefore, the planting density was one of the most important factors for the yield of paper mulberry, especially inner bark yield. In addition, the differences in total production resulting from variations in spacing depends on the length of time needed for the new stand to achieve full occupancy of the site. Therefore, the gross production of wood by stands planted at close spacing is usually greater than that of those planted at wide spacing (Satoo *et al.*, 1955). Based on our experiment, the 1x1 m spacing is the best for growing paper mulberry (Table 11).

CONCLUSION

According to this study, soil fertility had a significant effect on the growth rate and productivity of paper mulberry. Oldeman (1990) pointed out that every producing, living system depends upon its inputs from the environment: the higher the inputs, the higher the production. Soil texture does not seem to be an important factor for paper mulberry growth and yield, while based on the three phases analysis, percent of solid phase was significantly correlated with survival rate. Clay loam and loamy sand soil with high organic matter in KC, PR and PK were most suitable for paper mulberry plantation. SS and NN, among the 5 provenances, are recommended to be planted in the northern part, where the topography is mountainous with steep slopes. UN and RT provenances are recommended to be grown on flat lands with good drainage. Comparing the two species *B. papyrifera* and *B. kazinoki*, *B. papyrifera* provided a higher total and inner bark biomass than *B. kazinoki*, with the same growth rates. Consequently, for expanding paper mulberry plantations, *B. papyrifera* is recommended. The number of trees (plant density) had an important effect on biomass, especially, the inner bark biomass. Therefore, narrow spacing (1x1 m) is recommended in plantations, because of the highest biomass per unit area produced using this spacing. However, further investigation is needed concerning plantation management, insect and disease control on the plantations, improvement of the quality of paper mulberry (genetic engineering and quality of bast fiber) etc. It may be possible to grow paper mulberry in agroforestry systems and use it as a rehabilitation species on degraded lands. Fahrney *et al.* (1997) reported successfully planting paper mulberry in swidden rice fields and fallows in northern Laos, because of its attribute, which services both productivity and environmental friendly. However, it is still necessary to conduct more research on the effectiveness of paper mulberry in agroforestry systems.

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