ABSTRACT

ESPINOZA, JESÚS ALBERTO. Genetic Variation in Wood Density of *Gmelina arborea* planted on different sites in Western Venezuela. (Under the direction of William S. Dvorak.)

Variation in wood specific gravity from the base to the top of tree and from pith to bark was investigated for *Gmelina arborea* Roxb. plantations in western Venezuela. Increment cores were taken from 30 trees at five different sections up the stem: 0.1 m, 1.3 m, ½ total height, ¾ total height and at the stem top (10 cm of diameter). These trees were chosen from commercial plantations located at three different sites. Specific gravity was obtained using an X- ray densitometer. The results show that there is an increase in specific gravity from pith to bark. Changes in SG from pith to bark were greater at the top than the bottom of the trees. Slopes of the tendency lines of SG from pith to bark increased from the bottom to the top of tree and they were significantly different at $p = 0.012$. It was also evident that SG decreased from the base of the tree to ½ of the total height, then increased towards the top of the tree. These difference were significantly different at $\alpha = 0.05$. Phenotypic correlations between SG and total height of the tree were very low and ranged from -0.007 to 0.1 across the three sites. The correlations were non-significant at level $\alpha = 0.05$.

In a second study, variation of wood specific gravity among sites and provenances was investigated for *Gmelina arborea* in four provenance-progeny trials in Venezuela. Eighteen provenances and two controls were evaluated across the sites. Twelve or 5 mm increment cores were extracted from 25 trees in each provenance at every site, with the exception of one trial where 20 samples were taken. Specific gravity was obtained using the gravimetric method. The results indicated that there was high correlation (0.93) among samples taken at

2, 3 and 5 years of age in *Gmelina arborea*. Variation in wood specific gravity was high among provenances and varied from 0.447 at Muak Lek, (Thailand) to 0.360 at Pawlangyi and Kabaw (Myanmar). A negative correlation between diameter and specific gravity at the provenance level was found, and ranged from - 0.92 to - 0.30 depending on the specific method of calculation.

Key words: wood specific gravity, wood properties, provenances, correlation, genotype x environment interaction.

GENETIC VARIATION IN WOOD DENSITY OF *GMELINA ARBOREA* PLANTED ON DIFFERENT SITES IN WESTERN VENEZUELA

By
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Chair of Advisory Committee
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DEDICATION

To my wife, Nila

my children, Laura Andrea and Jesús Alberto,

my parents, my family and

to the memory of my sister Marisol and my friend Lendis.

BIOGRAPHY

Jesús Alberto Espinoza was born on July 23, 1967 in Encontrados, Zulia State, Venezuela. He graduated from Benito Puche high school in July 1984.

Jesus Espinoza received his forestry engineer degree at the Universidad de Los Andes in Mérida, Venezuela on October 23, 1992. He graduated Cum Laude in his class, received an academic award "La Excelencia" given by the state of Mérida and Venezuelan Board of National Science and Technology.

In 1993, He started his job as Inventory Engineer at the Smurfit Cartón of Venezuela company. Since1994, he works as Area Forester in the same company, and he has also been responsible for land preparation, plantation and weed control in different farms of the Forestry Division of Smurfit Cartón de Venezuela. The author is married to Nila Quevedo, and is the father of two wonderful children, Jesús Alberto and Laura Andrea.

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LITERATURE REVIEW

1 LITERATURE REVIEW

1.1 *GMELINA ARBOREA* ROXB.

Gmelina arborea (gmelina) is a medium to large tree that reaches 35 m in height and more than 3 m in diameter in natural stands in tropical and subtropical regions of Asia (Dvorak 2003). Hossain (1999) described *Gmelina arborea* as a medium-sized deciduous tree up to 40 m tall and 140 cm in diameter, but usually smaller than this. Duke (1983) and Pizzano (unknown) described this species as a deciduous tree 12-30 m height and 60-100 cm in diameter. It was introduced to tropical Africa from Southeast Asia (Rodgers 1913 in Ogbonnaya et al., 1992).

Gmelina arborea is a fast growing species member of *Verbenaceae* family (Chudnoff 1979) that has become a major international timber species over a wide range of sites in the tropics. The species occurs naturally from latitudes 5º to 30º N and longitudes 70º to 110º E. Its altitudinal range is approximately 50 to 1300 m in areas with distinct dry seasons in the countries of Bangladesh, Cambodia, China (Yunnan and Kwangsi Chuang provinces), India, Laos, Myanmar, Nepal, Pakistan, Sri Lanka, Thailand, and Vietnam (Dvorak 2003, Lauridsen et al, 1992, 2002; Duke 1983; Hossain 1999) (Figure 1-1).

Gmelina arborea grows well on deep, loamy, clay loams, calcareous, and moist soils with optimum rainfall from 1800 to 2300 mm per annum (Tewari, 1995; Lauridsen et al, 2002; Lamb, 1970 in Lauridsen et al, 2002; Wijoyo 2000; Espinoza 2003). In addition, Fred (1994) in Hossain (1999) said that the species needs soil acidity between pH 5.0 and 8.0. The species has been found in association with *Tectona grandis* (Teak) in semi-deciduous forests (Dvorak 2003) and it also has been reported in association with other species such as *Melia azedarach*, *Lagerstromia spp*., and *Pterocarpus macrocarpus*, depending on the forest ecosystems (Champion and Seth 1968 in Wijoyo 2000; Tewari 1995).

Gmelina arborea trees have smooth bark that is pale brown to grey color in young trees; in the old trees, it has a tan color (Patiño et al, 1982 in Patiño et al, 1993; Duke 1983). Gmelina heartwood also has pale brown to tan color and whitish colored sapwood. The wood color turns yellow brown upon exposure to the air after being sawn or chipped (Rao and Juneja 1971 in Dvorak 2003).

Gmelina arborea can be propagated from seeds, cuttings, and stumps. Seedlings require approximately 2 to 3 months in the nursery to be ready for planting. This species, in plantation, has rotation ages of 5 to 7 years for pulp and paper products and 8 to 15 years for solid wood products (Hornick et al, 1984; Ladrach 2003). In its natural range, gmelina is very seldom planted due to its susceptibility to diseases and insect attacks (Lauridsen and Kjaer 2002). Hornick et al. (1984) pointed out that one of the most serious pests in gmelina plantations in Brazil appears to be the leaf cutter ant. This species is a favorite target of leaf cutter ants and also this species suffers from cankers that form after pruning or other bark injury. In addition, it has been observed that termites cause a rather special problem in gmelina. They invade pockets of rot from injuries, carrying with them a little supply of mud for tunnel building. They deposit these little gobs of mud inside the cavity. After some time the gobs coalesce into a hard, pebble like deposit. When the tree is processed in the pulp mill, the pebbles break up into pieces the size of coarse sand. Similar problems have been reported in western Venezuela (Espinoza 2003).

The growth of the species is remarkably fast and on a good site can reach 20 m height in 5 years. The form of the tree is fairly good, with 6-9 m clear boles possible. Some trees can reach 3 m after a year from planting and 20 m after 4.5 years (Hossain 1999). The average yield of gmelina is approximately $21m^3$/ha/yr. A lower value is found (7 m^3/ha/yr) on poor sandy soil and the maximum of 50 m^3/ha/yr on clay loams (Ladrach 2003; Akachuku 1981 in Duke 1983; Hossain 1999).

The species has been recognized as suitable not only for pulp and paper production but also for solid wood products such as veneer, particleboard, furniture, plywood, pencils, pallets, etc. (Lauridsen and Kjaer 2002; Kpikpi 1989; Zobel and Buijtenen 1989; Chow and Lucas 1988). As a result, it is estimated that approximately 700,000 ha of gmelina plantations have been established in the tropics and subtropics. India (Southeast Asia and Pacific region) is the biggest geographic areas planted, with 371,000 ha (53%), followed by Africa with 252,000 ha (36%) and Latin America with 71,000 ha (11%), respectively (Dvorak 2003). Most plantations have been planted for pulp and paper production. In Nigeria, the high cost of newsprint and other papers sparked a search for suitable pulpwood to support the pulp and paper mills; *Gmelina arborea* was exhaustively studied and recognized as suitable for pulp and paper production (Kpikpi 1989). This species is now the most important pulpwood species in Nigeria (Chow and Lucas 1988).

1.2 WOOD SPECIFIC GRAVITY (OR DENSITY)

The terms density and specific gravity (SG) are both used to describe the mass of a material per unit volume. These terms are often used interchangeably although they each have precise, and different definitions (Bowyer and Smith 1998). Both terms are defined by Haygreen and Bowyer 1996; Zobel and Buijtenen 1989; and Hoadley 2000. Specific gravity is the ratio between the mass per unit volume of water, while wood density is defined as mass or weight per unit volume of water (such as pounds per cubic foot, grams per cubic centimeter, or kilograms per cubic meter). In other words, both terms are used to indicate the amount of actual wood substance present in a unit volume of wood and also both terms can be calculated from one another (Zobel and Jett 1995). Therefore, they will be used interchangeably.

Zobel and Jett (1995), pointed out that wood density is, in fact, not a single wood property but a combination of wood properties (latewood percent, wall thickness, cell size, and others). However, despite its complexity, wood density reacts generally as through it were a single, simple characteristic.

1.3 IMPORTANCE OF WOOD SPECIFIC GRAVITY (OR DENSITY)

Wood density, which is a way of expressing how much wood substance is present per unit volume, has a significant effect on the quality and yield of pulp and paper products and on strength and utility of solid wood products. Wood density is the most important within-species wood characteristic because knowledge about it allows the prediction of a greater number of properties than any other trait (Zobel et al., 1984; Bowyer and Smith 1998). In addition, it has a major effect on both yield and quality of the final product and it is strongly inherited (Zobel et al., 1984). Wood density is one important parameter in the assessment of raw-material quality for pulping. High densities are advantageous since they correspond to higher pulp yields on a raw-material volume basis, and to a better use of digester capacity (Miranda et al., 2001). The SG of wood is its single most important physical property. Most mechanical properties of wood are closely correlated to SG and density (Haygreen and Bowyer, 1996).

1.4 WOOD PROPERTIES AND SPECIFIC GRAVITY

As was pointed out before, wood SG allows the prediction of a greater number of properties than any other trait. Some wood properties that are closely related to wood specific gravity are: strength, dimensional stability with moisture content change, ability to retain paint, fiber yield per unit volume, suitability for making particleboard and related wood composite materials, and suitability as a raw material for making paper (Bowyer and Smith 1998). Due to the increased importance of wood as a raw material for pulp and paper products, this point will be described.

A key issue in making paper is bonding of wood elements. Fiber to fiber bonding is very important in a paper sheet, with hydrogen bonding being the single most important factor in connecting fibers. The best wood for manufacturing strong paper is often of low, rather than high, specific gravity (Bowyer and Smith 1998). Papers made from low-density wood present smoother, high tensile and busting strength characteristics, but low opacity, therefore, they are best suited to packaging products. Conversely, papers made from high-density wood often tend to be bulky, with an open structure, which is porous and more compressible giving the paper better printability and opacity characteritics (Downes 1997 in Gantz 2002). Zobel and Jett (1995) citing Van Buijtenen (1965) pointed out the close relationship between cell wall thickness and wood specific gravity. Increasing wall thickness increased tear strength but reduced tensile strength and burst.

Jett and Talbert (1982) found that for loblolly pine trees, moderate intensity selection (one in two individuals) for high SG produced about 10 kg/m^3 increment in dry wood weight in only one generation. High SG is usually preferred over other wood traits because it contributes to strength properties of paper such as tear and contains more mass per unit volume than lower SG woods; that is, it contributes to high yields in pulp. When wood is bought by volume, the greatest quantity of wood fiber in a given volume will be obtained from the highest SG wood (Bowyer and Smith 1998). Nevertheless, woods with low SG are preferred as a raw material for making high strength wood composite products such as standard particleboard, oriented strandboard, and parallel strand lumber.

1.5 SPECIFIC GRAVITY IN *GMELINA ARBOREA*

Wood densiy in gmelina ranges from 242 to 540 kg/m^3 at ages between 3 to 15 years with a overall average of 380 to 430 kg/m^3 at age 8 (Dvorak 2003, Lauridsen and Kjaer 2002, Zeaser 1998, Akachuku 1984). Wood density of this species is considered to be too low when it is compared with other hardwood species such *Acacia mangium* (470 kg/m^3) and the urograndis (*eucalyptus*) hybrid (500 kg/m^3) at approximately 6 to 8 years of age (Dvorak 2003). Studies carried out in Costa Rica found that wood SG in gmelina produced in the dry tropical region is higher SG than wood growing in the tropical region (Moya 2003). Similar results were found in a study carried out in Nigeria (Obbonnaya et al. 1992). In diffuse-porous hardwoods, like gmelina, growth rate usually has little effect on SG (Zobel and Van Buijtenen 1989). However, studies on growth and wood density in gmelina have produced contrasting results. A negative correlation between SG and growth has been found by Lauridsen and Kjaer (2002) and Keiding et al. (1984) in Zobel and Van Buijtenen 1989); but others have reported that fast growth does not change the density of gmelina wood appreciably (Hughes and Esan 1969 in Lauridsen and Kjaer 2002).

1.6 METHODS OF DETERMINING SPECIFIC GRAVITY

Many methods are used to determine wood SG (or density); however they can be expensive and often involve destructive methods for obtaining whole-tree estimates of wood density. Destructive wood density analysis has obvious disadvantages in tree breeding programs. This is because many forest species do not sprout when mature and can be vegetatively propagated only with great difficulty. Therefore, it is difficult to make tree selections operationally on the basis of their wood properties.

Of the many methods that have been used to determine wood density in trees (gravimetric, the pilodyn, beta-ray technology, the resistograph, radiation densitometry, and others), some are useful and practical, while others are of marginal value (Zobel and Jett, 1995). However, only gravimetric and radiation densitometry methods will be described here because they were the methods used to determine the SG values reported in chapter 2 (within tree density gradient in *Gmelina arborea*) and chapter 3 (wood density variation among provenances in *Gmelina arborea*).

1.6.1 **Gravimetric method**

In 1965, Phillips, in Zobel and Jett (1995), summarized methods and equipment for determining SG of small wood specimens and concluded that the most satisfactory measure of basic density is oven dry weight divided by the water-saturated or green volume. The volume of the wood sample being tested may be obtained in a variety of ways. For a piece that is regular in shape, the simplest method is to measure the dimensions as accurately as possible and calculate the volume. If the sample is irregular in shape, the volume can be obtained by the water displacement method. A third method involves use of a graduated cylinder. In this case, the volume is the difference between the fluid level before and after immersion (Haygreen and Bowyer 1996).

1.6.2 **Radiation densitometry method.**

Radiation densitometry is a commonly used technique for assessing density characteristics of wood samples (Cown and Clement 1983). Heger et al. (1974), Clauson and Wilson (1991), in Zobel and Jett (1995), pointed out that a frequently used method for assessing wood density is by X-ray densitometry. Akachuku (1985) used the X-ray technique for the determination of wood density in *Gmelina arborea*. This author also pointed out that it is a technique that is increasingly popular because of its versatility in wood quality studies. It is an efficient and rapid method, capable of measuring density at short intervals (as small as 0.001mm). The technique involves the extraction of increment cores or some similar wood sample, cutting the increment cores to a sample of approximately 2 mm thick, scanning the samples with gamma or X-rays and recording the pictures with a densitometer. The optical values are converted to wood density values (Polge 1978; Moschler and Winistorfer 1990; Chantre and Rozenber 1997 in Gantz 2002). One of the most important applications of radiation densitometry is the direct utilization of density records for anatomical, physiological and technological studies (Polge 1978).

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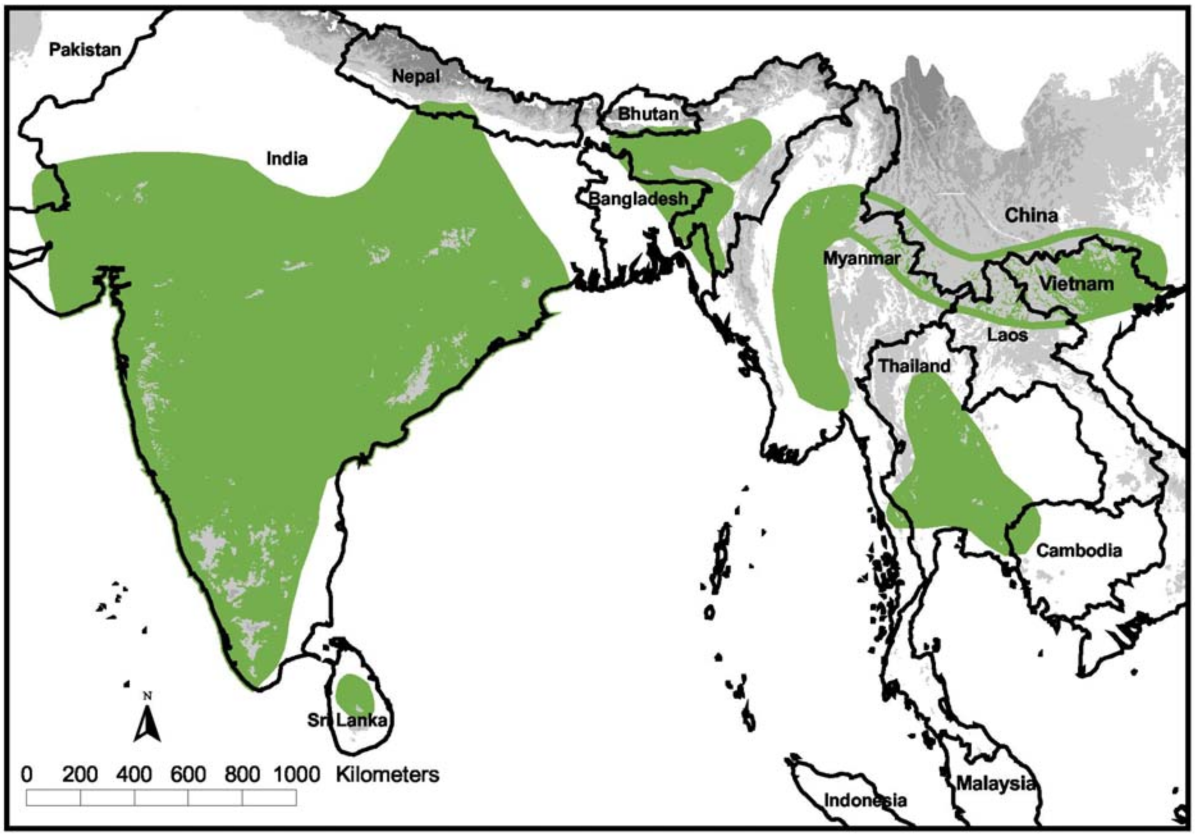

Figure 1-1. **Natural distribution of *Gmelina arborea* (from Dvorak 2003).**

CHAPTER 2

WITHIN TREE DENSITY GRADIENTS IN *GMELINA ARBOREA* IN VENEZUELA

2 WITHIN TREE DENSITY GRADIENTS IN *GMELINA ARBOREA* IN VENEZUELA

2.1 ABSTRACT

Variation in wood specific gravity (SG) from the base to the top of tree and from pith to bark was investigated for *Gmelina arborea* Roxb. plantations in western Venezuela. Increment cores were taken from 30 trees at five different sections up the stem: 0.1 m, 1.3 m, ½ total height, ¾ total height and at the stem top (10 cm of diameter). These trees were chosen from commercial plantations located at three different sites. Specific gravity was obtained using an X- ray densitometer. The results show that there is an increase in SG from pith to bark. Changes in SG from pith to bark were greater at the top than the bottom of the trees. Slopes of the tendency lines of SG from pith to bark increase from the bottom to the top of tree and they were significantly different at $p = 0.012$. It was also evident that SG decreased from the base of the tree to ½ of the total height, then increased towards the top of the tree. These difference were significantly different at $\alpha = 0.05$. Phenotypic correlations between SG and total height of the tree were very low ad ranged from – 0.007 to 0.1 across the three sites. The correlations were non-significant at level $\alpha = 0.05$.

Key words: *Gmelina arborea*, wood specific gravity, wood properties.

2.2 INTRODUCTION

Fast-growing and high-yielding tree species are being planted in different parts of the world to supply the growing demand for pulp and paper manufacturing and solid wood products. *Gmelina arborea* Roxb. (gmelina) is one of the fast-growing species native to the tropics that is gaining entry into pulp and paper manufacturing, match making, and veneers for plywood industries (Ogbonnaya et al., 1992; Arnold, 1995; Hornick et al., 1984).

Gmelina arborea is considered to be a very promising species due to the ease and low cost of establishment, rapid early growth, and promising wood characteristics suitable not only for pulp and paper production but also for solid wood products (Dvorak 2003; Lauridsen & Kjaer 2002; Kpikpi 1989; Zobel and Buijtenen 1989; Chow & Lucas, 1988).

Knowledge about the SG of the wood (weight of dry wood per unit volume) is vital to both the lumber and the pulp producer (Zobel & Buijtenen 1989). The term "density" is also used to indicate the amount of actual wood substance present in a unit volume of wood. In this paper, the two terms (specific gravity and wood density) will be used interchangeably.

The yield of pulp per unit volume as well as the strength and stiffness of the wood are directly related to SG. Most mechanical properties of wood are closely correlated to SG and density (Haygreen and Bowyer, 1996). Specific gravity is of key importance in forest products manufacturing because it has a major effect on both yield and quality of fiber and solid wood products (Zobel & Buijtenen 1989). "Density is probably the single most important intrinsic wood property for most products, particularly if we are contemplating adopting short rotations" (Burn, 1981, in Rozenberg & Cahalan 1997).

Wood SG is a variable factor within gmelina trees (Esan, 1966; Akachukwu, 1976 in Ogbonnaya et al., 1992, Zeaser 1998). Two of the most important patterns of variability in wood density within trees are changes from the pith to bark and the differences associated with different heights in the tree. There is often more variability in wood characteristics within a single tree than among trees growing on the same site or between trees growing on different sites (Larson 1967 in Zobel & Buijtenen 1989). In this study, gmelina wood density variation within trees (from the center outward, and from the base of the tree to its top) was studied in 5-year-old plantations on 3 different sites in western Venezuela using an X-ray densitometer.

2.3 MATERIALS AND METHODS

2.3.1 <u>Sample source</u>

Five-year-old *Gmelina arborea* plantations growing on three different sites (Bumbi, La Productora, and La Yaguara) at the Smurfit Cartón de Venezuela project in western Venezuela were used for this study. The seed source for these plantations was from Ston Forestal (Costa Rica). The site characteristics are described in Table 2-1.

Twelve-millimeter diameter increment cores were collected. At each location, 10 trees were chosen randomly from among the dominant and co-dominant trees. Five increment cores were taken at 0.1 m, 1.3 m (breast height, BH), ½ of total height, ¾ of the total height and at commercial height of the tree. The commercial height of the tree was defined as the height where the stem reached 10 cm of diameter. A total of 150 increment cores were collected.

2.3.2 Measurement of specific gravity

The X-ray densitometry technique was used for SG determination of gmelina wood in this study. It is an efficient and rapid method, capable of measuring SG or wood density at intervals as small as 0.01 mm (Akachuku, 1985). Half cores (pith to bark) were mounted and processed following the method described by Cumbie (2002). Four of the 150-incremement cores were broken during the process of sample preparation and were eliminated from the data set. The wood strips taken from the increment cores were then examined using the Quintek Measurement Systems™ Density Profile x-ray densitometers at the Forestry Department of the University of Georgia in Athens, GA. Measurements at intervals of 0.08 mm were used.

2.4 DATA MANIPULATION

2.4.1 Measurement of specific gravity from the base of the tree to its top

Specific gravity was also calculated for each sample height category (Stump, BH, ½ total height, ¾ total height, Top) using the samples taken at each height. An average height for each sample height category was also obtained. Analysis of variance was used to test differences in SG among height categories, and phenotypic correlation analyses were performed to determine the relationship, if any, between height and SG, and among SG at different heights. Because there is so much within-tree variation in wood properties, it was necessary to calculate an average or weighted-tree value, which was obtained using the values from the different sample points along the bole of the tree and weighted by the volume of the bolts they represent according to the formula recommended by Jett et al. (2002) (1). The analyses were done using SAS (1989) software.

$$WSG = \frac{\left[SG(B_1)\ x\ 0.0545d^2 xLB_1\right] + \left[SG(B_2)\ x\ 0.0545d^2 xLB_2\right] + \left[...etc\right]}{\sum Volume\ of\ \ all\ bolts\ combined} \qquad (1)$$

where WSG = Weighted specific gravity

B_1 = Bolt #1, B_2 = Bolt #2, etc.

LB_1 = Length of Bolt #1, LB_2= Length of Bolt #2, etc.

2.4.2 Radial changes in specific gravity

Each increment core was divided in 10 equal parts, corresponding to 10% of the length of the core. The SG was then averaged within each part. The average radius in mm was also calculated. These numbers were then used to develop a SG profile for an "average" tree. Simple linear regressions were fit to examine if there was any pith-to-bark trend in SG. Regressions were fit for each height category, and a model including height category and a height category x slope term was examined to determine if pith-to-bark slopes were different for different to height categories.

2.5 RESULTS AND DISCUSSION

2.5.1 <u>Specific gravity variation from the base to the top of the tree</u>

Many trees have wood properties that vary at different heights up in the stem. In conifers, as in hardwoods, the effect of height of the tree on wood properties is strong (Zobel and Buijtenen 1989). In this study, mean SG variation from the base to the top of the tree was determined for height categories. They were 0.442, 0.432, 0.419, 0.430, and 0.440 for Stump, BH, ½, ¾, and Top, respectively, with the SG of the Stump and the Top being significantly higher and different than the SG at ½ of height at $\alpha = 0.05$ (Table 2-2, Figure 2-1).

Specific gravity decreased from the stump to ½ of the tree height, then increased towards the top of the stem. This pattern is very different from that described by Lamb (1968) for gmelina in tropical lowlands, where the SG decreased with increasing tree height. This pattern also differs from that reported by Zeaser (1998) in Costa Rica; he found that SG increased from the base to top of the tree, but he did not report any decrease at some distance up the stem. Nevertheless, some hardwood species, such as *Swietenia macrophylla*, *Liriodendron tulipifera*, *Populus tremuloides*, and *Liquidambar styraciflua* (Briscoe et al. 1963; Taylor 1968; Einsphahr et al. 1972; Yanchuk et al. 1983a; Webb 1964 in Zobel and Buijtenen 1989) showed a similar pattern of SG variation to that found in this study, that is, high wood density at the base, decreasing for some distance up the stem, then increasing towards the top.

The author believes that this pattern (higher SG at the Stump and at the top than at ½ of height of the tree) could be caused by the formation of reaction wood (tension wood in hardwood) near to the base and top of the tree. Generally, reaction wood occurs when a stem is not straight or vertical and it is also formed in association with tree limbs. *Gmelina arborea* is a species that is characterized by the presence of a leafy crown and numerous large branches, which could account for the formation of this type of wood (tension wood) that often has greater SG than that of normal wood (Kaeiser and Boyce (1964) in Zobel and Van Buijtenen 1989). High SG at the base of the tree could also be due to planting problems, that is, trees planted with U or J roots that produce a malformation of the stem at the base of the tree. This problem becomes more acute tree when the trees become larger; high winds and rain will cause the trees to lean to produce tension wood (high SG) at the stump level of the tree.

Phenotypic correlation between SG and total height of the tree were very low (by site ranged from – 0.007 to 0.100 and 0.050 across site) and non-significant at $\alpha = 0.05$. Phenotypic correlations of SG among height categories were moderate and significant (Table 2-3). The highest correlation coefficient was found between ¾ and the top of the height categories with $r = 0.636$ ($p=0.0002$). The correlation between SG at breast height (BH) and whole tree was 0.621 with a p-value = 0.0039. This moderate correlation shows that SG at BH is not perfectly representative of the whole tree. This pattern is similar to that reported by Zeaser (1998) in Costa Rica who suggested that the best place to take samples to estimate whole tree specific gravity of gmelina was between 4.5 and 5.5 meters height on the stem.

2.5.2 Specific gravity variation from pith to bark

Specific gravity increased from pith to bark for all height categories, with a significant regression coefficient ($p < 0.001$) for all height categories (Figures 2-2a to 2-2e). It was observed that for all height categories, the SG decreased close to the bark (Figures 2-2a to 2-2e, see also Appendix 1, Table A2-1). Specifically, for all categories, the SG of the ninth section of the core (the section second-closest to the bark) was notably lower than the fitted regression line. It seems likely that this drop was a response to a climatic condition, such as temperature or water availability, which affected wood formation throughout the tree in a similar manner.

It also appeared that the slope coefficient relating SG to radial distance from pith was different for different height categories. The slope coefficient (b) was lowest at the stump, b = 0.0004, and increased to 0.0013 at the top. A linear regression model including height category and height x slope interaction indicated that differences among slope coefficients were significant at $p = 0.012$. Using the regression equations in Figures 2-2a to 2-2e, the change in SG from pith to bark at breast height is expected to be 0.091 (0.375 to 0.466). The change in SG from pith to bark is larger at the top of the tree, 0.061 (0.398 to 0.459), than at the stump, 0.046 (0.405 to 0.451), despite a much smaller pith-to-bark radius at the top of the tree.

A pattern of increasing SG from pith to bark were found by Akachuku (1985) for gmelina in Nigeria, and has also been found in other hardwood species such as *Swietenia macrophylla*, *Liquidambar styraciflua*, *Liriodendron tulipifera* (Zobel and Buijtenen 1989). In this study, the SG in gmelina increased from pith to bark, and the rate of increase was greater as one moved up the stem of the tree. Taking this into account, along with the observed decrease in SG in the middle of the stem, the SG profile of a typical 5-year-old *Gmelina arborea* in Venezuela is presented in Figure 2-3.

2.6 CONCLUSIONS

Wood specific gravity varies from the base to the top of the tree in gmelina. In this study, SG were 0.442, 0.432, 0.419, 0.430, and 0.440 for Stump, BH, ½, ¾, and Top heights, respectively, with the SG of the Stump and the Top being significantly higher and different than the SG at ½ of height at $\alpha = 0.05$. Specific gravity also varied from pith to bark for the different height categories. This variation was greater at the top than the bottom of the tree due to a higher rate of increase in SG moving from pith to bark. Specific gravity in gmelina at 5 years of age can vary from 0.346 to 0.5 from depending on pith to bark position and height in the tree.

Phenotypic correlation between SG and total height of the tree was very low (ranging from $r = -0.007$ to $r = 0.100$ across three sites) and was non-significant at $\alpha = 0.05$. Phenotypic correlations of SG of different height categories were moderate and significant. The highest correlation coefficient was found between the ¾ and Top height categories with $r = 0.636$ (significant at $p=0.0002$). The correlation between SG at breast height (BH) and whole tree was 0.621 with a p-value = 0.0039. This moderate correlation shows that SG at breast height is not perfectly representative of the whole tree. SG for the whole tree was better correlated with SG at ½ height (r = 0.880) than SG at breast height (r = 0.621). The use of means calculated from samples at breast height might be sufficient to rank families or provenances, but selections of individual trees would be more precise if based on samples taken at ½ the total height.

High variation in SG from the base to the top and/or from pith to bark can affect yield and quality of pulp. For many species, the value of wood uniformity has been emphasized. Much of the breeding for wood density is primarily aimed at producing more uniform wood, as desired by the processors and manufacturers of wood products.

An understanding of the patterns of variation within trees could have impacts on product quality, optimum harvest age and how trees are processed at the mill. It is common knowledge that wood cost is the single most important element of pulp cost, and pulp cost is often the largest factor in paper cost. By definition, high SG woods contain more mass per unit volume than lower SG woods.

Additional research is underway to characterize the amount of provenance and phenotypic variation in density in gmelina. It is important to understand and take advantage of variation in SG among *Gmelina arborea* trees in order to produce trees with the characteristics required for different industries and end products, and to increase its value in the pulp and solid wood product industries.

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Table 2-1. Location and site characteristics for *Gmelina arborea* wood sampling (Ston source) growing in Smurfit Cartón de Venezuela farms in Venezuela.

Site name:	La Yaguara, Lote 52	La Productora, Lote 03	Bumbi, Lote 8
Latitude:	07° 48' N	09° 20' N	9° 24' N
Longitude:	64° 43' W	69° 21' W	69° 22' W
Elevation:	150 m	150 m	150 m
Annual precipitation:	1108 mm	1501 mm	1170 mm
Soil texture	Sandy-clay-loam	Clay loam	Clay

Table 2-2. Specific gravity by height category for *Gmelina arborea* trees at three sites in Venezuela

Sample	N	Height (m)[1]	Std. error Height	SG[2]	Std. error SG	Radius (cm)	Std. error Radius
Stump	29	0.10	0.0000	0.442 A	0.0050	13.42	0.011
BH	29	1.30	0.0000	0.432 A B	0.0040	11.58	0.010
½	28	7.12	0.0319	0.419 B	0.0055	9.79	0.011
¾	30	10.68	0.0454	0.430 A B	0.0049	8.12	0.008
Top	30	14.24	0.0606	0.441 A	0.0049	5.57	0.005
Whole tree	30	-	-	0.426	0.0036	-	-

[1] Average height where wood samples from height category were taken.
[2] SG means of the wood samples from height category. Means with the same letter are not significantly different at $\alpha = 0.05$, using Duncan's multiple range tests.

Table 2-3. Phenotypic correlation of weighted area specific gravity for wood samples taken at different heights in 5 years old *Gmelina arborea* trees at three different sites in Venezuela

Sample		BH	½	¾	Top	Whole Tree
Stump	r[1]	**0.436**	**0.477**	**0.441**	**0.346**	**0.537**
	p[2]	0.0204	0.0103	0.0167	0.0658	0.0027
	n[3]	28	28	29	29	29
BH	r		**0.569**	**0.478**	**0.462**	**0.621**
	p		0.0019	0.0088	0.0117	0.0003
	n		27	29	29	29
½	r			**0.628**	**0.494**	**0.883**
	p			0.0003	0.0076	<0.0001
	n			28	28	28
¾	r				**0.636**	**0.803**
	p				0.0002	<0.0043
	n				30	30
Top	r					**0.637**
	p					0.0002
	n					30

[1] r = Phenotypic correlation
[2] p = P-value for statistical significance
[3] n = Sample size

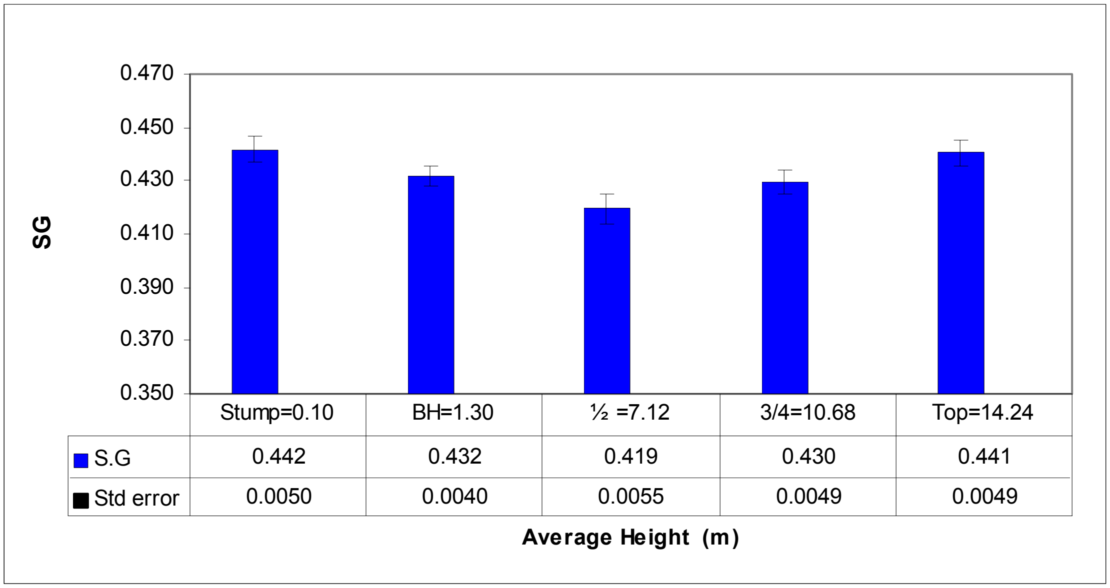

Figure 2-1. Specific gravity variation from the stump to the top of the tree of 5-year-old *Gmelina arborea* in Venezuela.

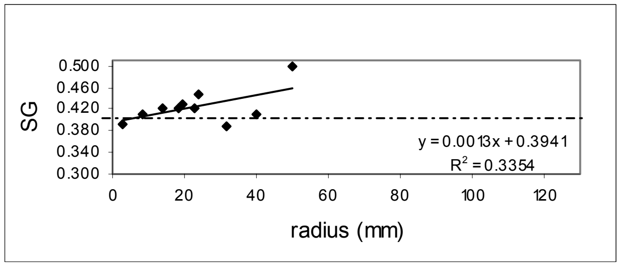

Figure 2-2a. ***G. arborea*** **SG from pith to bark (Top)**

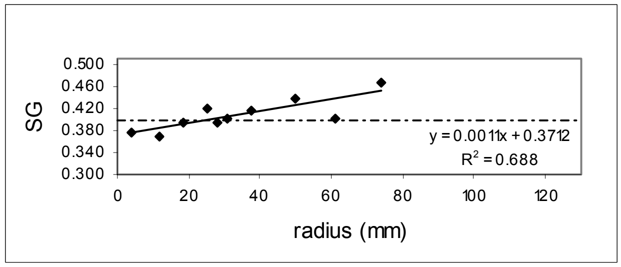

Figure 2-2b. ***G. arborea*** **SG from pith to bark (¾)**

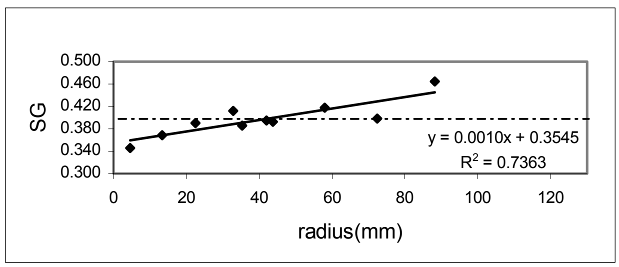

Figure 2-2c. ***G. arborea*** **SG from pith to bark (½)**

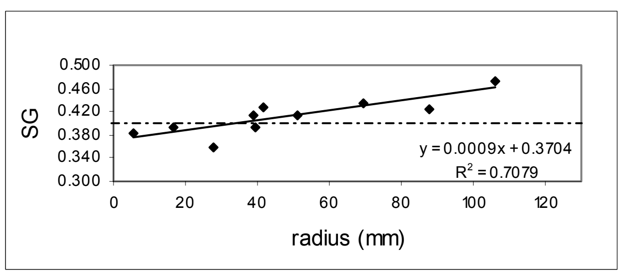

Figure 2-2d. ***G. arborea*** **SG from pith to bark (BH)**

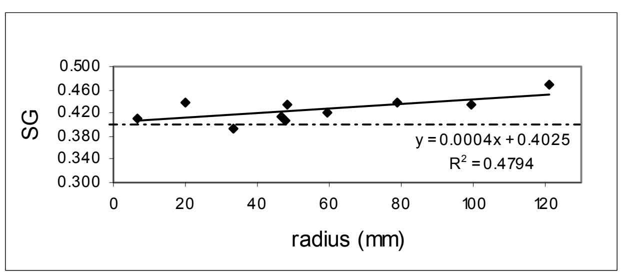

Figure 2-2e. ***G. arborea*** **SG from pith to bark (Stump)**

All regression lines are significant at $p < 0.001$.

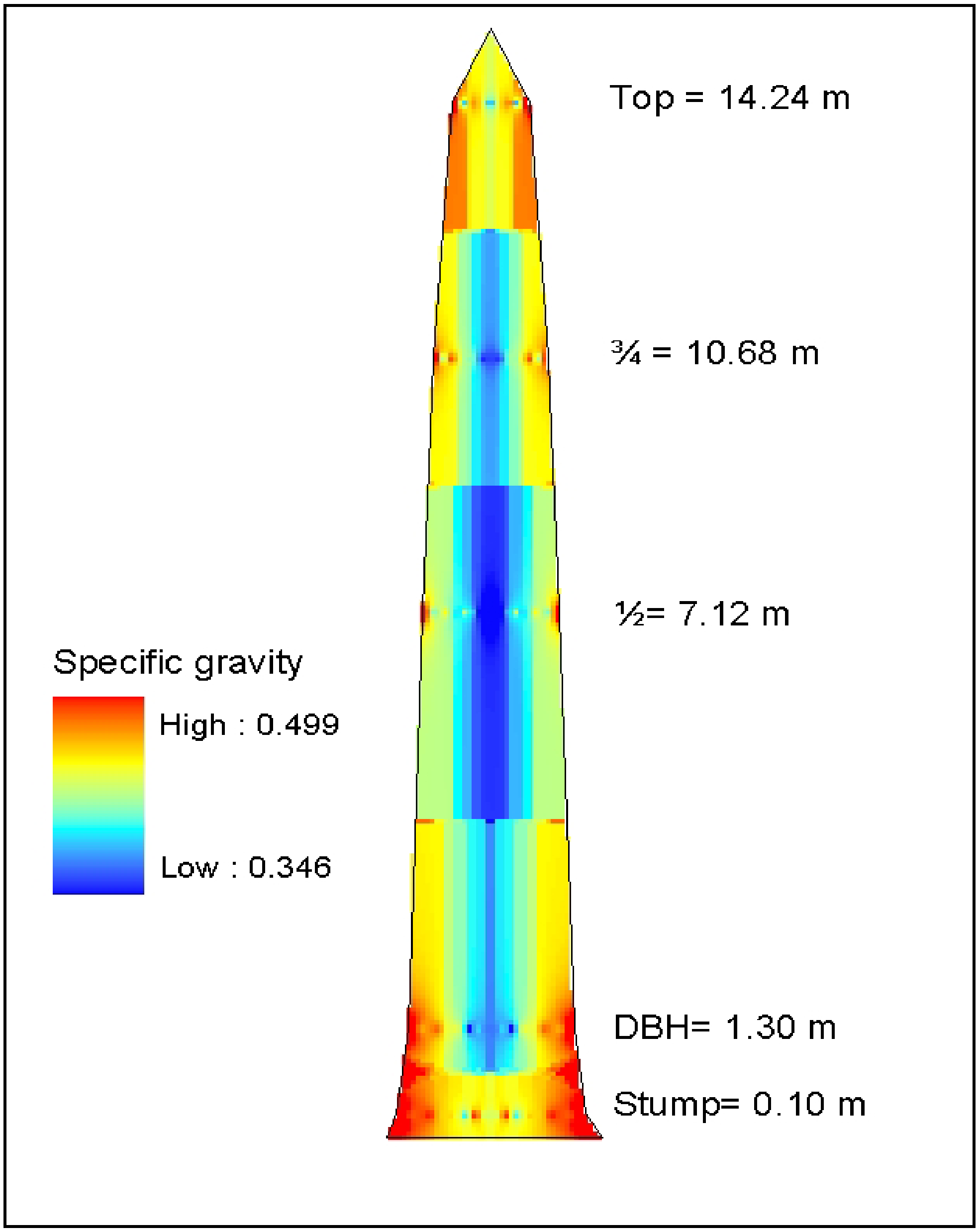

Figure 2-3. Specific gravity variation from the stump to the top of the tree for 5-year-old *Gmelina arborea* in Venezuela

Appendix 1

Table A2-1. Specific gravity (SG) from pith to bark for different sample height for 5-year-old *Gmelina arborea* planted on three different sites in Venezuela.

Category	Section	SG	Std. error (SG)	Radius (mm)	Std. Error (radius)
Top	1	0.390	2.025	2.74	0.044
Top	2	0.411	1.309	8.28	0.049
Top	3	0.422	1.757	13.84	0.059
Top	4	0.430	2.160	19.39	0.071
Top	5	0.421	1.747	22.97	0.184
Top	6	0.423	1.394	18.35	0.244
Top	7	0.447	1.476	24.10	0.212
Top	8	0.387	2.799	31.82	0.188
Top	9	0.411	3.379	40.27	0.178
Top	10	0.500	1.747	50.00	0.151
¾	1	0.377	1.506	3.92	0.056
¾	2	0.370	1.237	11.79	0.073
¾	3	0.395	1.144	18.69	0.127
¾	4	0.418	1.315	24.97	0.174
¾	5	0.403	1.458	30.55	0.234
¾	6	0.395	1.063	27.80	0.282
¾	7	0.415	1.020	37.79	0.252
¾	8	0.437	1.152	49.67	0.225
¾	9	0.402	2.425	61.26	0.228
¾	10	0.467	2.405	73.74	0.209
½	1	0.346	1.170	4.59	0.060
½	2	0.369	1.362	13.27	0.082
½	3	0.391	1.364	22.40	0.094
½	4	0.413	1.375	32.79	0.107
½	5	0.394	1.323	41.99	0.201
½	6	0.385	1.079	35.31	0.364
½	7	0.393	0.989	43.78	0.331
½	8	0.417	1.054	57.97	0.304
½	9	0.399	2.085	72.46	0.308
½	10	0.464	2.287	88.21	0.298
BH	1	0.382	1.461	5.54	0.063
BH	2	0.394	1.771	16.67	0.072
BH	3	0.360	1.278	27.80	0.087
BH	4	0.414	1.457	38.94	0.106
BH	5	0.429	1.511	41.59	0.313
BH	6	0.392	0.979	39.64	0.338
BH	7	0.413	0.800	50.92	0.294
BH	8	0.434	0.951	69.37	0.253
BH	9	0.425	1.528	87.91	0.244
BH	10	0.474	2.184	106.17	0.273
Stump	1	0.409	1.077	6.64	0.072
Stump	2	0.439	1.599	19.99	0.088
Stump	3	0.394	1.351	33.38	0.112
Stump	4	0.414	1.244	46.70	0.140
Stump	5	0.434	1.250	48.34	0.373
Stump	6	0.408	0.923	47.74	0.370
Stump	7	0.421	0.830	59.69	0.345
Stump	8	0.439	0.733	78.96	0.320
Stump	9	0.434	1.178	99.65	0.309
Stump	10	0.468	2.001	121.12	0.323

CHAPTER 3

GENETIC VARIATION IN WOOD DENSITY AMONG PROVENANCES OF *GMELINA ARBOREA* GROWN IN VENEZUELA

3 GENETIC VARIATION IN WOOD DENSITY AMONG PROVENANCES OF *GMELINA ARBOREA* GROWN IN VENEZUELA

3.1 ABSTRACT

Variation of wood specific gravity among sites and provenances was investigated for *Gmelina arborea* Roxb. in four provenance-progeny trials in Venezuela. Eighteen provenances and two checklots were evaluated across the trials. Twelve or 5 mm increment cores were extracted from 25 trees in each provenance at every site, with the exception of one trial where 20 samples were taken. Specific gravity was obtained using the gravimetric method. X-ray densitometry of 29 breast height 5-year-old increment cores indicated that there is high correlation (0.93) among samples taken at 2, 3 and 5 years of age in *Gmelina arborea*. Interaction between site and provenances was significant at the $\alpha = 0.1$ level. Variation in wood specific gravity was high among provenances and varied from 0.447 Muak Lek, (Thailand) to 0.360 Pawlangyi, (Myanmar). A strong negative phenotypic correlation (-0.918) was found between specific gravity and diameter growth rate (diameter) at the provenance level.

Key words: *Gmelina arborea*, wood specific gravity, provenance.

3.2 INTRODUCTION

It is not possible to discuss exotics without at the same time considering geographic variation, or as it is commonly called, provenance variation. In this study “provenance” denotes the original geographic area from which seed or other propagules were obtained (Eldridge et al. 1994; Zobel and Talbert 1984; Zobel et al. 1987; Zobel and Van Buitenen 1989; Zobel and Jett 1995). This term is frequently confused with the seed source, which is defined by the same authors as the area from which the seed was obtained; that is, seed source is where the seed is collected while provenance denotes the indigenous origin of the trees.

Provenance studies are one of the most cost-effective forms of investment in forestry research and development because as soon as superior provenances are identified, they can be put to use immediately in establishing plantations (Eldridge et al., 1994). Variation in wood properties can be caused by environmental and genetic control of the wood. An indication that wood properties are under strong genetic control is when they change little across location (Zobel and Van Buijtenen 1989; Zobel and Jett 1995).

One of the best clues to the potential usefulness of a species in a new location is its performance in its native habitat (Wright 1962). *Gmelina arborea* has been reported to be quite a site-specific species as an exotic. The best growth of this species has been found predominantly on clay loam soils with high base status and a depth of at least 60 cm (Dvorak 2003, Henri 2000). Success in the establishment and productivity of forest tree plantations is determined mainly by the species used and the source of seed within species (Lardsen 1954; Callahan 1964; Lacaze 1978 in Zobel and Talbert 1984). Lauridsen & Kjaer (2002) add that early gains could also be obtained by proper choice of the best provenances to meet immediate demand for planting. The use of genetically based geographic variation is the first step in tree breeding when assembling a suitable population for future generation of selection, crossing, and genetic improvement (Eldridge et al. 1994).

Wood specific gravity (SG) differences among provenances are usually studied at an early stage in tree improvement programs. Akachuku (1984) found that there was sufficient variation in gmelina wood qualities to encourage genetic improvement by breeding those trees with the best wood density in *Gmelina arborea* Roxb. There have been several efforts to assess provenance variation in gmelina during the last four decades due to its high value for wood products. *Gmelina arborea* is a fast growing tree, that has been extensively used in reforestation and agro-forestry activities, and attracts plantation growers due to its high economic importance.

One of the most important projects with gmelina in the last decades has been the international provenance trials sponsored by the FAO Panel of Experts on Forest Genetic Resources and coordinated by the DANIDA Forest Seed Centre (Lauridsen & Kjaer 2002). CAMCORE, (International Gene Conservation and Tree Domestication Cooperative) from North Carolina State University, more recently has been working on the *ex situ* gene conservation and seed collection of gmelina in countries where the species grows naturally. Provenance/progeny tests have been established in 8 countries where the species has high potential to grow well. In 1994, CAMCORE, in collaboration with the Royal Forest Department of Thailand, initiated *ex situ* gene conservation and seed collection programs of *Gmelina arborea* in native forest of Thailand (Donahue 1994, in Wijoyo 2000). In a similar manner, CAMCORE has been working with the Forestry Department of Myanmar. Smurfit Cartón de Venezuela (SCV) has established 8 trials with the CAMCORE seed collections in 1995, 1997, 1998 and 1999 in two different physiographic zones. This study has been conducted to evaluate and quantify the genetic variation in wood density among provenances, age and site for 4 of these trials.

3.3 MATERIALS AND METHODS

3.3.1 Description of area of study

The land owned by SCV represents four physiographic zones: piedmont, mesas, high flatland (llanos altos) and low flatland (llanos bajos) (Rojas et al. 2000). These descriptions are the first approximation of the land classification system for SCV, and all forest management decisions are based primarily on these physiographic zones. As Pritchett and Fisher (1987) mentioned, the influence of physiographic variables on forest productivity has been recognized longer than that of most other site components. Topography exerts an effect on growth through local modification of climate and edaphic variables, particularly moisture, light, and temperature regimes. The four trials are located on two of those four physiographic zones (Figure 3-1).

3.3.2 Climatic conditions

The annual distribution of precipitation at the trial sites is shown in figure 3-2. The precipitation pattern is almost the same at all of these sites; there is a dry season that goes from November to the middle of May and a rainy season from the middle of May to October with a peak of rain in June and July. The mean annual temperature is 27.5 ^{o}C. According to Holdridge (1967), this area is classified as Tropical Dry Forest.

3.3.3 Trial characteristics

Smurfit Cartón de Venezuela and CAMCORE established four trials on two different physiographic zones to evaluate the performance of 18 provenances of *Gmelina arborea*. These trials were established in four different years; 1995, 1997, 1998 and 1999 (Table 3-1).

The test designs were randomized complete blocks with provenance plots located randomly within replication and families located randomly within provenances. Each of the open-pollinated families was established in six-tree row plots with 9 replications at 3 m x 3 m spacing. Two seed lots, one local (from El Hierro farm, SCV, Venezuela) and one from Costa Rica (Ston Forestal) were included as checklots.

3.3.4 Wood sampling

Samples were taken in provenance/progeny tests of different ages (three, four, five and seven) growing in two different physiographic areas. The location and information of the provenance-progeny tests used are summarized in table 3-2 and 3-3.

Twenty-five samples at breast height were randomly taken from dominant and co-dominant trees in the trials trying to sample at least a tree from each family. Two of the sources were bulk lots from Muak Lek, Thailand and an unknown source from an Indian provenance in trial 47-03-02B2 (La Productora) purchased from the Asean Sean Canada Company and Singapore Training Company, respectively. The other sources were from the CAMCORE collections. Only 20 samples were taken in trial 47-03-01F (La Yaguara) from each provenance (Samantwadi and Herur) because of lack of sufficient genetic material. Twelve-millimeter diameter increment cores were removed at breast height for trials 47-03-01F and 47-03-02B2 located in La Yaguara and La Productora farms, whereas 5 mm increment cores were taken on trials 47-03-04E1 and 47-03-05A1, located in La Joya and Garachico farms respectively. A total of 640 increment cores were collected.

3.3.5 Measurement of wood specific gravity

Specific gravity of the wood samples was measured by the gravimetric method; as the ratio of the oven-dry weight to its original green volume. The dry weight of the samples was obtained by drying the cores at 85 ºC for 48 hours to a constant weight, while the green volume was determined by the displacement method where the scale or balance records the weight of the fluid (water) displaced (Jett et al. 2002; Haygreen and Bowyer 1996).

3.4 DATA MANIPULATION

In this study, the overall objective was to examine provenance variation in SG, and to rank provenances for SG. It is complicated by the fact that the test sites are of different age, and that sub-sets of the provenances are tested only on one site. Nevertheless, the sites all contain the common checklots El Hierro and Ston. Therefore, the following analyses were done in order to reach the objectives mentioned above.

3.4.1 Approximate age-age correlations

The objective for calculating these correlations was to determine if sampling at different ages at breast height would have changed the performance ranks of the trees. The procedure used to determine these correlations was to calculate wood SG using X-ray densitometry, where density measurements were taken every 0.08 mm. To do this, 29 increment cores at breast height, 10 at each site except La Productora site where 9 cores were taken (see chapter 2) from commercial plantations that were 5 years of age. Each half-increment core used was divided into 5 equal parts, and each part was assumed to approximate 1 year of growth. Phenotypic correlations among the core SG at "age 2", age "3" and age "5" were examined.

3.4.2 ANOVA of check lot x site interaction

The objective of this analysis was to determine if checklots change ranks or change difference in SG depending on site using the following linear model: $\mathbf{Y_{ijk} = \mu + S_i + P_j + S_iP_j + e_{ijk}}$.

Where $\mathbf{Y_{ijk}}$ = SG measurement of k^{th} tree of j^{th} provenance in k^{h} site

$\boldsymbol{\mu}$ = Overall mean

$\mathbf{S_i}$ = fixed effect of i^{th} site

$\mathbf{P_j}$ = fixed effect of j^{th} provenance

$\mathbf{S_i\,P_j}$ = random interaction of i^{th} site with j^{th} checklot

$\mathbf{e_{ijk}}$ = error term, residual of the ijk^{th} phenotypic measurement and null expectation

3.4.3 Calculation of Least Square Means (LS means) for SG for each provenance across site

The objective of this calculation was to compare provenances by using LS means to adjust SG to a common site. The validity of this approach assumes no rank change or interaction with age or site. Because the provenances are represented only on one site, LS means calculated using a linear model including a term for provenance x site would be inestimable. Thus, the simple main effect model was used: $\mathbf{Y_{ijk} = \mu + S_i + P_j + e_{ijk}}$.

Where $\mathbf{Y_{ijk}}$ = SG measurement of Kth tree of Jth provenance in Ith site

$\mathbf{\mu}$ = Overall mean

$\mathbf{S_i}$ = fixed effect of Ith site

$\mathbf{P_j}$ = fixed effect of Kth provenance

$\mathbf{e_{ijk}}$ = error term, residual of the ijkth phenotypic measurement and null expectation

3.4.4 Correlation of Diameter Growth and SG

This correlation was determined to examine the relationship between growth and density at the provenance level. Using the same approach as described above, LS means were calculated for diameter inside bark (DIB) as measured on the increment cores used in the X-ray densitometry measurements of SG. In addition, provenance effects for DBH were estimated by Best Linear Unbiased Prediction (BLUP) using SAS Proc Mixed. This approach used all trees in the tests, not just the dominants and co-dominants sampled for SG. A provenance mean correlation was calculated using LS means for SG and DIB, and for SG and provenance BLUPs for DBH.

3.5 RESULTS AND DISCUSSION

In regard to approximate age-age correlations, the simple phenotypic correlation between "2-year" and "5-year" and between "3-year" and "5-year" core SG at each site ranged from 0.90 to 0.96 and from 0.93 to 0.96, respectively. Combining data across all sites, the correlations were both 0.93 (Table 3-4). The high correlations indicate that at the individual tree level there is little change in rank from measuring SG of gmelina at approximately ages 2, 3 and 5 years. Therefore, these results suggest that there is probably a high correlation at the end of the rotation, about age 7 years. If this is true at an individual tree level, then it should also be true at the family mean or provenance mean level, and one would expect correlations around 0.90 from assessments made at different ages. These results are very similar to these reported by Van Buijtenen (1963), Matziris and Zobel (1973), and Megraw (1985) for *Pinus taeda.*

Analysis of variance (ANOVA) of checklot x site interaction shows no significant provenance (checklot) effect (p=0.3014). However, this is not a powerful test since there are only two checklots (Table 3-5). There is some changing of ranks in the checklots, but it appears that is because the checklots have similar SG. Wood densities of the checklots were within ±13 kg/m^3 of each other at three of the locations. Trees at El Hierro were slightly denser in the two tests (La Yaguara and La Joya) than Ston and slightly lower at Garachico. El Hierro was 29 kg/m^3 lower than the Ston checklot at La Productora (Table 3-6).

Reports in the literature generally indicate very little genotype x environment interaction for SG, or other wood properties. Barker (1973) and Van Buijtenen (1978) in Zobel and Van Buijtenen (1989) reported no genotype x environment interaction in SG for loblolly pine planted at different sites. Very weak genotype x environment interaction was found by Lima (1987) in *Pinus oocarpa* grown in Brazil and Colombia, and by Ferrari and Scaramuzzi (1980) in hybrid poplars. Wright (1990) reported no significant genotype x environment interaction for SG in *Pinus caribaea*. Zobel and Jett (1995) cited "… In general, G x E with wood properties is small except where grossly differing environments are involved". Zobel and Van Buijtenen (1989) pointed out that for gmelina and eucalypts, wood generally varies little with provenance of seed.

The only statement that can be made is that there is always some genotype x environment interaction, but it is important to determine whether this interaction is large enough to change the performance ranking of given genotypes when grown in different environments. In this study, the genotype x environment interaction was not sufficient enough to alter the ranking of the genotypes in the checklots. The average performance of the two checklots can be used to compare other provenances from different tests to one another.

Unadjusted and LS means for SG for each provenance is shown in Table 3-6. Unadjusted site means range from 0.369 to 0.421. The site with the oldest trees (La Yaguara = age 7) had the highest SG (0.421) and the site with the youngest trees (Garachico = age 3) had the lowest SG (0.369). La Productora site (age = 5) had slightly lower SG than La Joya site (age = 4). However, considering only the checklots, which were common to all sites, the highest SG is at La Joya (age = 4) followed by La Yaguara (age=7), Garachico (age = 3) and La Productora site (age =5), suggesting that site effects may play a more important role in density than age. Despite the fact that there are highly significant site effects (Table 3-7), LS means adjusted the SG of each provenance by eliminating the effect of site. In this study, sites vary both in environment and age, but this approach assumes that there is no interaction or rank change associated with either environment or age.

LS means for SG ranged from 0.447 for the Singapore source to 0.360 for the Kabaw and Pawlangyi, Myanmar provenances (Table 3-6). It indicates huge differences in SG among provenances, which is potentially very important because it means improvements can be made through selection and breeding. Once the best provenances, the best families within provenances and the best trees within families are chosen, they can be used for commercial plantation establishment.

Unadjusted diameter means and LS means for diameter inside bark (DIB) by provenance and across sites is shown in Table (3-8). There was large variation among provenances in DIB, from 9.296 cm for Singapore to 15.415 cm for Moeswe. A strong negative relationship was found between SG and DIB (r = -0.92) (Table 3-9 and Figure 3-3). The correlation between provenances BLUP for DBH (based on all trees in the test) produced a lower, but still negative, correlation (r = -0.30) (Table 3-9, Figure 3-4). This result is similar to others reported for gmelina by Lauridsen and Kjaer (2002), Keiding et al. (1984) and differs from that reported by Lamb (1968) in Zobel and Van Buijtenen 1989. Nevertheless, when the phenotypic correlation was calculated at the individual tree level, it was found be much less important (- 0.09) than at the provenance level, so it shows that individual selection can identify trees with both acceptable SG and acceptable growth.

Knowing the relationship between growth rate and SG is very important. With a negative correlation between SG and growth rate, selection for SG alone would also indirectly select for slow growth. Therefore, this type of situation must be avoided or the selection must be done according to the priority and/or need of the tree improvement program that is being developed.

3.6 CONCLUSIONS

Phenotypic correlation between "2-year" and "5-year" and between "3-year" and "5-year" core SG at each site ranged from 0.90 to 0.96 and from 0.93 to 0.96, respectively. Combining data across all sites, the correlations were both 0.93.

Analysis of variance (ANOVA) of checklot x site interaction shows no significant provenance (checklot) effect (p=0.3014). However, this is not a powerful test since there are only two checklots.

Unadjusted site means ranged from 0.369 to 0.421. The site with the oldest trees (La Yaguara = age 7) had the highest SG (0.421) and the site with the youngest trees (Garachico = age 3) had the lowest SG (0.369). La Productora site (age = 5) had slightly lower SG than La Joya site (age = 4).

At checklots levels, which were common to all sites, the highest SG is at La Joya (age = 4) followed for La Yaguara (age=7), Garachico (age = 3) and La Productora site (age =5). It suggests that site effects may play a more important role in wood density than age.

LS means for SG ranged from 0.447 for the Singapore source to 0.360 for the Kabaw and Pawlangyi, Myanmar provenances. It indicates huge differences in SG among provenances, which is very important because it means improvements can be made through selection and breeding

Large variation in diameter inside bark was found among provenances. It varied from 9.296 cm (Singapore source) to 15.415 cm (Moeswe provenance). The DBH based on all trees in the tests varied from 8.4 cm (Muak Lek, Thailand provenance) to 10.8 cm (Waibon, Myanmar provenance).

A strong negative relationship was found between specific gravity and diameter inside bark ($r = -0.92$) at the provenance level. The correlation between provenances BLUP for DBH (based on all trees in the test) produced a lower, but still negative, correlation ($r = -0.30$). However, at the individual tree level, the phenotypic correlation was found to be much less significant (- 0.09) than at provenance level, so this indicates that selection and breeding can be made at family and individual level in order to get individuals with acceptable SG and growth.

Because there appears to be a strong negative correlation between SG and growth rate (diameter), it is suggested that provenances be selected with rapid growth and then make selection of families and individual trees with high SG from among those with rapid growth. Another option could be to use a selection index to improve volume and wood density at the same time. The ideal is to find families or individual trees within provenances that have both high SG and high growth rate, in order to make an improvement in both traits. Obviously, in this process of choosing provenances, not only SG and growth but also good survival, form and health need also be evaluated.

Provenance variation is important in gmelina. Proper choice of the best provenances can bring early gains in operational programs, especially when there is a high correlation between wood densities at different ages.

Understanding how wood density varies in species of high economic value is very important due to its effect on both yield and quality of the final product. In the pulp and paper industry, genetic improvement in wood density and growth rate is a way to increase yields per unit of land and the yields from mills, in spite of the fact that the value of including wood properties in a genetics program is not always accepted.

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Table 3-1. Detailed information of *Gmelina arborea* provenances established in four different provenance-progeny tests in Venezuela.

Provenance	Country	Latitude	Longitude	Precipitation (mm/yr)	Elevation (a.m.s.l)
El Hierro	Venezuela	09º 52' N	69º 21' W	1601	150
Ston	Costa Rica				
Herur	India	12º 30' N	75º 55' W	1025	1000
Samantwadi	India	15º 54' N	73º 46' W	2750	200
Poppa	Myanmar	20º 56' N	95º 14' E	713	838
Pyin Oo Lwin	Myanmar	21º 00' N	96º 00' E	1520	
Sin Thaut	Myanmar	19º 47' N	96º 23' E	1270	234
Singapore	India				
Kabaw	Myanmar	18º 30' N	96º 30' E	1270	91
Moeswe	Myanmar	19º 53' N	95º 59' E	1651	198
Pawlangyi	Myanmar	18º 50' N	95º 30' E	1270	457
Phet Sut	Myanmar	24º 14' N	96º 17' E	1270	
Kyun Taw	Myanmar	23º 52' N	95º 55' E	1778	
Waibon	Myanmar	23º 58' N	95º 43' E	1778	
Ladagyi	Myanmar	19º 49' N	95º 58' E	1270	
Kintha	Myanmar	20º 36' N	96º 16' E	1271	
Saiyokei	Thailand	14º 25' N	98º 50' E	1400	50
Pong Nam Ron	Thailand	13º 00' N	102º 15' E	1500	200
Pak Chong	Thailand	16º 35' N	101º 13' E	1500	260
Muak Lek	Thailand				

Table 3-2. **Location of provenance-progeny tests of *Gmelina arborea* growing at Smurfit Cartón de Venezuela farms in Venezuela.**

Test Identification:	**47-03-01F**	**47-03-02B2**	**47-03-04E1**	**47-03-05A1**
Site Name:	La Yaguara Lote 23	La Productora, Lote 23	La Joya, Lote 3	Garachico, Lote 25
Latitude:	07º 48’ N	09° 20' N	09° 24' N	09° 34' N
Longitude:	64º 43’ W	69° 21' W	69° 22' W	69° 45' W
Elevation:	150 m	150 m	170 m	140 m
Annual Precipitation:	1108 mm	1501 mm	1830 mm	1805 mm
Soil type	Sandy-clay loam	Clay- Loam	clay	Clay- Loam
Date Planted:	June 1995	May 1997	June 1998	June 1999

Table 3-3. **Sampling design for wood specific gravity in *Gmelina arborea* growing at Smurfit Cartón de Venezuela farms in Venezuela.**

Test Identification	**47-03-01F**	**47-03-02B2**	**47-03-04E1**	**47-03-05A1**
Site Name:	La Yaguara, Lote 23	La Productora, Lote 23	La Joya, Lote 3	Garachico, Lote 25
No. Provenance sampled	5	5	4	4
Provenances sampled:	Thailand (Saiyoke, Pong Nam Ron, Pak Chong) India (Herur, Samantwadi)	Myanmar (Poppa, Sinthaut, Pyin Oo Lwin), India (Singapore), Thailand (Muak Lek)	Myanmar (Kabaw, Moeswe, Pawlangyi, Phet Sut)	Myanmar (Kyun Taw, Waibon, Ladagyi, Kintha)
Check lot:	El Hierro, Ston	El Hierro, Ston	El Hierro, Ston	El Hierro, Ston
No. Samples per provenance:	25	25	25	50
No. Samples per check lot:	10	10	10	20
Total samples per test:	135	145	120	240
Total Samples:	640			

Table 3-4. Correlation between age 2 and age 5 and between age 3 and age 5 by site and across sites in *Gmelina arborea* in Venezuela.

Site: Bumbi

Variable	N	Mean	Std Dev
SG 5-year	10	0.402	0.02328
SG 3-year	10	0.412	0.02016

Correlation

	SG 2-year	SG 3-year	SG 5-year
SG 2-year	1	-	0.9054
			0.0002
SG 3-year	-	1	0.9342
			<.0001
SG 5-year	-	-	1

Site: La Productora

Variable	N	Mean	Std Dev
SG 5-year	9	0.40554	0.03117
SG 3-year	9	0.42447	0.02172

Correlation

	SG 2-year	SG 3-year	SG 5-year
SG 2-year	1	-	0.9581
			<.0001
SG 3-year	-	1	0.9293
			0.0003
SG 5-year	-	-	1

Site: La Yaguara

Variable	N	Mean	Std Dev
SG 5-year	10	0.40062	0.03117
SG 3-year	10	0.4142	0.02172

Correlation

	SG 2-year	SG 3-year	SG 5-year
SG 2-year	1	-	0.9212
			0.0002
SG 3-year	-	1	0.9293
			0.0003
SG 5-year	-	-	1

Site: All

Variable	N	Mean	Std Dev
SG 5-year	29	0.40277	0.02939
SG 3-year	29	0.41674	0.02289

Correlation

	SG 2-year	SG 3-year	SG 5-year
SG 2-year	1	-	0.9260
			<.0001
SG 3-year	-	1	0.92866
			<.0001
SG 5-year	-	-	1

Table 3-5. Analysis of Variance for the *Gmelina arborea* checklots in Venezuela.

Source	DF	Sum of square	Mean Square	F Value	Pr > F	
Dependent variable: SG						
Model	7	0.07243868	0.01034838	15.24	<.0001	
Error	92	0.06248974	0.00067924			
Corrected Total	99	0.13492843				
	R-Square	Coeff Var	Root MSE	SG Mean		
	0.536867	6.733436	0.026062	0.387056		
Source	DF	Type III SS	Mean Square	F Value	Pr > F	
Site	3	0.06676376	0.02225459	32.76	<.0001	
Provenance	1	0.00073358	0.00073358	1.08	0.3014	ns
Site*Provenance	3	0.00439731	0.00146577	2.16	**0.0983**	ns

Table 3-6. Unadjusted means and least square means for specific gravity by provenance and across sites for *Gmelina arborea* in Venezuela.

Provenance	Country	Farms: Yaguara (1995 - age 7)	Farms: Productora (1997 - age 5)	Farms: Joya (1998 – age 4)	Farms: Garachico (1999 - age 3)	SG LSMEAN	Standar Error	Ranking
Herur	India	0.440	-	-	-	0.416	0.008	4
Samantwadi	India	0.415	-	-	-	0.391	0.008	10
Singapore	India	-	0.414	-	-	0.447	0.007	1
Poppa	Myanmar	-	0.384	-	-	0.417	0.007	3
Sin Thaut	Myanmar	-	0.369	-	-	0.404	0.007	5
Pyin Oo Lwin	Myanmar	-	0.364	-	-	0.398	0.007	7
Phet Sut	Myanmar	-	-	0.407	-	0.377	0.007	17
Moeswe	Myanmar	-	-	0.396	-	0.366	0.007	18
Kabaw	Myanmar	-	-	0.391	-	0.360	0.007	19
Pawlangyi	Myanmar	-	-	0.390	-	0.360	0.007	20
Waibon	Myanmar	-	-	-	0.376	0.397	0.006	8
Kintha	Myanmar	-	-	-	0.370	0.390	0.006	11
Ladagyi	Myanmar	-	-	-	0.367	0.388	0.006	12
Kyun Taw	Myanmar	-	-	-	0.363	0.383	0.006	16
Pak Chong	Thailand	0.423	-	-	-	0.399	0.007	6
Saiyoke	Thailand	0.416	-	-	-	0.387	0.007	15
Pon Nam Ron	Thailand	0.411	-	-	-	0.387	0.007	14
Muak Lek	Thailand	-	0.387	-	-	0.421	0.007	2
El Hierro	Venezuela	0.415	0.351	0.428	0.364	0.388	0.004	13
Ston	Costa Rica	0.412	0.380	0.414	0.377	0.395	0.004	9
Unadjusted overall mean		**0.421**	**0.384**	**0.396**	**0.369**			
Checklot average		**0.414**	**0.366**	**0.421**	**0.371**			
LS mean		**0.417**	**0.360**	**0.424**	**0.373**			

Table 3-7. Analysis of Variance and least square means for SG across sites for *Gmelina arborea* in Venezuela.

Source	DF	Sum of square	Mean Square	F Value	Pr > F
Model	22	0.31930769	0.01451399	19.83	<.0001
Error	617	0.45152758	0.00073181		
Corrected Total	639	0.77083527			
	R-Square	Coeff Var	Root MSE	SG Mean	
	0.414236	6.971225	0.027052	0.388052	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
Site	3	0.06676376	0.02225459	30.41	<.0001
Provenance	19	0.08324647	0.00438139	5.99	<.0001

Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Site	SG LSMEAN	Standard error	Pr > |t|	LSMEAN number	Ranking
Joya	0.42362492	0.00547093	<.0001	2	1
Yag	0.41745256	0.00512562	<.0001	4	2
Gar	0.37322837	0.00435361	<.0001	1	3
Prod	0.36012645	0.00512562	<.0001	3	4

Least Squares Means for effect Site
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: SG

i/j	1	2	3	4
1		**<.0001**	0.2896	**<.0001**
2			**<.0001**	0.8885
3				**<.0001**
4				

Table 3-8. Unadjusted means and least squares means for diameter inside bark by provenance and across sites for *Gmelina arborea* in Venezuela.

		Farms						
Procedencia	**Country**	**Yaguara (1995 – age 7)**	**Productora (1997- age 5)**	**Joya (1998- age 4)**	**Garachico (1999-age 3)**	**Diameter LSMEAN**	**Standar Error**	**SG LSMEAN Ranking**
Herur	India	11.5				10.989	0.617	19
Samantwadi	India	11.7				11.189	0.617	17
Singapore	India		15.8			9.296	0.580	20
Poppa	Myanmar		18.2			11.668	0.580	16
Sin Thaut	Myanmar		18.6			12.092	0.580	15
Thin Ka Don	Myanmar		19.6			13.120	0.580	13
Phet Sut	Myanmar			10.9		15.035	0.580	3
Moeswe	Myanmar			11.3		15.415	0.580	1
Kabaw	Myanmar			11.1		15.195	0.580	2
Pawlangyi	Myanmar			10.9		14.995	0.580	4
Waibon	Myanmar				10.3	13.226	0.438	11
Kintha	Myanmar				10.9	13.794	0.438	6
Ladagyi	Myanmar				10.8	13.762	0.438	8
Kyun Taw	Myanmar				10.2	13.160	0.438	12
Pak Chong	Thailand	12.9				12.368	0.580	14
Saiyoke	Thailand	14.0				13.396	0.580	10
Pong Nam Ron	Thailand	14.3				13.780	0.580	7
Muak Lek	Thailand		17.5			11.052	0.580	18
El Hierro	Venezuela	13.4	19.4	10.1	10.7	13.437	0.304	9
Ston	Costa Rica	15.2	21.1	9.1	11.0	14.041	0.304	5
Unadjusted overall mean		**12.9**	**17.9**	**11.0**	**10.6**			
Checklot average		**14.3**	**20.2**	**9.6**	**10.8**			
LS mean		**13.6**	**19.6**	**8.9**	**10.1**			

Table 3-9. Provenance mean correlation using LS means for specific gravity and diameter inside bark (SG, DIB) and for specific gravity and diameter breast height (SG, DBH) in *Gmelina arborea* tests in Venezuela.

Provenance[1]	Country	SG LSMEAN	Standard Error	DIB LSMEAN	Standard Error	DBH BLUP	Standard Error
Singapore	India	0.447	0.007	9.3	0.304	9.2	0.755
Muak Lek	Thailand	0.421	0.007	11.1	0.580	8.4	0.757
Poppa	Myanmar	0.417	0.007	11.7	0.580	9.9	0.756
Herur	India	0.416	0.008	11.0	0.304	10.1	0.832
Sin Thaut	Myanmar	0.404	0.007	12.1	0.580	10.2	0.756
Pak Chong	Thailand	0.399	0.007	12.4	0.438	9.6	0.779
Thin Ka Don	Myanmar	0.398	0.007	13.1	0.438	10.6	0.756
Waibon	Myanmar	0.397	0.006	13.2	0.438	10.8	0.515
Ston	Costa Rica	0.395	0.004	14.0	0.580	11.1	0.309
Samantwadi	India	0.391	0.008	11.2	0.580	9.9	0.831
Kintha	Myanmar	0.390	0.006	13.8	0.580	10.5	0.515
Ladagyi	Myanmar	0.388	0.006	13.8	0.580	10.4	0.515
El Hierro	Venezuela	0.388	0.004	13.4	0.580	10.9	0.319
Pong Nam Ron	Thailand	0.387	0.007	13.8	0.580	9.8	0.779
Saiyoke	Thailand	0.387	0.007	13.4	0.580	9.8	0.779
Kyun Taw	Myanmar	0.383	0.006	13.2	0.438	10.2	0.515
Phet Sut	Myanmar	0.377	0.007	15.0	0.580	10.0	0.740
Moeswe	Myanmar	0.366	0.007	15.4	0.617	9.8	0.740
Kabaw	Myanmar	0.360	0.007	15.2	0.617	9.8	0.740
Pawlangyi	Myanmar	0.360	0.007	15.0	0.580	9.7	0.740
Correlation LS mean SG-DIB				-0.92			
Correlation LS mean SG-BLUP DBH						-0.30	

[1]Age of the trees when the samples were taken by provenances: Herur, Samantwadi, Pak Chong, Saiyoke, Pong Nam Ron, Ston, El Hierro = age 7; Singapore, Poppa, Sin Thout, Think Ka Don, Muak Lek, Ston, El Hierro = age 5; Phet Sut, Moeswe, Kabaw, Pawlangyi, Ston, El Hierro = age 4; Waibon, Kintha; Ladagyi, Kyun Taw, Ston, El Hierro = age 3.

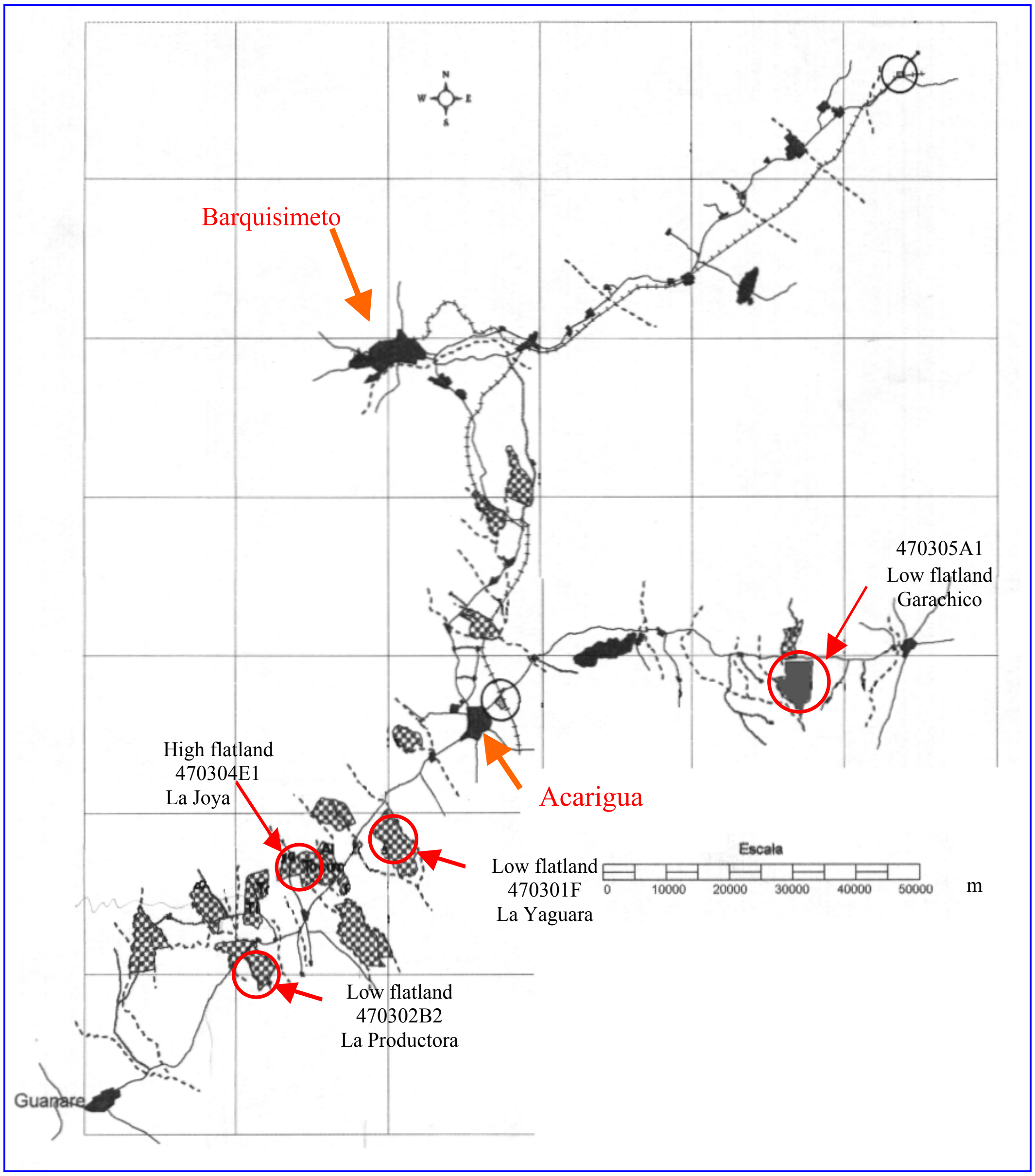

Figure 3-1. Location of tests at Smurfit's farms in Venezuela.

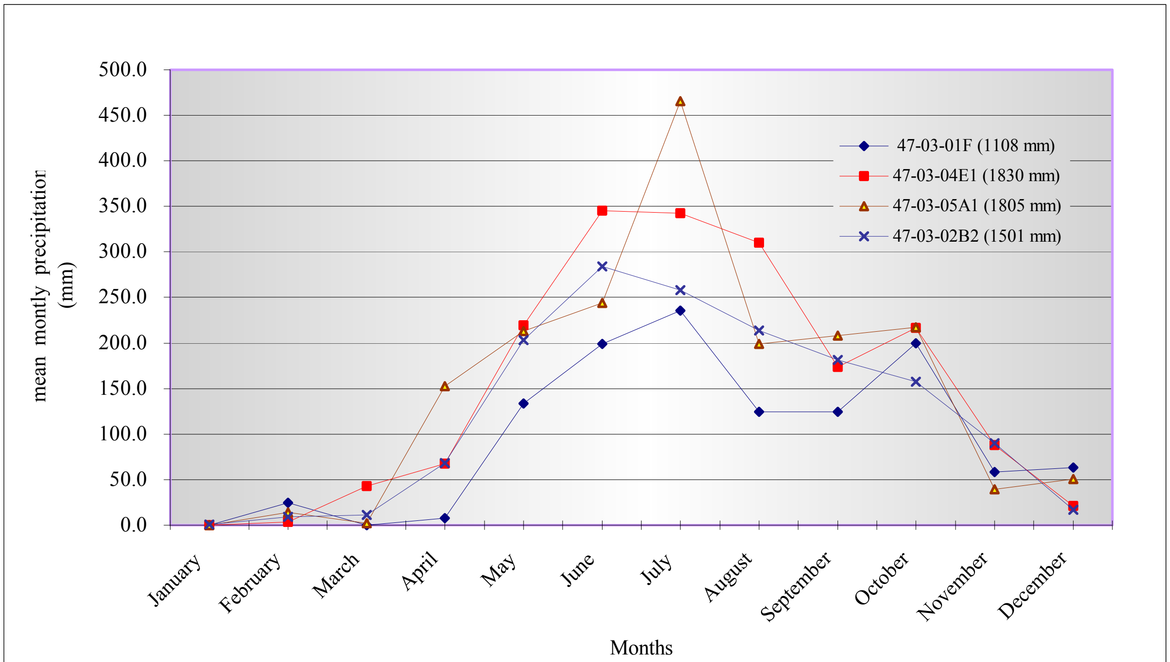

Figure 3-2. Annual distribution of precipitation in the four sites where the trials are established in Smurfit Cartón de Venezuela forests in Venezuela.

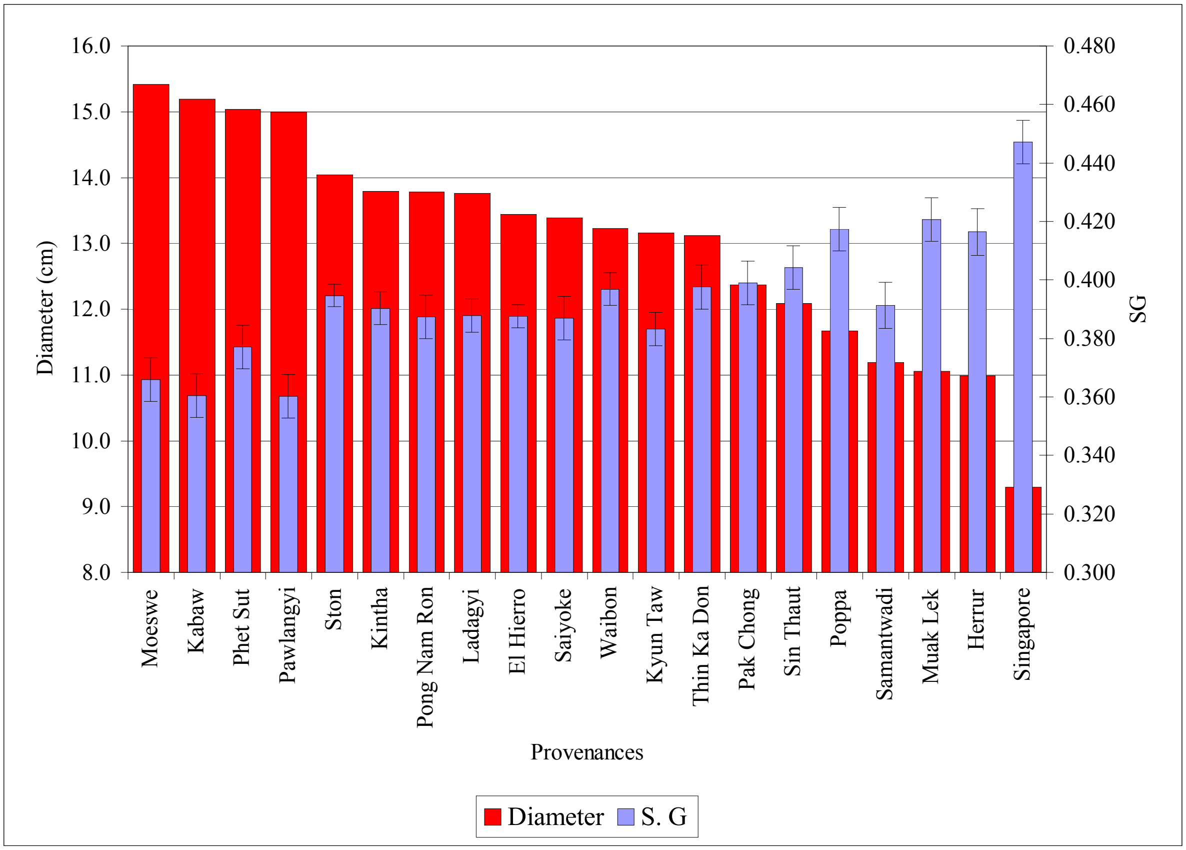

Figure 3-3. Phenotypic correlation between specific gravity and growth rate (DIB, diameter inside bark) among provenances for *Gmelina arborea* in Venezuela. DIB and SG measured on 30 dominant & co-dominant trees for each provenance.

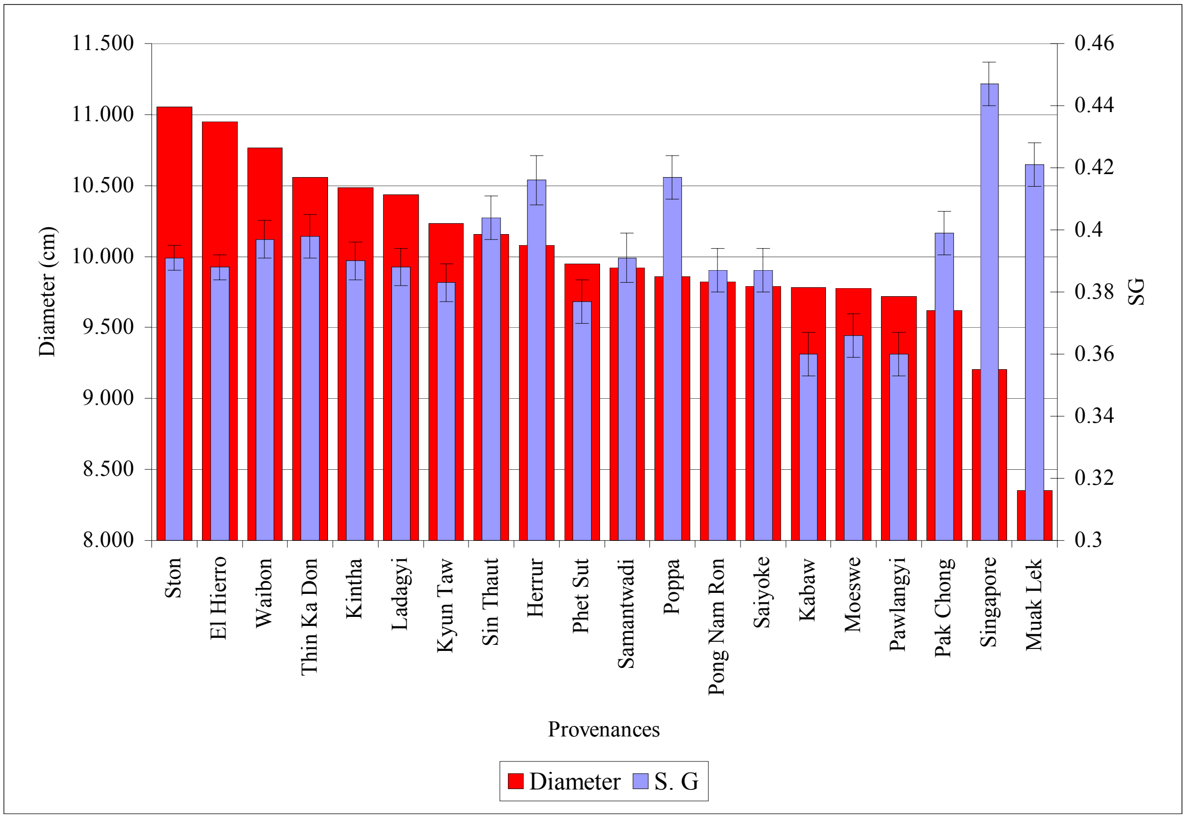

Figure 3-4. Phenotypic correlation between specific gravity and growth rate (DBH, diameter at breast height) among provenances of *Gmelina arborea* in Venezuela. DBH measured on all trees in the provenance trial, and SG measured on 30 dominant & co-dominant trees for each provenance.