INFLUENCE OF REGENERATION METHOD ON JUVENILE JACK PINE CLEAR WOOD STATIC BENDING PROPERTIES AND SPECIFIC GRAVITY

by

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ABSTRACT

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Keywords: jack pine, juvenile wood, modulus of elasticity, modulus of rupture, regeneration methods, specific gravity, vertical position.

The effects of regeneration method on three wood properties of jack pine, along different vertical positions, grown in northwestern Ontario were evaluated. A multi-staged nested sampling design was used to randomly select 12 trees, approximately 25 years of age, from four stands that were aerial seeded, Bräcke seeded, planted and post fire naturally regenerated. Within each tree, small clear wood samples (2 cm × 2 cm × 30 cm) were obtained from three vertical positions: 1 m, 2 m and 4 m, for the determination of static bending properties – modulus of elasticity (MOE) and modulus of rupture (MOR) – and specific gravity. Data analysis revealed that all three wood properties, MOE, MOR and specific gravity were not significantly different statistically ($\alpha \leq 0.05$) between regeneration methods. Further analysis into the influence of vertical positions revealed that MOE was not significantly different with height for all regeneration methods. In contrast, MOR was found to significantly vary between the bottom and top positions for the aerial seeded and naturally regenerated stands. With respect to specific gravity, a significant difference in vertical position was evident between the bottom and top bolts for the aerial seeded, Bräcke seeded and natural stands. These findings have revealed that wood properties of juvenile jack pine are quite variable no matter what regeneration method is implemented. Moreover, in the future there may be potential in dividing jack pine logs along the stem for various uses based on regeneration method.

The relationship between MOR and specific gravity, and MOE and specific gravity were investigated for all vertical positions and for each regeneration method. Linear and curvilinear equations were used to compare the variation in mechanical properties as a function of specific gravity. In all cases, a significant ($\alpha \leq 0.05$) positive relationship existed between specific gravity and MOR or MOE. The relationship between MOR and specific gravity is equally well explained by linear and curvilinear equations, whereas the relationship between MOE and specific gravity is better explained by a linear equation than by a curvilinear equation.

TABLE OF CONTENTS

TABLES

FIGURES

ACRYNOMS AND SYMBOLS

ANOVA	analysis of variance
dbh	diameter at breast height
FSP	fibre saturation point
kJ/m^3	kilojoules per metre cubed
MFA	microfibril angle
MOE	modulus of elasticity
MOR	modulus of rupture
MPa	mega Pascal
psi	pounds per square inch
r	correlation coefficient
R^2	coefficient of determination
S_1	inner wall layer of the secondary wall of a tracheid
S_2	middle wall layer of the secondary wall of a tracheid
S_3	outer wall layer of the secondary wall of a tracheid
$\parallel$	parallel
$\perp$	perpendicular

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1.0 INTRODUCTION

In Ontario, silvicultural practices are applied to jack pine to control establishment, structure and growth. Silvicultural practices have primarily focused on increasing jack pine tree growth and thus volume within shorter harvest rotations. This species is of great importance to the economy as it accounts for 33% of the total softwood volume harvested (OMNR 2008). Consequently, the influence of silvicultural practices on jack pine wood properties must be examined. This knowledge will assist forest managers in determining how to best manage and utilize jack pine timber for specific end products, such as dimensional lumber.

Researchers have addressed aspects of silvicultural practices on jack pine stem growth and quality. Past studies have focused on the effect of initial spacing on stem quality and growth (Godman and Cooley 1970; Janas and Brand 1988; Bell *et al.* 1990; Kang *et al.* 2004; Tong *et al.* 2005). Also, effects of precommercial thinning on stem quality and tree growth of jack pine have been investigated (Bella and DeFranceschi 1974; Vassov and Baker 1988; Morris *et al.* 1994; Tong *et al.* 2005; and Zhang *et al.* 2006). In general, these researchers have observed that wide initial spacings and wide spacings formed from precommercial thinning cause unfavourable characteristics. For example, thicker branches caused by wide heavy crowns, larger stem taper and lower mechanical property values.

The influence of these silvicultural practices on wood quality is critical; however, there is a lack of knowledge regarding the mechanical properties of jack pine when grown under various regeneration methods. The present study evaluates the effects of four contrasting regeneration methods, in northwestern Ontario, on jack pine wood mechanical and structural properties critical to describing the strength of dimensional lumber. The regeneration methods of interest were aerial seeding, direct seeding with a Bräcke scarifier (Bräcke seeding), planting and left to naturally regenerate following fire.

The first objective of this study was to compare modulus of elasticity (MOE) in static bending, modulus of rupture (MOR) in static bending and specific gravity between the four regeneration methods. It is hypothesized that MOE, MOR and specific gravity would be influenced by regeneration method since regeneration method has been demonstrated to influence jack pine tree form and growth (Janas and Brand 1988; Van Damme and McKee 1990). Also, researchers have demonstrated that wood properties decrease with increasing height (Spurr and Hsiung 1954; Okkonen *et al.* 1972; Markstrom *et al.* 1983; Duchesne 2006). Within this study, the second objective was to compare MOE and MOR in static bending as well as specific gravity at three vertical positions to determine if regeneration method influences vertical variation. Lastly, specific gravity – mechanical property relationships were evaluated within each regeneration method at three vertical positions.

The static bending tests were performed on small clear wood samples using a Tinius Olsen H10KT testing machine. The same specimens used for the static bending tests were used for the determination of specific gravity. Analysis of variance (ANOVA) models were used to compare MOE, MOR and specific gravity for four regeneration methods. Both linear and non-linear regression analyses were used to examine the relationships between MOE and specific gravity, and between MOR and specific gravity.

This thesis is organized into six sections. Section two reviews the literature related to jack pine characteristics and silvicultural practices, as well as descriptions of wood properties of interest and their variability. Section three describes the methodology for data collection and statistical analysis to address the research hypotheses. This is followed by section four, which presents the results and summaries of sample tree attributes for each regeneration method as well as the statistical analyses for the determination of treatment effects and mechanical property – MOE and MOR – specific gravity relationships. Section five discusses the major findings of this research and section six concludes with implications of these findings and recommends directions for future research.

2.0 LITERATURE REVIEW

2.1. JACK PINE

2.1.1. Characteristics

Jack pine is the most widely distributed pine species in Canada, primarily distributed throughout the Boreal Forest region (Cayford *et al.* 1967; Galloway 1986; Farrar 1995). In Ontario, jack pine represents 13% of the provincial growing stock (OMNR 2008). In comparison to other softwoods, it is ranked second to black spruce (*Picea mariana* (Mill.) BSP.), which represents 36% of the total provincial growing stock (OMNR 2008). Throughout its vast range, jack pine inhabits a variety of site conditions. It generally grows on level to gently rolling sand plains occupying numerous soil types ranging in texture from sands, sandy-loams, loams, clay-loams to very dry coarse and medium sands (Cayford *et al.* 1967; Rudolph and Laidly 1990). It has the ability to grow on poor sites, such as rock outcrops, shallow soils, and in some cases permafrost, but is rarely found on poorly drained soils (Cayford *et al.* 1967; Farrar 1995). In northwestern Ontario, jack pine is predominately found on deep, dry to fresh, coarse sandy soils and deep, fresh, fine sandy to coarse loamy soils (Bell 1991). Jack pine site indices gradually diminish as soil texture changes from very fine, to fine, and to medium sand (Bell 1991).

Jack pine is a pioneer species in succession and is, correspondingly, shade-intolerant. Fire has been recognized as an important ecological factor in the renewal of jack pine. Forest fires provide the intense heat required to open jack pine's serotinous cones to release seed. At the same time fire provides suitable seedbeds for germination by exposing mineral soil or decomposed organic matter (Cayford and McRae 1983). Following large disturbances, such as fire; jack pine forms even-aged pure or mixed stands. Densities of these stands depend on the available seed source and seedbed.

Common Boreal Forest associate tree species include trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* (Moench) Voss), black spruce and balsam fir (*Abies balsamea* (L.) Mill.) (Cayford *et al.* 1967). Jack pine stands are often found in drier and less fertile areas that are unfavourable for other tree species within its range (Rudolph and Laidly 1990).

The growth of jack pine is initially slow, but it shows rapid growth in the fourth and fifth years (Cayford *et al.* 1967; Rudolph and Laidly 1990). This rapid growth tends to decline after approximately 50 years (Bell 1991). On high quality sites, jack pine stands begin to deteriorate after 80 years while decline commences around 60 years on poor sites (Rudolph and Laidly 1990).

Generally, jack pine trees are small, reaching 20 m in height with 30 cm diameter at breast height (dbh). Trees that are open and forest grown exhibit different characteristics: open grown trees have wide, conical crowns with branches ascending or arching and a tapered stem while forest grown trees have short crowns with slender, straight stems having little taper (Farrar 1995).

2.1.2. Silvicultural Practices – Site regeneration

The Boreal Forest region is disturbance driven, whereby fire, insects and wind create landscapes comprised mainly of even-aged forest stands. These stands are dominated by species that have adapted to these conditions (OMNR 1997). In Ontario, jack pine is harvested using the clearcut silviculture system where, depending on site conditions, conventional or single seed-tree harvesting methods are applied (OMNR 1997). This system is used for jack pine because its silvics requires a harvest method that is similar to the disturbance pattern of fire (Galloway 1986). Following harvesting, a form of site preparation is often applied for natural or artificial regeneration (Davison 1984; Kennedy 1984).

2.1.2.1. Site Preparation

Site preparation is the disturbance of the forest floor and top soil to create suitable conditions for natural or artificial regeneration. In northwestern Ontario, site preparation methods for jack pine include prescribed fire, chemical and mechanical means, or a combination of these methods.

In Ontario, mechanical site preparation began in the 1950s with the use of bulldozers that had attachments, such as rakes. Since then, equipment has advanced from simple attachments to powered equipment, which was first introduced in the 1980s (Ryans and Sutherland 2001). In northwestern Ontario, jack pine has been regenerated on sites that have been prepared using TTS discs, barrels and chains, straight blades, Bräcke cultivators, brush cut plows, root rakes, Rome discs, pads and chains, Young's teeth and Leno discs (Galloway 1986).

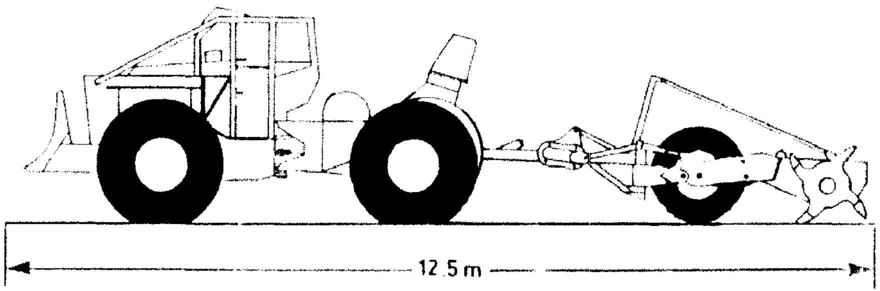
2.1.2.2. Regeneration

Regeneration of jack pine occurs naturally from seed and artificially from seeding and planting. Jack pine is a good candidate for natural regeneration because its serotinous cones provide an abundant seed supply, its germination characteristics are suitable and its initial stage of growth is rapid. Whether a stand is suitable to regenerate naturally depends on seed source (Groot *et al.* 2001). It was noted by Galloway (1986) that in Ontario, natural regeneration of jack pine accounted for only 6% of the jack pine working group. It currently accounts for a small portion of jack pine regeneration.

Artificially, jack pine is regenerated by direct seeding or planting. Direct seeding is the systematic sowing of seeds by manual or mechanical means. Within Ontario, direct seeding tends to be classified into two distinct categories: broadcast and precision (OMNR 1997). Broadcast seeding is the sowing of seeds more evenly over a given area, such as aerial seeding, whereas precision seeding involves more control over the location of where the seeds will be sown, such as spot seeding.

Mechanically, seed can be applied to a site simultaneously with site preparation. This is done either through spot seeding, also known as patch seeding, and row seeding (Fleming *et al.* 2001). Introduced to Ontario in the 1970s, the Swedish built scalper-seeder, the "Bräckekultivatorn" also known as the Bräcke patch scarifier-seeder is an apparatus that is attached to a prime mover that creates scarified patches distributed two metres apart (Figure 1) (Coates and Haeussler 1987). The Bräcke patch scarifier-seeder creates a microsite and drops seed in one pass by overturning the humus layer and mineral cap and delivering seed (Parker 1972). The number of seeds dropped ranges from 3 to 15. Row seeding involves dropping seeds simultaneously along furrows as they are created. In the 1960s and 1970s, prototypes of these machines were developed in Ontario. Both patch seeding and row seeding have been used successfully to regenerate jack pine (Fleming *et al.* 2001).

a)



b)

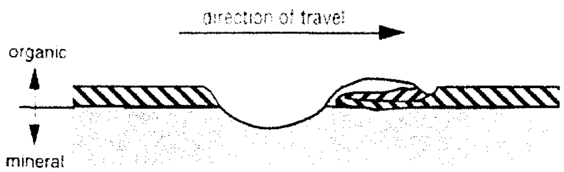


Figure 1. a) Illustration of the standard Bräcke configuration (Van Damme *et al.* 1988); b) cross-sectional view of a Bräcke scalp (Sutherland and Foreman 1995).

In addition to seeding, jack pine has been regenerated through planting of bareroot and container stock. Presently, the latter method is predominately practiced. The planting standard is 1.8 × 1.8 m with approximately 2,500 stems/ha (Bell *et al.* 1990).

Exact statistics of the amount of area regenerated following the above methods for jack pine for northwestern Ontario are not available; however, an overall trend for Ontario can be provided. Aerial seeding is the predominate method of regeneration followed by planting, precision seeding and natural regeneration [S. Duckett (pers. comm., June 2, 2008)].

2.1.3. Wood Uses, Description and Properties

Uses of jack pine timber include pulpwood and constructional material such as framing, sheathing, scaffolding and interior woodwork. When treated with preservatives it is used as railway ties, posts and poles (Perem *et al.* 1981). In the northwest and north central region of Ontario 70% of harvested jack pine timber is converted to pulpwood while the remainder is used for sawlogs, ties or poles (Bell *et al.* 1990).

The sapwood of jack pine is nearly white in colour with light brown heartwood; formation of heartwood is often delayed until 40 to 50 years of age. The wood has a resinous odour, with a medium texture that has somewhat of an uneven grain. It is moderately heavy and soft in texture with an approximate green and oven-dry specific gravity of 0.40 and 0.45, respectively. The growth rings are distinct with an abrupt transition from earlywood to latewood delineated by a dark band of latewood cells that are much denser. Both the earlywood and latewood zones are variable in width (Panshin and de Zeeuw 1980). Various mechanical properties of jack pine are presented and compared with other species in Table 1. Overall, jack pine is characterized as moderate in strength.

2.2. WOOD QUALITY

There are many ways in which the quality of wood is measured. The method chosen is dependent upon the specific end use of a given piece of wood. If wood is to be converted into pulp for paper production, such characteristics as tracheid length and chemical composition are of key interest. If furniture is to be produced, grain characteristics are important; for example, straight grain maple is aesthetically more favourable than maple containing knots. In the case of products requiring timber of high strength and/or flexibility, such as structural lumber for housing, mechanical properties

Table 1. Physical and mechanical properties of jack pine (Source: Porter 1981).

Species	Moisture Condition	Relative Density[a]	MOR[b] (MPa)	MOE[c] (MPa)	Compression ∥ to Grain (MPa)	Compression ⊥ to Grain (MPa)	Shear Strength (MPa)
Eastern white pine	green	0.36	35.4	8140	17.9	1.64	4.28
	air-dry	0.37	65.0	9380	36.2	3.39	6.10
Jack pine	green	0.42	43.5	8070	20.3	2.31	5.67
	air-dry	0.44	77.9	10200	40.5	5.70	8.23
Red pine	green	0.39	34.5	7380	16.3	1.94	4.90
	air-dry	0.40	69.7	9450	37.9	4.96	7.50
Black Spruce	green	0.41	40.5	9100	19.0	2.07	5.49
	air-dry	0.43	78.3	10400	41.5	4.25	8.65
White Spruce	green	0.35	35.2	7930	17.0	1.69	4.62
	air-dry	0.37	62.7	9930	36.9	3.45	6.79

[a]Also known as specific gravity; green is basic and air-dry is nominal specific gravity
[b]Modulus of rupture
[c]Modulus of elasticity

determine end use suitability. When discussing wood quality, it is of great importance to specify what specific measures one is referring to. Within the context of this study, specific gravity, MOE and MOR in static bending were examined from jack pine trees regenerated by different methods to determine if regeneration method influences jack pine wood quality. These methods were aerial seeding, Bräcke seeding, planting and naturally regenerated from fire.

2.2.1. Specific Gravity

The amount of wood substance present within a given volume of wood is expressed by specific gravity or wood density. Specific gravity, also referred to as relative density, is the ratio of the density of the wood to the density of water at a specified reference temperature. Foresters are interested in specific gravity as it is highly correlated with final product yield and quality. Also, it is the property most frequently used for standard comparison between species or products. Specific gravity is based on oven-dry weight and volume at any given moisture content (Simpson and TenWolde 1999). The value of specific gravity depends on the moisture content at which the volume is determined. Typical values are based on oven-dry condition, nominal (12% moisture content) condition or green condition (basic specific gravity) when wood is above the fibre saturation point (FSP) (Table 2).

Table 2. Basic, nominal and oven-dry specific gravity values for various Canadian tree species (Source: Porter 1981).

Species	Specific Gravity		
	Basic	Nominal	Oven-dry
Eastern white cedar	0.30	0.30	0.31
Balsam fir	0.34	0.35	0.37
White spruce	0.35	0.37	0.39
Eastern white pine	0.36	0.37	0.38
Red pine	0.39	0.40	0.42
Lodgepole pine	0.40	0.41	0.46
Black spruce	0.41	0.43	0.44
Jack pine	0.42	0.44	0.45
Tamarack	0.48	0.51	0.54

In addition to moisture content, other natural factors influencing specific gravity have been documented. Longitudinal tracheids are the principal cell type within softwoods constituting approximately 90 to 94% of total wood volume (Mark 1967; Panshin and de Zeeuw 1980). Therefore, tracheids are primarily responsible for the specific gravity of a given piece of wood. Structurally, a tracheid is comprised of a primary and secondary wall with the later subdivided into three layers denoted by Bailey and Kerr (1934) as S_1, S_2 and S_3 (Mark 1967; Cave 1969; Panshin and de Zeeuw 1980). A middle lamella lies between the primary walls of adjacent cells (Figure 2). The S_2 layer is the thickest cell wall layer constituting the bulk of the cell wall (Panshin and de Zeeuw 1980). Consequently, the S_2 layer highly influences wood properties.

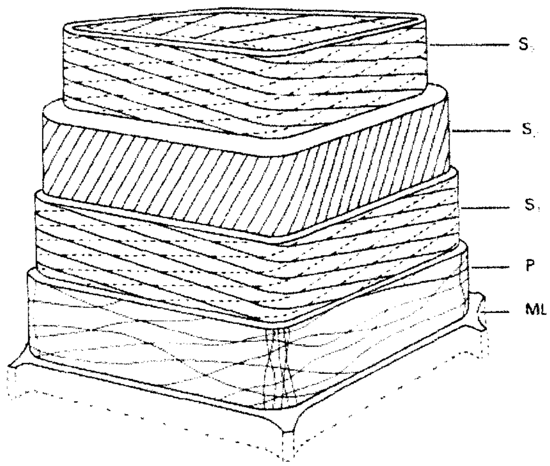


Figure 2. A three dimensional illustration of cell wall layers and associated microfibril angles. ML- middle lamella; P – primary wall; S – secondary wall subdivided into corresponding layers (Wilson and White 1980).

Wood substance is comprised of structural (cellulose, hemicellulose and lignin) and non-structural (extractives) components. Cellulose, hemicellulose and lignin contribute 40 to 50%, 35 to 50% and 15 to 35% of the dry weight of cell wall substance, respectively (Panshin and de Zeeuw 1980). As cellulose constitutes the greatest portion of oven-dried material, it is largely responsible for the given properties of wood (Panshin and de Zeeuw 1980). The amount of extractives within a piece of wood ranges from 1 to 20% or more based on oven-dry weight (Tsoumis 1991). Extractives add weight to wood samples, which in turn increases specific gravity. For example, Taras and Saucier (1967) found a 6.0 to 7.5% overestimation of specific gravity for four major southern pine species when unextracted increment cores were analyzed. Also, Keith (1969) found a significant difference between samples of extracted and unextracted red pine (*Pinus resinosa* Ait.) specific gravities with averages of 0.337 and 0.349, respectively. Extractive removal is generally not carried out for young trees; values may be slightly higher but all values will be slightly inflated by approximately the same amount (Zobel and van Buijtenen 1989).

Anatomically, specific gravity is influenced by cell size, thickness and proportion of latewood (Zobel and Talbert 1984). If two cells of the same type have the same cell wall thickness, but one cell is larger, the larger cell will have a lower specific gravity (Figure 3). Similarly, if two cells of the same size have varying cell wall thickness, the cell with the thicker cell wall will have a higher specific gravity.

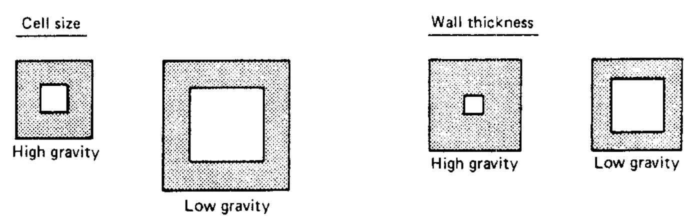


Figure 3. Illustrations of the effects of cell size and wall thickness on specific gravity (Zobel and Talbert 1984).

Compression wood is a specialized tissue produced by a tree to correct a leaning stem into a vertical position or to maintain branch orientation. Compression wood is formed by the cambium, but it is a localized phenomenon (Westing 1965). Cells, primarily tracheids, comprised of compression wood are characteristically different than cells within normal wood. They differ from normal wood in cell length and thickness, microfibril angle (MFA), chemical composition and physical and mechanical properties

(Westing 1965; Butterfield and Meylan 1980; Timell 1986; Dhubhain *et al.* 1988). For example, the length of normal wood tracheids of black spruce, jack pine and eastern white cedar (*Thuja occidentalis* L.) were found to be 1.91 μm, 2.16 μm and 2.56 μm while the length of compression wood tracheids were much less at 1.78 μm, 1.67 μm and 1.81 μm, respectively (Timell 1986). Chemically, compression wood is comprised of a greater amount of lignin and hemicellulose with cellulose content approximately 10% lower than normal wood (Panshin and de Zeeuw 1980).

In addition to changes in cell length and chemical composition, the secondary wall of compression wood tracheids differ. The S_3 layer found in normal wood is lacking and under mild conditions, a rudimentary S_3 layer may be present (Wardrop and Davies 1964; Westing 1965; Panshin and de Zeeuw1980; Timell 1986; Singh *et al.* 2003). Also, the S_1 and S_2 layers become thicker with the S_2 layer often developing deep helical fissures. The S_2 layer contains an inner portion containing fissures and an outer, solid region containing more lignin and less cellulose (Panshin and de Zeeuw 1980; Timell 1986).

The variation in structure between normal cells and compression cells results in a variation in specific gravity. Compression wood has a higher specific gravity than normal wood because it is comprised of short tracheids with thicker cell walls (Timell 1986). Seth and Jain (1978) found a definite positive correlation for blue pine (*Pinus wallichiana* A.B. Jackson) between specific gravity and percentage of compression wood with a coefficient of determination (R^2) of approximately 0.84. Comparisons of compression and normal wood specific gravity values for some species are presented in Table 3.

Table 3. Comparisons of specific gravity between compression and normal wood for various coniferous species (Panshin and de Zeeuw 1980).

Species	Normal Wood		Compression Wood	
	Moisture Content (%)	Specific Gravity	Moisture Content (%)	Specific Gravity
Ponderosa pine	133	0.354	87	0.467
	12.0	0.372	12.6	0.499
Redwood	113.7	0.380	102	0.506
	9.9	0.380	10.5	0.510
Douglas fir	58.3	0.428	43.4	0.513
	11.5	0.459	12.1	0.527

Wood properties may be affected by any factor that changes the growth pattern of the tree (Zobel and van Bujitenen 1989). Consequently, the environment in which a tree grows influences the quality of wood it produces. Such environmental factors include site, soil, climate, growing space and moisture. In the case of site influences, Zobel and van Buijtenen (1989) conclude that site is not very suitable for wood quality predictions as it is a combination of many factors that by themselves or through interactions with other factors influence wood quality. Jayne (1958) concludes that specific environmental factors that comprise a site should be studied when determining the effect of site on specific gravity.

Wilde *et al.* (1951) demonstrated that soil type influences jack pine specific gravity (Table 4). In addition to soil type, soil moisture has been found to influence the transition of earlywood to latewood (Kraus and Spurr 1961). The literature outlines that latewood proportion is a major factor that influences specific gravity (Panshin and de Zeeuw 1980; Zobel and van Buijtenen 1989; Tsoumis 1991). Latewood is greater in specific gravity than earlywood because of thicker cell walls. Latewood has also been documented to be influenced by day length (Larson 1960). Shorter day lengths produce more latewood like cells.

Table 4. Specific gravity of jack pine at two height levels grown on five different soil types (Wilde *et al.* 1951).

Soil Type	Specific Gravity	
	5 feet above ground line	25 feet above ground line
Aeolian sand	0.421	0.384
Melanized sand	0.413	0.382
Podzolic sand	0.399	0.369
Gley-podzolic sand	0.402	0.376
Moss peat	0.436	0.361

Regional variation in specific gravity has been demonstrated in loblolly pine by Zobel and McElwee (1958), for shortleaf pine (*Pinus palustris* P. Mill) by Gilmore (1963) and for jack pine by Paul (1963). It appears that for loblolly pine and shortleaf pine, as one moves inland, specific gravity decreases.

Other environmental factors, such as light availability, temperature, elevation and slope, may influence specific gravity as these factors may influence tree growth. In addition, it has been documented that specific gravity is strongly inherited (Zobel and Talbert 1984). Individual tree specific gravity values are quite variable, which is thought to be largely due to genetics (Megraw 1985). In one study of jack pine Villeneuve *et al.* (1987) found a narrow sense heritability range of 0.49 to 0.93 for specific gravity on an individual tree basis and a range of 0.55 to 0.73 on a family basis. Also, Okwuagwu and Guries (1980) found a narrow sense heritability estimate of 0.72 for jack pine. As these values are close to the index of 1, specific gravity of jack pine can be improved *via* selection. Currently in Ontario tree improvement studies focusing on jack pine specific gravity are being implemented [P. Charrette (pers. comm., July 28, 2008)].

From the above descriptions, it is apparent that tree growth is affected by a vast array of factors. How trees respond to these factors will influence specific gravity.

2.2.1.1. Variability of Specific Gravity

Within the literature, it has been documented that specific gravity varies within a growth ring (Panshin and de Zeeuw 1980; Megraw 1985; Tsoumis 1991), radially from pith to bark (Spurr and Hsiung 1954; Megraw 1985; Zobel and van Buijtenen 1989) and vertically from stump to top log (Spurr and Hsiung 1954; Okkonen *et al.* 1972; Panshin and de Zeeuw 1980).

A growth ring is comprised of earlywood and latewood cells. Latewood cells have thicker walls and are generally smaller in tangential and radial diameters compared to earlywood cells (Panshin and de Zeeuw 1980). This anatomical difference results in the latewood portion having a higher specific gravity than the earlywood portion (Tsoumis 1991). Megraw (1985) states that for loblolly pine, within an individual growth ring, minimum specific gravity values are approximately 0.25, while maximum values reach 0.8 to 0.9. This wide variation is mainly attributed to differing earlywood and latewood characteristics.

Radially, specific gravity of hard pines, which jack pine is categorized as, has been observed to rapidly increase from the pith followed by a period of levelling off with over-mature trees often exhibiting a reduction towards the bark (Zobel and van Buijtenen 1989). In a study of jack pine specific gravity, Spurr and Hsiung (1954) found the pattern of increasing specific gravity from pith to bark with the inner five rings at 0.365 and the outermost five rings at 0.410, these values were both obtained at a height of one foot above ground.

The vertical pattern of variation involves the decrease of specific gravity with height. This pattern is evident in Table 4 and Table 5 for jack pine. Okkonen *et al.* (1972) explain that the trend of decreasing specific gravity with height is attributed to the increase in percentage and density of latewood with age from pith to bark. Wood

Table 5. Specific gravity of jack pine at various radial and height positions (Spurr and Hsiung 1954).

Growth Rings (age)	Height Above Ground (feet)			
	1	6	11	Mean
26-30	0.410	0.389	0.368	0.389
21-25	0.399	0.376	0.363	0.379
16-20	0.389	0.363	0.344	0.365
11-15	0.384	0.346		0.365
6-10	0.365			0.365
Mean	0.389	0.369	0.358	0.375

produced higher in the stem exhibits more earlywood characteristics than latewood characteristics, which become more prominent at the base as a tree ages.

The variability that exists radially from pith to bark and vertically from stump to top log is explained *via* the concept of juvenile and mature wood. Over time, it has been established that the age of the cambium determines the characteristics of wood (Rendle 1959; Larson 1969; Zobel and van Buijtenen 1989; and Zobel and Sprague 1998). In general, a young cambium produces juvenile wood and an older cambium produces mature wood. Wood properties vary between these two zones (Figure 4). Juvenile wood properties are characterized by thinner cell walls, larger lumen spaces, larger MFAs, lower specific gravity, higher compression wood content, lower lignin content, higher cellulose content, lower strength, lower transverse shrinkage, higher longitudinal shrinkage and a lower percentage of latewood (Bendsten 1978; Zobel and van Buijtenen 1989). The demarcation between juvenile and mature wood is not distinct with all properties changing at once. Zobel and Sprague (1998) explain as ring number

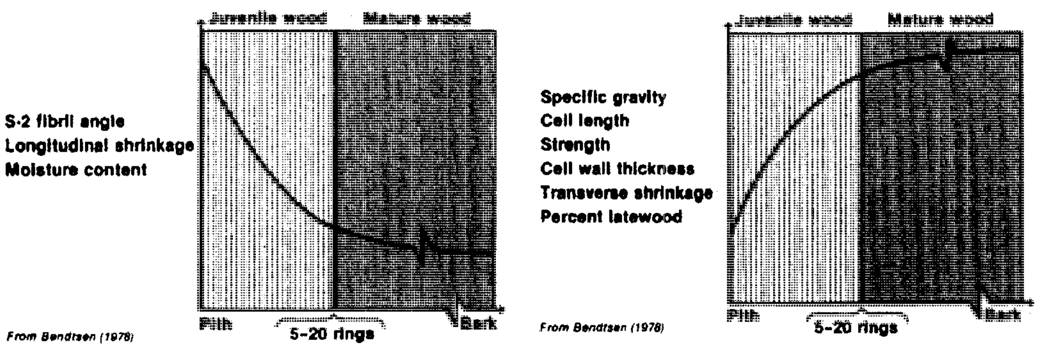


Figure 4. Schematic diagrams of wood property changes from juvenile to mature wood (Bowyer *et al.* 2003).

increases from pith, an area of transition wood exists where changes in properties become less than those changes found within juvenile wood. Furthermore, the juvenile zone is dependent upon what characteristics are used to define the area. They conclude that the most common characteristic used to differentiate between juvenile and mature wood is specific gravity, but other characteristics, such as cell length, are used.

A schematic diagram of juvenile and mature wood within a tree stem is presented in Figure 5. The top portion of the tree will always be comprised of juvenile wood so long as height growth continues (Rendle 1959). This occurs because the tree top always contains a young cambium (Zobel and van Buijtenen 1989). The shape of the juvenile wood has been described as cylindrical (Rendle 1959) and conical (Yang *et al.* 1986; Feng 2001).

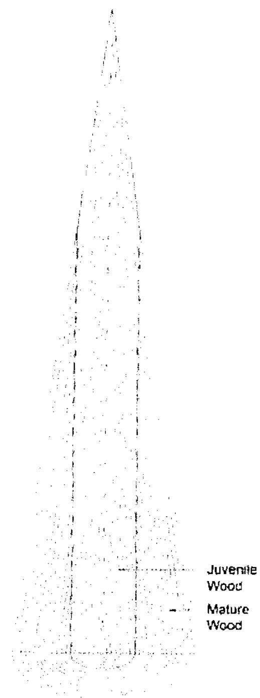


Figure 5. The distribution of juvenile and mature wood in a longitudinal section of a 20 year old tree. In this example the juvenile core comprises seven years with the top being entirely juvenile. A gradual transition from juvenile to mature wood occurs from top to base of the tree (Rendle 1959).

Most researchers believe that juvenile wood extends from 5 to 20 growth rings from the pith depending on species (Bendtsen 1978; Zobel and van Buijtenen 1989). For example, Yang (1994) found that a plantation of black and white spruce established in 1951 contained 14 to 16 rings and 12 to 16 rings, respectively, of juvenile wood depending on spacing. Bodie (1988) found that based on specific gravity and tracheid length, the juvenile wood of 12 planted jack pine trees 34 years of age extend on average 18.5 and 12.6 years from pith. Bendtsen (1978) concluded that the size of the juvenile core depends upon growth rate and the proportion of juvenile wood depends on tree age.

If a tree initially has a fast growth rate, there will be a larger core of juvenile wood versus a tree with constant slow growth rate. The juvenile proportion of wood decreases with tree age because the relative amount of juvenile to mature wood declines (Figure 6). For example, in one study, 15 year old loblolly pines were comprised of 85% juvenile wood, while 40 year old loblolly pines were comprised of 19% juvenile wood (Zobel and Sprague 1998).

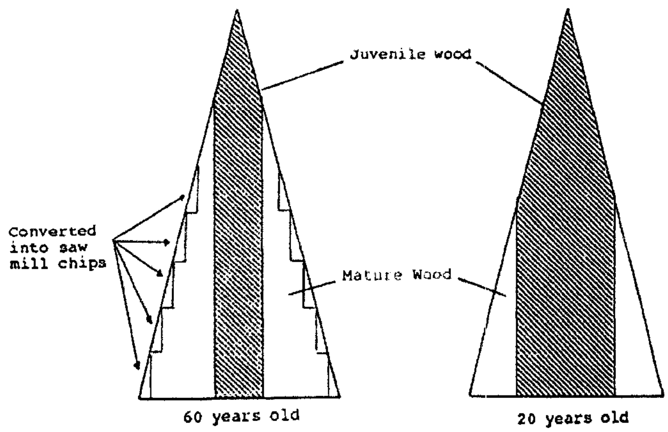


Figure 6. An illustration demonstrating the varying portions of juvenile wood with respect to tree age and the associated amount of mature wood (Zobel and Sprague 1998).

There is a wide array of literature on the influence of growth rate on specific gravity, including Spurr and Hsiung (1954); McMillan (1968); Yao (1970); Taylor and Burton (1982); Zobel and van Buijtenen (1989); Zhang (1995); and Kärenlampi and Riekkinen (2004). During the 1960's and 1970's there was much debate and controversy over the influence of growth rate on specific gravity. There are two opposing views found in the early stages of research on this subject: 1) slow growth results in high specific gravity while fast growth results in low specific gravity and 2) growth rate has little or no relationship to specific gravity for the hard pines (Zobel and

Talbert 1984). For the hard pines the most commonly accepted view is the latter: "it appears that for the hard pines there is generally little or no relationship between wood specific gravity and growth rate of the individual tree" (Zobel and Talbert 1984). For red pine, Larocque and Marshall (1995) did not observe a consistent relationship between ring relative density and growth rate. At young ages they found a weak relationship, at slightly older ages they found a relatively good relationship and then at older ages the relationship began to decrease.

Bendsten (1978) states that researchers who have studied the available literature in depth "generally conclude that low specific gravity and 'poor' fibre characteristics are mostly related to age of the wood from tree centre, not growth rate." The confusion of growth rate effects on specific gravity often exists because juvenile wood is close to the pith and is characterized by wide growth rings. In contrast, mature wood is found near the bark and is characterized by narrow growth rings (Saranpää 2004). Rings of wide width formed by rapid growth after a certain ring age can contain dense wood (Rendle and Phillips 1958).

Overall specific gravity of hard pines has been found to increase with distance from pith and decrease with distance from stump due to the characteristics of juvenile and mature wood. Compared to mature wood, juvenile wood is lower in specific gravity because it contains a greater portion of earlywood than latewood and has thinner cell walls (Zobel and Sprague 1998).

2.2.2. Modulus of Elasticity and Modulus of Rupture

Wood has various strength properties; consequently, when describing the strength of wood it must be qualified in some way (Desch and Dinwoodie 1981).

Wood is prevalently subject to forces causing it to bend, for example in beams, floor and ceiling joists, and tabletops. To test the ability of a wood to resist slowly applied stresses, static bending tests are performed (Wakefield 1957). A static bending test slowly applies a force to a member of wood causing it to bend, which mimics the stresses that are subjected to beams and joists. Within this study, wood strength of jack pine is based on MOE and MOR in static bending. These tests can be carried out in a laboratory on small clear wood specimens or on service size lumber; this study follows the former method. In both cases there are testing standards outlined by organizations such as the International Standards Organization and the American Society for Testing and Materials.

Strength, when the term is applied to a material such as wood, is defined as "... the ability of the material to resist external forces or loads tending to change its size and alter its shape" (Desch and Dinwoodie 1981). As a material is stressed, internal forces trying to resist the stress cause the material to deform and change shape; the amount of change caused by the stress is referred to as strain. A linear relationship exists between stress and strain up to a certain point referred to as the proportional limit (Hooke's Law). Below the proportional limit, when a stress is removed the induced strain is recovered while beyond this limit the stress induced deformation is unrecoverable (Figure 7) (Panshin and de Zeeuw 1980; Bowyer *et al.* 2003). MOE in static bending is the ratio of stress to strain within the proportional limit. It is the variable used to describe the flexibility or stiffness of a wood; the greater the MOE the stiffer the member, the lower the MOE, the more flexible (Desch and Dinwoodie 1981). When the strain limit has been reached, failure occurs resulting in the rupturing of the member. MOR in static

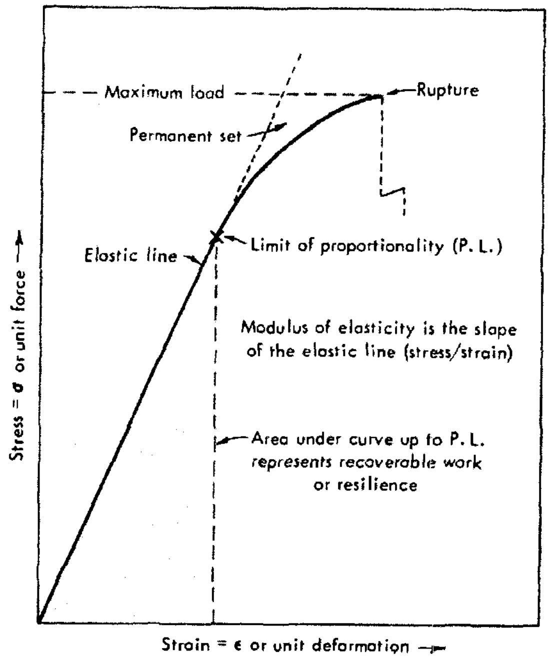


Figure 7. Typical stress-strain diagram for static bending to failure (Panshin and de Zeeuw 1980).

bending measures the force required to cause a member to fail (Desch and Dinwoodie 1981; Tsoumis 1991). Some of the strength variables for various coniferous Canadian tree species determined from static bending are presented in Table 6.

In general, moisture content of wood is inversely related to strength and elastic properties below the FSP (Table 6). The increase of strength with decreasing moisture content is related to the bonding of the cells microfibrils. As moisture is removed from wood below the FSP, the bonds between the cellulose structures strengthen (Stamm 1964; Tsoumis 1991; Bowyer *et al.* 2003). Also, shrinkage occurs with the removal of water below the FSP causing there to be more cell substance within a given area.

As previously mentioned, the principle cell type within softwoods is the tracheid. The cell wall layers of a tracheid are comprised of microfibrils that are very long chains

Table 6. Strength variables determined in static bending for some Canadian tree species (Jessome 1977).

Species	Moisture Condition[a]	Static Bending					
		Stress at Proportional Limit (MPa)	MOR[b] (MPa)	MOE[c] (MPa)	Work in Bending (kJ/m^3)		
					To Proportional Limit	To Maximum Load	Total
Jack pine	green	23.8	43.5	8070	4.1	49	170.0
	air-dry	48.8	77.9	10200	13.7	68	109.0
Red pine	green	19.9	34.5	7380	3.1	41	174.0
	air-dry	40.6	69.7	9450	9.9	67	111.0
Eastern white pine	green	20.7	35.4	8140	3.0	37	88.3
	air-dry	41.5	65.0	9380	10.3	61	84.1
Black spruce	green	21.3	40.5	9100	2.9	58	177.0
	air-dry	44.6	78.3	10400	11.3	63	117.0
White spruce	green	19.2	35.2	7930	2.7	41	109.0
	air-dry	36.7	62.7	9930	7.7	50	84.1

[a]Green - mean for unseasoned condition, air-dry - mean for air-dry condition adjusted to 12 per cent moisture content
[b]Modulus of rupture
[c]Modulus of elasticity

of aggregated polysaccharides. The cell becomes rigid with the deposition of lignin and extractives. Within the cell wall, microfibrils are aggregated and appear to be arranged in sheets (lamellae) that lie parallel to the wall surface (Panshin and de Zeeuw 1980). The lamellae are helically arranged with orientation dependent upon location within the cell wall (Barnett and Bonham 2004; Hisashi and Funada 2005). Within the primary wall the microfibrils are loosely and irregularly arranged while the secondary wall layers are more orderly (Panshin and de Zeeuw 1980; Megraw 1985). Within the thin S_1 layer the lamellae follow helical patterns of both the “S” left-handed and “Z” right-handed orientation (Figure 2) (Mark 1967; Panshin and de Zeeuw 1980; Barnett and Bonham

2004). The same pattern has been demonstrated in the S_3 layer (Barnett and Bonham 2004; Hisashi and Funada 2005). The S_2 layer is distinctly different in that it only contains helical windings in the "Z" orientation (Panshin and de Zeeuw 1980; Barnett and Bonham 2004; Hisashi and Funada 2005).

The angle between the long axis of a tracheid and the microfibrils as they wind around the cell is termed the microfibril angle (MFA). In general, the S_1 and S_3 layers have a flat microfibril orientation to the cell axis giving way to large MFAs while they are much more steeply aligned in the S_2 layer resulting in smaller MFAs (Barnett and Bonham 2004). Panshin and de Zeeuw (1980) found in general, the average MFA to be 50° to 70°, 10° to 30°, and 60° to 90° for the S_1, S_2 and S_3 layers, respectively.

Several investigators have determined that mechanical properties are influenced by the S_2 MFA (Cave 1969; Meylan and Probine 1969; Mark and Gillis 1973; Tsehaye *et al.* 1998; Booker *et al.* 1997; Cave and Walker 1998; Deresse *et al.* 2003). In a study of red pine static bending, Kraemer (1950) found high negative correlation coefficients between MFA and MOR ($r = -0.782$) and MOE ($r = -0.783$). Similarly, Tsehaye *et al.* (1998) found a high correlation between stiffness in static bending and MFA for radiata pine (*Pinus radiata* D. Don), $r = -0.913$. Cave and Walker (1994) emphasize that "there can be no doubt that microfibril angle plays a major role in determining the stiffness of juvenile wood in fast-grown pine plantations". They further refute that the MFA in the S_2 layer of tracheids is the only known physical characteristic of wood capable of causing large changes in stiffness.

In addition to MFA, compression wood influences strength properties. Panshin and de Zeeuw (1980) state that under green conditions compression wood is stronger than normal wood in bending, compression and toughness; however, under dry conditions normal wood is stronger. They further describe that compression wood is higher in specific gravity due to an increase in cell wall thickness, but based on equal amounts of cell wall material compression wood is still inferior in strength and lower in elastic properties. They explain that these reductions in mechanical properties are due to a reduction in cellulose content, coupled with high MFA angles and spiral checking. Furthermore, lignin content is greater in compression wood and cell shape is more circular thus reducing cell to cell contact.

Dhubhain *et al.* (1988) performed a preliminary study on the influence of compression wood on MOE and MOR in static bending for machine graded structurally sized planks of Sitka spruce (*Picea sitchensis* (Bong.) Carr.). They found that MOE decreases as the compression wood content increases while MOR was not influenced. However, during MOR testing they observed that 70% of the planks containing greater than 10% compression wood ruptured in a brash manner.

Overall, when utilizing wood that contains compression wood there are many drawbacks: extensive longitudinal shrinkage, brash rupture, extreme hardness, and low ability to increase strength as it dries (Timell 1986).

Specific gravity is used as an index for the strength of wood (Panshin de Zeeuw 1980; Porter 1981; Tsoumis 1991; Desch and Dinwoodie 1996; Green *et al.* 1999; Bowyer *et al.* 2003). Panshin and de Zeeuw (1980) state that in general specific gravity and mechanical properties are related in the form $S = K(G)^n$, where S is the strength property, K is a constant, G is the specific gravity and n is an exponent that defines the shape of the curve. Green *et al.* (1999) present curvilinear functions of the relationship of specific gravity to various mechanical properties based on averages of 43 softwoods and 66 hardwoods. However, they suggest that when analyzing an individual species a linear relationship should be investigated.

In the majority of cases, the relationships between MOE and specific gravity and MOR and specific gravity have been investigated following a linear method (Pearson and Gilmore 1971; Bendsten and Senft 1986; Deresse *et al.* 2003; Mackes *et al.* 2005). In all cases a positive relationship was observed. Unlike these researchers, Mackes *et al.* 2005 observed a very low adjusted R^2 values for MOE and MOR. They suggest that relatively high percentages of abnormal wood (in the form of juvenile or compression wood) is the cause of the deviation from the generally accepted relationship between specific gravity and mechanical properties of larger, slower grown trees.

Unlike these studies, Zhang (1997) investigated the influence of specific gravity on MOE and MOR in static bending using both linear and curvilinear regressions. He compared the two methods in terms of the goodness at predicting mechanical properties through specific gravity. The author found that MOR is almost linearly related to specific gravity, whereas MOE was poorly related linearly to specific gravity. Overall, based on the coefficients of determination, the author concludes that at a species level the curvilinear equation is better at predicting mechanical properties.

2.2.2.1. Variability of Modulus of Elasticity and Modulus of Rupture

It has been demonstrated that physical properties influence the strength and flexibility of wood. The variability of physical properties is primarily due to differences in juvenile and mature wood; thus, variability of MOE and MOR will be discussed based on this concept.

Bendtsen and Senft (1986) have found that MOE and MOR values for loblolly pine are lower in juvenile wood compared to mature wood. In fact, they found an approximate fivefold increase in the average MOE (300,000 to 1,600,000 psi) and an approximate threefold increase in the average MOR (4,000 to 12,000 psi) from early juvenile wood to late mature wood. Weighted averages of these two properties along with associated physical properties are presented in Table 7. Furthermore, Kretschmann and Bendtsen (1992) found that in a fast grown 28-year-old loblolly pine plantation,

Table 7. Weighted average juvenile and mature wood properties of loblolly pine (Bendtsen and Senft 1986).

Type of Wood	Modulus of Rupture (Psi)	Modulus of Elasticity (10^6 Psi)	Specific Gravity	Cell Length	Fibril Angle
Juvenile	6,850	0.706	0.475	2.64	31.1
Mature	11,500	1.510	0.565	3.74	18.9

strength and stiffness decreased with increasing amounts of juvenile wood. In pieces comprised entirely of juvenile wood, they found that MOE values ranged from 51 to 63% to that of pieces composed entirely of mature wood samples, depending on lumber grade.

In a study of 10 species grown in China, (five coniferous and five deciduous), Bao *et al.* (2001) results are in agreement with the previously mentioned studies. Juvenile wood was considerably lower in MOE and MOR compared to mature wood for both natural and plantation stands. Differences were attributed to either larger MFAs or lower wood density in the juvenile wood. In the case of the two exotic species studied, loblolly pine and slash pine (*Pinus elliottii* Engelm.), wood density of the juvenile wood was much greater than that of mature wood. The authors suggest a variation in MFA as the root cause of strength differences for these species, not wood density. Like most properties, MFA varies within a tree stem. The typical pattern of the mean MFA (S_2) is to decrease from pith outwards (Bendtsen and Senft 1986; Walker and Butterfield 1996). Therefore, juvenile wood has a higher MFA than that of mature or outer wood and higher MFAs have been observed to result in lower strength and stiffness. Overall, it appears that by reducing the amount of juvenile wood, an increase in mechanical properties occurs.

2.2.3. Forest Management Practices

Larson (1969) describes wood formation as a biological process and wood quality as an arbitrary evaluation of a piece of wood's variation in physical and chemical structure; formation is the process and quality is the result of the process. Consequently, altering formation alters quality. In the field of forestry differing silviculture methods are utilized in an attempt to control tree growth and form, which in turn affects wood properties. Common practices include fertilization, irrigation, pruning, thinning and controlling initial stem density. The later two are more relevant to northwestern Ontario.

The influence of precommercial thinning on jack pine has been studied for both form (Buckman 1964; Bella and DeFranceschi 1974; Morris *et al.* 1994; Tong *et al.* 2005; and Zhang *et al.* 2006) specific gravity (Markstrom *et al.* 1983; Barbour *et al.* 1994; and Scott *et al.* 1982) and static bending (Zhang *et al.* 2006) responses. In general, as thinning intensities increase, stem and crown characteristics change. For example, crown length, branch size and stem taper have been found to increase with increasing thinning intensities (Morris *et al.* 1994; Zhang *et al.* 2006). The response of specific gravity to thinning is quite variable in jack pine. It has been documented to have no effect (Markstrom *et al.* 1983), a negative effect (Barbour *et al.* 1994) and a positive effect (Scott *et al.* 1982).

Precommercial thinning has also been found to influence static bending properties. In a study of jack pine response to precommercial thinning, Zhang *et al.* (2006) observed that static bending MOE and MOR lumber sized samples decreased as thinning intensity increased. Twenty years following thinning, a reduction of 15% and more than 20% in MOE and MOR, respectively, occurred between trees spaced to 1.22 m and trees spaced to 2.13 m. The presence of large knots was the dominant factor accounting for the reduced MOR. In addition, the authors studied MOE and MOR in relation to thinning intensity and log height. Both MOE and MOR decreased with log height for all intensities, including the control. The authors concluded that this variation occurred because of a higher frequency and greater size of knots and juvenile wood proportion within the top log.

In addition to precommercial thinning, it has been well documented that initial planting spacings influence tree characteristics. Factors studied have included form characteristics (Ralston 1953; Bella 1986; Bell *et al.* 1990), specific gravity (Maeglin 1967; Larocque and Marshall 1995; Kang *et al.* 2004) and static bending properties (McAlister *et al.* 1997; Middleton and Monroe 2001; Zhang *et al.* 2002; Zhang *et al.* 2005). Similar to the response of increased thinning intensity, increases in initial planting spacings change stem and crown characteristics. For example, larger crowns tend to be produced at wider spacings.

In a study of the effects of initial spacing on wood density of the oldest jack pine initial spacing trial in North America (est. 1941) by Kang *et al.* (2004), a relationship between wood density and spacing was apparent. The authors observed that wood density decreased as initial spacing increased from 1.5 to 2.1 to 2.7 m, with initial spacings of 1.5 m generally having the highest wood density. In contrast, Maeglin (1967) did not find a definitive relationship between the specific gravity of jack pine and different planting spacings. Trees within that study were 15 years old, which may have been a factor as to why a relationship was not found. For example, Larocque and Marshall (1995) observed that differences in relative density with increased spacing became more apparent past age 20 years for red pine. In Larocque and Marshall's study, the general trend of decreasing specific gravity with increased initial spacing was apparent past 20 years.

Research into the influence of initial spacing on MOE and MOR in static bending has revealed a general trend of decreasing stiffness and strength with an increase in initial spacing. This has been demonstrated by McAlister *et al.* (1997) for slash pine, by Middleton and Monroe (2001) for second-growth western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) by Zhang *et al.* (2002) for black spruce and by Zhang *et al.* (2005) for jack pine.

From the jack pine study, Zhang *et al.* (2005) observed that the MOR from the 2.13 m (40.2 MPa) and 2.74 m (39.0 MPa) spacings were lower than the 1.52 m (41.5 MPa) spacing. A similar trend was observed for MOE: 9218 MPa, 8828 MPa and 8538 MPa, respectively, for the 1.52 m, 2.13 m, 2.74 m spacings. Overall, MOE and MOR were 7.4% greater for the smallest spacing compared to the largest spacing with marginal differences between the intermediate and largest spacing. Also, the authors observed that these properties tended to decrease with increasing log height (Table 8).

Table 8. Lumber modulus of rupture and modulus of elasticity in relation to initial planting spacing and log position for jack pine (Zhang *et al.* 2005).

Log Height (feet)	Modulus of Rupture (MPa)			Modulus of Elasticity (MPa)		
	5×5 (feet)	7×7 (feet)	9×9 (feet)	5×5 (feet)	7×7 (feet)	9×9 (feet)
0-8	47.0	41.4	37.0	10401	9322	8621
8-16	42.6	35.6	34.7	9986	8282	8335
16-24	39.6	37.6	37.0	9305	8244	8188
24-32	43.1	34.4	37.9	9193	8087	8435
32-40	40.6	36.6	42.0	8667	8090	8331
40-48			20.8			6536

The above thinning and spacing studies indicate that controlling the amount of growing space available to a tree induces changes in tree form and timber quality. A majority of these studies have mentioned that such changes may be combated by not drastically reducing rotation age. Dechesne's (2006) study focuses on the influence of rotation age on lumber visual grade and bending properties of jack pine grown under natural conditions. She studied three naturally regenerated jack pine stands originating from fire aged 50, 73 and 90 years. The MOE and MOR of the 50-year-old stand were significantly lower than both the 73 and 90 year-old stands (Table 9). The author notes a significant difference was not found between the 73 and 90 year old stands for both these measures as the stands had likely reached maturity. The lower strength and stiffness values of the 50-year-old stand are attributed to the presence of a higher proportion of juvenile wood compared to the older stands. As the strength and stiffness properties in bending increased over time followed by a levelling off, the author has concluded that in natural jack pine stands maximization of lumber quality can be achieved through a moderate rotation age, approximately 70 years.

Table 9. Stand level lumber MOR and MOE at 12% equilibrium moisture content for jack pine in relation to rotation age (Dechesne 2006).

Rotation Age (yrs)	Modulus of Rupture (MPa)	Modulus of Elasticity (MPa)
50	42.32	9441
73	49.06	11234
90	48.45	10927

There is a lack of literature discussing the influence of various regeneration methods, besides initial planting spacing, on tree form and wood attributes of softwood species. One published study was found in Sweden by Eriksson *et al.* (2006). They evaluated the effects of two silvicultural regimes of Scots pine (*Pinus sylvestris* L.) on wood physical and mechanical properties for two different wood tissues, sapwood and heartwood. Analyses were performed at two different heights, stump and intermediate top height. Trees from a 56 year old widely planted site without crown closure and trees from an 85 year old densely spaced site that was direct seeded were evaluated. Based on means of all samples, the authors found that trees directly seeded had significantly higher stiffness (MOE) and bending strength (MOR) by 150 and 70%, respectively. All other mechanical properties and physical properties were also significantly different with average values greatest for the directly seeded stand, except for ring width, which was smaller. They observed that between the two regimes, stump height had greater differences in properties than at intermediate height. The authors attribute this difference to differences in cell morphological characteristics.

Overall, Eriksson *et al.* (2006) state that "maturation of characteristics related to cambial age seems faster in a regime with dense spacing and differences are weaker at intermediate top heights in trees than at stump level." They believe that a silviculture regime can be used as a tool to regulate wood production to produce a more homogeneous wood material.

3.0 MATERIALS AND METHODS

3.1. FIELD PROCEDURES

3.1.1. Stand Selection

In northwestern Ontario, approximately 60 km east of Ignace, four jack pine stands were selected for this study. Each stand was subjected to a different regeneration method: aerial seeding, Bräcke seeding, planting and naturally regenerating post-fire. The stands were in close proximity to each other with the natural stand extending the furthest, approximately 70 km to the northeast of the three other stands (Figure 8). The

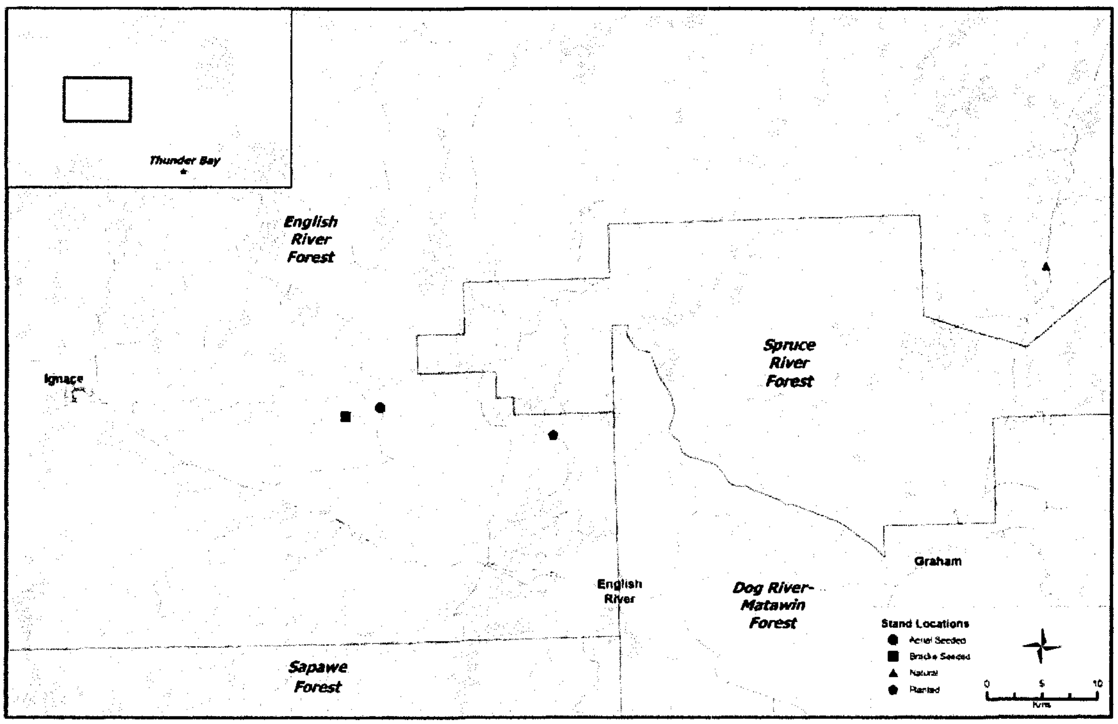


Figure 8. Stand locations within this study.

aerial seeded, Bräcke seeded and planted stands were regenerated in 1982 while the natural stand was depleted by fire in 1980 and declared free to grow in 1992. Based on the forest resource inventory (FRI) the approximate age of trees within the stands at time of study was 25 years. The planted stand may have been a fill plant.

Stand size was fairly consistent with the naturally regenerated stand as the exception: aerial seeded – 55 ha, Bräcke seeded – 41 ha, planted – 40 ha (divided into three adjacent stands) and natural – 8 ha. These four stands did not receive stand tending following establishment. The areas of study were all categorized as site class two. Initial stem densities and stocking for each stand studied were unknown.

3.1.2. Tree Selection

Within each stand, 12 trees were randomly selected for destructive sampling following a stratified random sampling procedure. To ensure randomization, prior to entering the field, Hawth's Analysis Tools Version 3.26 was used in ArcMap 9.0 to randomly locate four plots within each stand. In the field, a global position system (GPS) unit was used to locate the centre points of the plots.

The plots were circular with a radius of 5.64 m. Within each plot, trees greater or equal to 5.0 cm dbh were numbered beginning with one going in a clockwise direction from a starting azimuth that was determined from a random numbers table. All numbered trees were then measured for dbh. Those trees that were greater or equal to 10 cm dbh and free from visual defects, such as sweep, were declared possible sample trees. Three of these trees were then randomly selected using a random numbers table and felled for destructive sampling. If jack pine trees meeting the above criteria could not be located within the predetermined plot location, the plot was moved to a nearby area that met the selection requirements. For the natural stand, the random plot locations often did not contain jack pine trees, or trees of the required size. Thus, plots were moved to meet the selection criteria. In summary, four circular plots were established randomly within each stand; within each plot, three trees were randomly selected for destructive sampling, thus 12 trees were sampled per regeneration method for a total sample of 48 trees.

3.1.3. Tree Measurements

For each destructively sampled tree the following attributes were measured: dbh, total height, height to live crown, length of live crown, crown diameter (mean value of north to south and east to west measurements). Both dbh and crown diameter were measured prior to felling. Total height, height to live crown and length of live crown were measured once the tree was felled.

Stem sections (bolts) 60 cm long in longitudinal direction and as free from branching as possible were removed at approximately 1, 2, and 4 m heights starting from tree base. All bolts were labelled with a metal tag indicating stand type (regeneration method), tree number and bolt number. Bolts removed from the 1, 2 and 4 m heights were correspondingly labelled bolt 1, 2 and 3, respectively. For example, bolt 1, tree 1 of the aerial seeded stand was labelled A1.1, bolt 2 from the same tree was labelled A1.2 and so forth. The centre points of the bolts were at the specified heights of 1, 2 and 4 m; however, deviations occurred ± 30 cm due to branches (Figure 9). The exact distance from each bolt centre point to live crown was calculated in the laboratory. These bolts were then removed from the field and brought back to the Lakehead University Wood Science and Testing Facility (LUWSTF) for further processing into samples for determination of the mechanical properties MOE and MOR in static bending as well as the physical property, specific gravity.

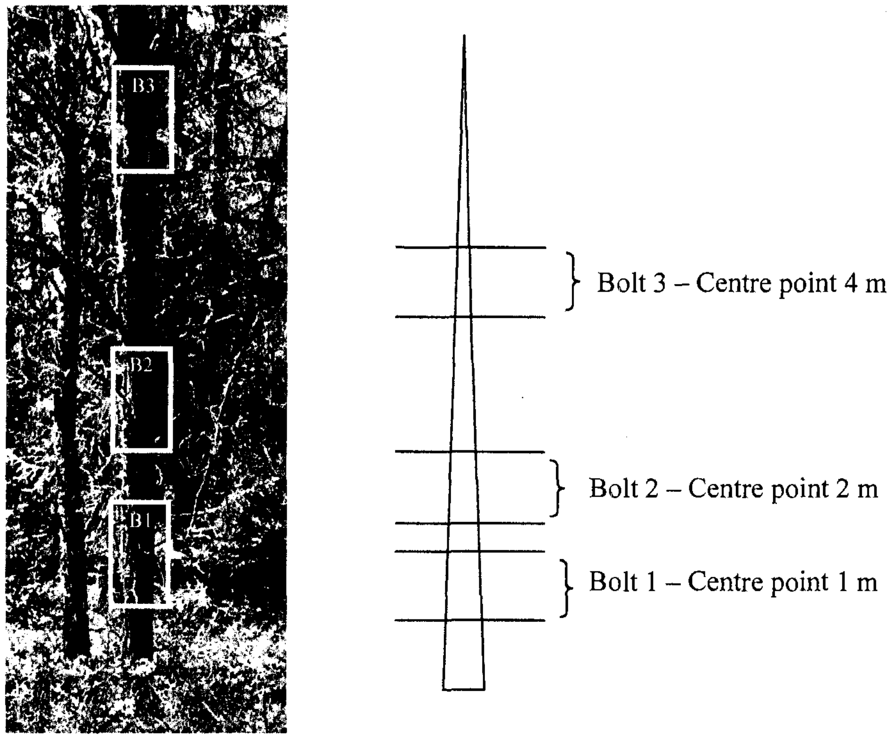


Figure 9. Picture and illustration presenting where the bolts were removed from each tree.

3.1.4. Collection Dates

Field collection occurred over a span of 11 months. Collections occurred in December of 2006 and January, June, July, October and November of 2007.

3.2. LABORATORY PROCEDURES

3.2.1. Static Bending Sample Preparation

The universal wood testing machine at the LUWSTF used to test the samples was a Tinius Olsen H10KT run with Test Navigator software. For static bending tests, small clear test specimens of the size 2×2×30 cm were required ("clear" refers to free of knots and other defects). To achieve test samples of this size the bolts brought back from the field were processed several times. First the top portion of each bolt was marked with the pattern displayed in Figure 10 with the pith at the centre; each square represented 2.5×2.5 cm. Generally, samples lying within the cross pattern are only used in testing;

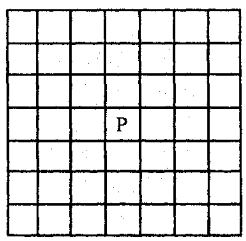


Figure 10. The pattern of clear samples to be removed from each bolt; the shaded area is the top of a 60 cm bolt, the grid is the 2.5 by 2.5 cm pattern marked on each bolt with the pith (P) as the centre point.

however, due to the small diameter of the bolts all 2.5×2.5 cm samples suitable for testing were used to increase sample size.

Once the pattern was marked, a band saw was used to cut the bolts into planks. Excess saw dust was brushed from the planks to increase drying speed. The boards were stickered, labelled and left to air-dry (Figure 11). Once the planks had reached an acceptable moisture content (approximately 18%) they were sawn into 2.5×2.5×60 cm

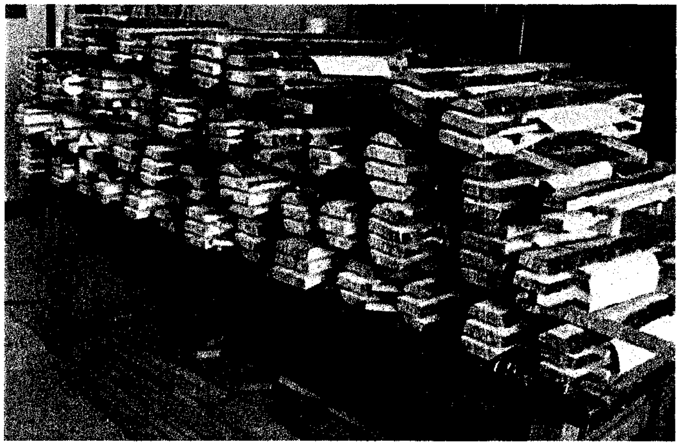


Figure 11. Bolts that had been sawn into boards, stickered, labelled and left to air-dry.

specimens. The moisture content of boards and specimens were determined using a GE Protimeter Surveymaster moisture meter. The pith is very weak and specimens (2.5×2.5×60 cm) containing it were discarded. Each specimen was labelled following a predetermined system that described regeneration method, bolt location, and sample location within the bolt. For example, A3.2.6 described a sample stick from the aerial seeded stand, tree number three, bolt number two and specimen number six within that bolt.

Once the 2.5×2.5×60 cm samples reached an approximate moisture content of 14% they were cut to 2×2×60 cm, stickered and left to further air dry. These pieces were cut down to the test size of 2×2×30 cm once moisture content neared 12%. Each specimen was reduced from 60 cm in length to 30 cm in length by determining which section along the length of the 60 cm specimen provided the most suitable clear 30 cm sample. The stages required to machine the bolts into test samples are displayed in Figure 12. Often due to knots or the presence of pith, test samples had to be discarded

Figure 12. Stages of processing bolts into test specimens. Left - bolts are cut into boards, Centre - boards are cut into 2×2×60 cm specimens and Right - the 2.5×2.5×60 cm specimens are further cut to 2×2×60 cm specimens which were then cut down into test specimens 30 cm in length.

because a suitable clear sample could not be obtained. The number of test samples per bolt varied due to varying bolt diameters, presence of knots and pith.

3.2.2. Static Bending Tests

The specimens were tested using the Tinius Olsen H10KT, with a maximum load capacity of 1100 kg, in accordance with the methods outlined by the International Organization for Standardization: *Wood – Determination of ultimate strength in static bending*: ISO 3133-1975 (E). With respect to ISO 3133-1975 (E) procedure 6.3 was not followed as the Test Navigator software measured deflection of the neutral plane at the proportional limit.

The static bending tests were performed on samples 2×2×30 cm in size in 3-point flexure with a load span of 24 cm. The test samples were placed with growth rings positioned perpendicular to the span supports and loading head. The loading head was applied at a rate of 8 mm/min. until failure was reached (Figure 13).

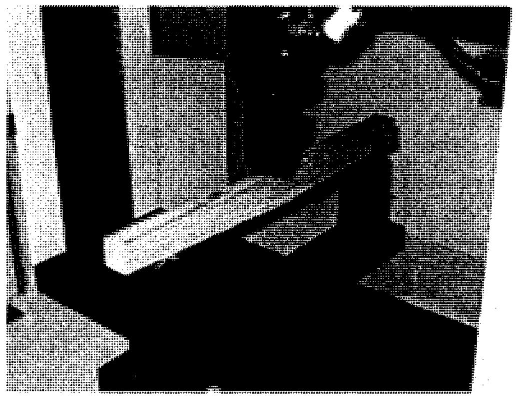


Figure 13. The 3-point flexure test of a wood sample for the determination of modulus of elasticity.

A data acquisition computer using Test Navigator software recorded the load-deflection curve for each test sample and calculated the MOE (Equation 1), where MOE = modulus of elasticity, P′ = load at proportional limit, l = length between beam supports, D = deflection of the neutral plane at the proportional limit, b = width of beam and d = depth of beam. The MOR was calculated using Equation (2), where MOR = modulus of rupture, P = ultimate load, and the other parameters are as previously defined. Results were recorded to the nearest mega Pascal (MPa).

$$MOE\,3pt = \frac{P'l^3}{4Dbd^3} \tag{1}$$

$$MOR = \frac{1.5P^3 l}{bd^2} \tag{2}$$

Following each test a portion of the specimen (25 ± 5 mm) near the rupture was sampled to determine moisture content of the test piece at time of testing. The procedure was in accordance with *Wood – Determination of moisture content for physical and mechanical tests*: ISO 3130-1975 (E), except volatile organic substances were not removed. Once the moisture content of each piece was determined the corresponding MOE and MOR values were adjusted to 12% moisture content following the moisture adjustment procedures in *ASTM Standard Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens [D 1990 – 00 (2002)]*. All MOE and MOR values presented have been adjusted to 12% moisture content.

3.2.3. Specific Gravity Determination

The small block of wood removed from each test specimen for the determination of moisture content at time of test was also used to determine specific gravity. The volume by measurement methodology outlined in *ASTM Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials (D 2395 – 02)* was used to determine specific gravity, which was based on oven-dry weight and volume at test. Digital calipers were used to measure the length, width and depth of each piece to the nearest tenth of a millimetre while the weight was measured to the nearest one hundredth of a gram. Extractives were not removed from the wood specimens. The specific gravity of each specimen was then converted to nominal (12% moisture content) basis following formula X1.4 within the Appendix of ASTM D 2395 – 02.

3.3. STATISTICAL ANALYSIS

3.3.1. Treatment Effects on Wood Properties

The first objective of this study was to determine if a significant difference in the properties MOE, MOR and specific gravity existed between trees from stands regenerated by the four different methods. The influence of vertical position within each stand was also considered.

To address these objectives, analysis of variance tests were carried out using the General Linear Model method in SPSS 15.0 to test the null hypotheses: a) that regeneration method had no effect on MOE, MOR or specific gravity and b) that vertical position within individual regeneration methods had no effect on MOE, MOR or specific gravity.

The experimental design of this study was a multi-staged nested sampling design. The model included the components Stand, Plot, Tree and Bolt. Plot was nested within Stand and Tree was nested within Plot. Both Stand and Bolt were fixed effects while the factors Plot and Tree were random. The experimental unit was the mean value of MOE, MOR and specific gravity of the bolts. The mathematical model for this experiment is presented in Equation (3).

The expected mean squares associated with Equation (3) are presented in Table 10. Hypotheses tests for Equation (3) are displayed in Table 11. Direct tests were available for factors Stand, Plot and Bolt as well simultaneously for the effects of Stand and Bolt, and Plot and Bolt.

$$Y_{ijkl} = \mu + S_i + P_{(i)j} + T_{(ij)k} + B_l + SB_{il} + PB_{(i)jl} + TB_{(ij)kl} + \varepsilon_{(ijkl)} \quad (3)$$

$$i = 1, 2, 3, 4; \quad j = 1, 2, 3, 4; \quad k = 1, 2, 3; \quad l = 1, 2, 3$$

Where,

Y_{ijkl} = the modulus of elasticity (or modulus of rupture, or specific gravity) of the l^{th} bolt from the k^{th} tree within the j^{th} plot within the i^{th} stand.

μ = the overall mean

S_i = the fixed effect of the i^{th} stand

$P_{(i)j}$ = the random effect of the j^{th} plot within the i^{th} stand

$T_{(ij)k}$ = the random effect of the k^{th} tree within the j^{th} plot within the i^{th} stand

B_l = the fixed effect of the l^{th} bolt

SB_{il} = the interaction effect of the i^{th} stand with the l^{th} bolt

$PB_{(i)jl}$ = the interaction effect of the l^{th} bolt with the j^{th} plot within the i^{th} stand

$TB_{(ij)kl}$ = the interaction effect of the l^{th} bolt with the k^{th} tree within the j^{th} plot within the i^{th} stand

$\varepsilon_{(ijkl)}$ = the random effect of the l^{th} bolt from the k^{th} tree within the j^{th} plot within the i^{th} stand.

Table 10. Expected mean square derivation for Equation (3).

	4	4	3	3		
	F	R	R	F		
Source[a]	i	j	k	l	Expected Mean Squares	df
S_i	0	4	3	3	$\sigma^2 + 3\sigma_T^2 + 9\sigma_P^2 + 36\sigma_S^2$	(I-1)
$P_{(i)j}$	1	1	3	3	$\sigma^2 + 3\sigma_T^2 + 9\sigma_P^2$	I(J-1)
$T_{(ij)k}$	1	1	1	3	$\sigma^2 + 3\sigma_T^2$	IJ(K-1)
B_l	4	4	3	0	$\sigma^2 + \sigma_{TB}^2 + 3\sigma_{PB}^2 + 48\Phi(B)$	(L-1)
SB_{il}	0	4	3	0	$\sigma^2 + \sigma_{TB}^2 + 3\sigma_{PB}^2 + 12\Phi(SB)$	(I-1)(L-1)
$PB_{(i)jl}$	1	1	3	0	$\sigma^2 + \sigma_{TB}^2 + 3\sigma_{PB}^2$	I(J-1)(L-1)
$TB_{(ij)kl}$	1	1	1	0	$\sigma^2 + \sigma_{TB}^2$	IJ(L-1)(K-1)
$\varepsilon_{(ijkl)}$	1	1	1	1	σ^2	(I)(J)(K)(L)

[a]S = stand type; P = plot; T = tree; B = bolt

From the SPSS ANOVA outputs the sums of squares and mean square values were obtained. The test statistic (calculated F-value) for each source was determined from the ratios shown in Table 11. The standard table for upper 5% critical values for the F-distribution was used to determine associate critical F-values (Lorenzen and Anderson 1993). The null hypothesis of no treatment effect was rejected whenever the calculated F-value exceeded the critical F-value.

Table 11. Hypotheses tests for the nested model, Equation (3).

Hypothesis	Test Statistic[a]	Reference Distribution
$\sigma_S^2 = 0$	MS(S)/MS(P)	F(3,12)
$\sigma_P^2 = 0$	MS(P)/MS(T)	F(12,32)
$\sigma_T^2 = 0$	–	–
$\Phi(B) = 0$	MS(B)/MS(PB)	F(2,24)
$\sigma_{PB}^2 = 0$	MS(PB)/MS(TB)	F(6,24)
$\sigma_{TB}^2 = 0$	–	–

[a]MS = mean square, S = stand, P = plot; T = tree; B = bolt

If the null hypothesis was rejected, the Tukey's honestly significant difference (HSD) test was performed to determine which means significantly differed from one another. For this study, the significance value or experimentwise error rate was 0.05.

3.3.2. Mechanical Properties as Related to Specific Gravity

The relationships between wood specific gravity and MOR, and wood specific gravity and MOE for each regeneration method at three vertical positions (1, 2 and 4 m) were investigated by both simple linear, Equation (4), and curvilinear, Equation (5), regressions using SPSS 15.0. Furthermore, for each regeneration method, samples from the three bolt positions were combined and the relationships of MOR and MOE to specific gravity were investigated.

$$MOR\ or\ MOE = a + bSG \tag{4}$$

$$MOR\ or\ MOE = \alpha SG^{\beta} \tag{5}$$

With respect to both linear and curvilinear methods, the null hypothesis that the slope of the model was equal to zero, and that is there was no linear or curvilinear relationship between specific gravity and MOR was tested. The same hypothesis applied to specific gravity and MOE. The alternative hypothesis for both linear and curvilinear analyses was that a significant relationship existed. That means the slope of the models did not equal zero. Each regression equation was tested, using an ANOVA model, to determine if the relationship between specific gravity and MOR or MOE was significant ($\alpha = 0.05$).

The curvilinear regression analyses were performed by converting the curvilinear equation to a simple linear equation, Equation (6). As indicated by Equation (6), the

$$\ln MOR\ or\ \ln MOE = \ln \alpha + \beta \ln SG \tag{6}$$

natural log of MOR and the natural log of specific gravity were used to determine the curvilinear relationship between specific gravity and MOR. The same process was performed for the curvilinear regression analyses of specific gravity and MOE.

Within this study, both linear and curvilinear regression analyses were compared for each regeneration method using the respective coefficients of determination to determine if the variation in the mechanical properties due to specific gravity for jack pine was best explained by a linear or curvilinear function. It was hypothesized that the linear function best represented the relationship between specific gravity and the respective mechanical properties studied for each regeneration method.

Furthermore, comparisons of the relationships of specific gravity to the mechanical properties within each regeneration method at each bolt position were investigated. The coefficients of determination were used for the comparison.

To test the assumptions of regression, the Shapiro-Wilks test of normality was performed and the standardized predicted values versus standardized residual values were graphed to test for normality and homogeneity of variance, respectively, for each regression analysis. Scatter plots of specific gravity versus MOR and specific gravity versus MOE were created to determine if there were any outliers. If outliers were found they were removed.

4.0 RESULTS

Mean tree attributes of each regeneration method subdivided by plot number are presented in Tables 12 and 13. On average, the Bräcke seeded stand contained the most stems per plot at 40 (Table 12). The natural stand had the second greatest number of stems per plot followed by the aerial seeded and planted stands (Table 12). Although stem densities varied, the average diameters of each regeneration method were similar. Also, in most plots, crown closure had yet to occur. The planted stand had the greatest mean dbh, height, height to live crown, live crown length and live crown diameter (Table 13). Trees within the natural and aerial seeded stands had similar attributes.

Tree form characteristics within the same regeneration method were variable. For example, within the planted stand average dbh in plots 9 and 12 differed by 5.4 cm. Also, there was more than a 2.0 m average height difference between aerial seeded plots 3 and 4 and over a 3.0 m difference in average live crown length between plots 5 and 7 within the Bräcke seeded stand.

4.1. TREATMENT EFFECT ON WOOD PROPERTIES

4.1.1. Treatment Effect on Modulus of Elasticity

A statistical summary of the mean MOE values for each regeneration method is presented in Table 14. The natural stand had the highest mean MOE value of 5854 MPa

Table 12. Mean jack pine diameter per plot for each stand type: aerial seeded, Bräcke seeded, planted and natural (Source: Appendix I).

Stand Type	Plot No.	No. of Stems per Plot[a]	No. of Jack Pine Stems per Plot[b]	Average Diameter of Jack Pine Stems[c] (cm)
Aerial seeded	1	28	17	10.0 (2.7)[d]
	2	32	25	8.2 (2.0)
	3	26	22	10.7 (2.2)
	4	18	18	10.7 (2.7)
	Mean	**26**	**20**	**9.9 (2.4)**
Bräcke seeded	5	36	35	9.7 (2.4)
	6	41	41	8.8 (1.9)
	7	33	26	11.0 (3.2)
	8	53	48	8.2 (2.6)
	Mean	**40**	**37**	**9.4 (2.5)**
Planted	9	22	15	10.9 (2.4)
	10	24	16	11.6 (3.4)
	11	15	14	14.4 (4.1)
	12	32	26	13.5 (4.0)
	Mean	**23**	**17**	**12.6 (3.5)**
Natural	13	39	38	8.6 (2.7)
	14	39	39	8.8 (2.2)
	15	20	9	10.0 (1.6)
	16	31	31	8.0 (2.2)
	Mean	**32**	**29**	**8.9 (2.2)**

[a]Number of stems of all species ≥ 5.0 cm dbh within a 5.64 m radius circular plot
[b]Number of jack pine stems ≥ 5.0 cm dbh within a 5.64 m radius circular plot
[c]Average diameter of the jack pine trees ≥ 5.0 cm dbh within a 5.64 m radius circular plot
[d]Standard deviation

Table 13. Mean tree characteristics per plot for each stand type: aerial seeded, Bräcke seeded, planted and natural (Source: Appendix I).

Stand Type	Plot No.	No. Stems per Plot[a]	Sample Trees[b] DBH (cm)	HT (m)	HT to LC (m)	LCL (m)	LCD (m)
Aerial seeded	1	28	12.8 (1.63)[c]	9.87 (0.99)	4.47 (0.21)	5.40 (0.83)	2.83 (0.73)
	2	32	11.6 (0.70)	9.53 (0.91)	4.17 (0.51)	5.37 (0.85)	2.02 (0.25)
	3	26	11.8 (1.99)	9.03 (0.60)	4.15 (0.33)	4.88 (0.60)	2.80 (0.36)
	4	18	12.4 (0.55)	11.10 (0.70)	5.00 (0.26)	6.10 (0.92)	2.13 (0.65)
	Mean	**26**	**12.2 (1.22)**	**9.88 (0.80)**	**4.45 (0.33)**	**5.44 (0.80)**	**2.44 (0.50)**
Bräcke seeded	5	36	12.0 (1.60)	10.51 (0.82)	6.45 (0.43)	4.07 (1.10)	2.47 (0.56)
	6	41	10.7 (0.72)	10.58 (0.53)	5.72 (0.42)	4.87 (0.95)	2.24 (0.24)
	7	33	13.5 (2.17)	11.53 (0.51)	4.37 (1.80)	7.17 (2.31)	2.30 (0.78)
	8	53	11.2 (1.56)	10.23 (0.31)	4.68 (0.08)	5.55 (0.35)	1.97 (0.52)
	Mean	**40**	**11.8 (1.51)**	**10.72 (0.54)**	**5.3 (0.68)**	**5.41 (1.18)**	**2.24 (0.53)**
Planted	9	22	11.8 (0.47)	11.37 (0.83)	6.77 (0.70)	4.60 (0.53)	2.20 (0.40)
	10	24	13.0 (2.25)	10.26 (0.67)	3.09 (0.94)	7.17 (1.61)	3.12 (1.09)
	11	15	13.7 (0.10)	13.20 (0.70)	6.47 (1.10)	6.73 (0.49)	2.35 (0.74)
	12	32	17.2 (1.87)	13.47 (0.67)	6.67 (1.19)	6.80 (0.53)	2.47 (0.83)
	Mean	**23**	**13.9 (1.17)**	**12.07 (0.72)**	**5.75 (0.98)**	**6.33 (0.79)**	**2.53 (0.76)**
Natural	13	39	11.9 (1.33)	10.93 (0.58)	5.70 (0.61)	5.23 (0.06)	2.35 (0.70)
	14	39	12.3 (1.10)	10.87 (0.21)	4.83 (0.76)	6.03 (0.67)	2.27 (0.20)
	15	20	12.9 (1.56)	9.57 (0.38)	2.73 (1.36)	6.83 (1.72)	3.50 (0.79)
	16	31	11.2 (0.90)	9.77 (1.16)	5.00 (0.75)	4.77 (0.46)	1.65 (0.44)
	Mean	**32**	**12.1 (1.22)**	**10.28 (0.58)**	**4.57 (0.87)**	**5.72 (0.73)**	**2.44 (0.53)**

[a]Number of stems of all species ≥ 5.0 cm dbh within a 5.64 m radius circular plot

[b]DBH: diameter at breast height; HT: height; LC: live crown; LCL: length of live crown; LCD: live crown diameter; tree attributes for each plot were the mean of three trees

[c]Standard deviation

Table 14. Modulus of elasticity statistical summary of the four regeneration methods: aerial seeded, Bräcke seeded, planted and natural.

Stand Type	Plot No.	Bolt Position[a] Bolt 1	Bolt 2	Bolt 3	Mean
Aerial Seeded	1	5442[b] (3[c]–820[d]–15[e])	5168 (3–787–15)	4283 (3–355–8)	**4964** (9–794–16)
	2	4876 (3–959–20)	4261 (3–610–14)	3778 (3–861–23)	**4305** (9–858–20)
	3	5368 (3–694–13)	5956 (3–1095–18)	5481 (3–816–15)	**5602** (9–812–14)
	4	6210 (3–1159–19)	5275 (3–1010–19)	5633 (3–1174–21)	**5706** (9–1050–18)
	Mean	**5474** (12–933–17)	**5165** (12–990–19)	**4794** (12–1097–23)	**5144** (36–1019–20)
Bräcke Seeded	5	4361 (3–253–6)	4958 (3–1043–21)	4594 (3–456–10)	**4637** (9–639–14)
	6	4511 (3–519–12)	4568 (3–478–10)	4960 (3–138–3)	**4680** (9–417–9)
	7	6171 (3–257–4)	6225 (3–747–12)	6137 (9–455–7)	**6177** (9–457–7)
	8	6179 (3–80–1)	5963 (3–858–14)	6113 (3–312–5)	**6085** (9–468–8)
	Mean	**5305** (12–950–18)	**5428** (12–994–18)	**5451** (12–782–14)	**5395** (36–889–16)
Planted	9	5140 (3–919–18)	4871 (3–752–15)	4898 (3–848–17)	**4969** (9–741–15)
	10	5130 (3–1190–23)	4615 (3–536–12)	5398 (3–1436–27)	**5048** (9–1030–20)
	11	6536 (3–629–10)	6879 (3–648–9)	6884 (9–528–8)	**6766** (9–551–8)
	12	5064 (3–957–19)	5261 (3–853–16)	4982 (3–931–19)	**5103** (9–802–16)
	Mean	**5468** (12–1032–19)	**5406** (12–1100–20)	**5541** (12–1187–21)	**5472** (36–1078–20)
Natural	13	5578 (3–268–5)	5198 (3–340–7)	4241 (3–1188–28)	**5006** (9–869–17)
	14	7057 (3–1258–18)	6451 (3–768–12)	5866 (3–1144–20)	**6458** (9–1066–17)
	15	5556 (3–2056–37)	5069 (3–989–20)	5357 (9–1355–25)	**5327** (9–1344–25)
	16	6564 (3–674–10)	6968 (3–1428–20)	6343 (3–1373–22)	**6625** (9–1082–16)
	Mean	**6189** (12–1268–20)	**5921** (12–1180–20)	**5452** (12–1355–25)	**5854** (36–1271–22)

a – centre point of bolts 1, 2 and 3 are located at 1, 2 and 4 m, respectively, from base to top of tree, b – mean value (MPa), c – number of samples, d – standard deviation (MPa) and e – coefficient of variation (%)

while the aerial seeded stand had the lowest value of 5144 MPa. Figure 14 displays comparative boxplots of the MOE data (Table 14) for each regeneration method. The median MOE of each stand type were similar and an overlap in spread occurred. The Bräcke seeded MOE data was the least variable while the natural stand was the most variable.

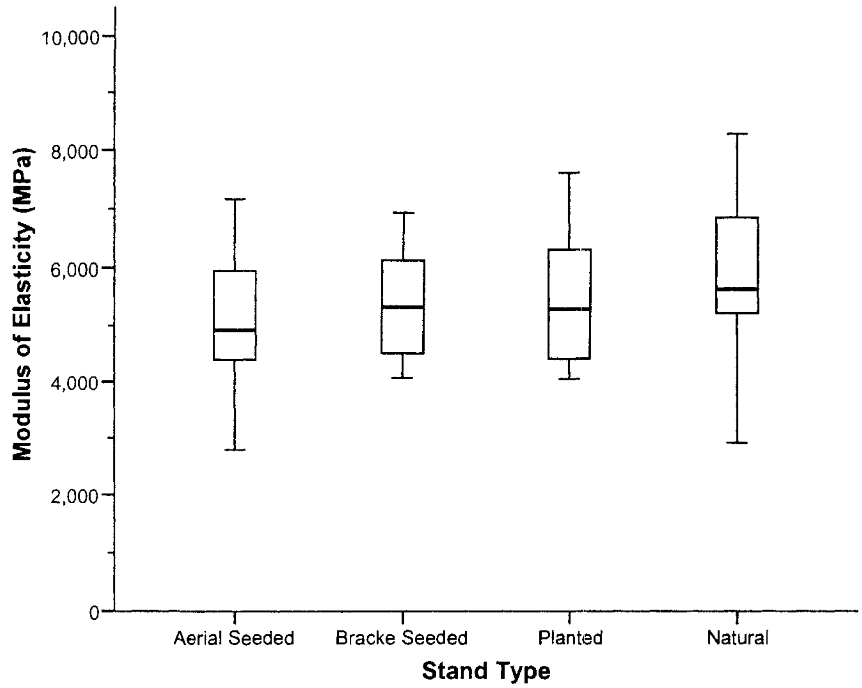


Figure 14. Comparative boxplots of modulus of elasticity for each regeneration method.

Variation in MOE existed within each regeneration method Table 14. Within the aerial seeded stand, plots 1 and 2 had lower mean MOE values compared to plots 3 and 4. The Bräcke seeded stand also had two plots that exhibited much higher MOE mean values, plots 7 and 8 compared to 5 and 6. Within the planted stand, three of the four plots had similar mean MOE values while plot 11 had a much greater mean value. The mean MOE plot values of the natural stand followed a similar pattern to that of the aerial and Bräcke seeded stands; plots 14 and 16 had much greater mean values than 13 and

15. Comparative boxplots of each plot with respect to MOE are displayed in Figure 15. Outliers were found within plots 1, 5 and 10 while extremes were present in plots 5 and 13.

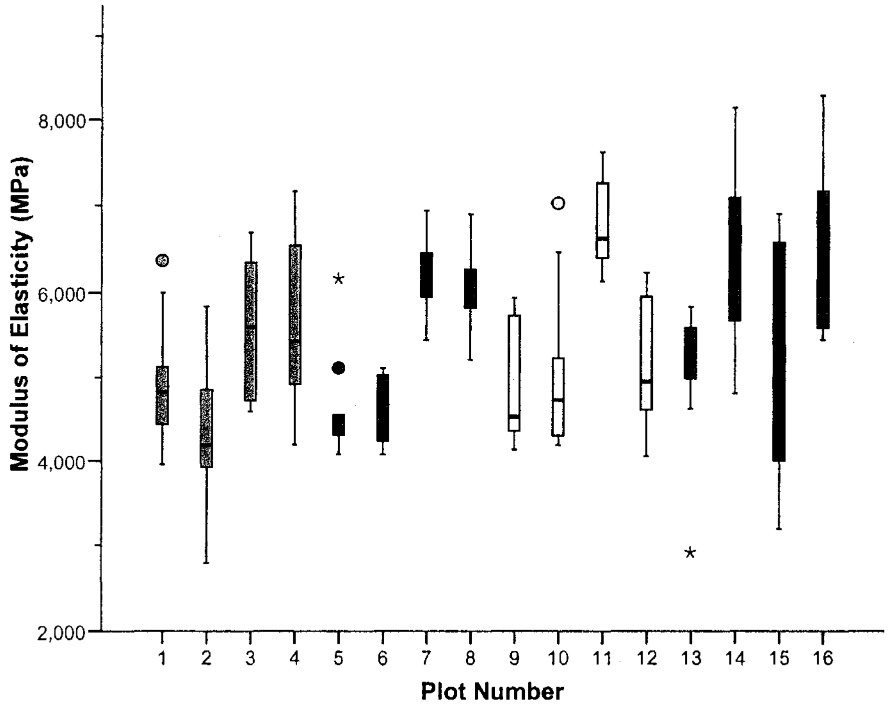


Figure 15. Comparative boxplots of modulus of elasticity for each plot. Aerial seeded: plots 1 – 4; Bräcke seeded: 5 – 8; planted: 9 – 12; natural: 13 – 16.

Both the aerial seeded and natural stands exhibited mean MOE values that decreased with increasing height (Table 14). In contrast, the Bräcke seeded stand exhibited the opposite pattern with increasing mean MOE with height. The planted stand did not follow these vertical patterns as bolt 3 had the highest mean MOE value followed by bolt 1 and 2.

The ANOVA generated to test the null hypotheses that a) regeneration method had no effect on mean MOE values and that b) vertical position had no effect on mean MOE values within individual regeneration methods is presented in Table 15. Although a difference in mean MOE values was observed between regeneration methods (Table 14), this difference was not statistically significant (Table 15). Therefore, the null hypothesis that regeneration method had no effect on mean MOE values could not be rejected (Table 15). Similarly, bolt position and the interaction between stand type and bolt position were not significantly different (Table 15). Therefore, the null hypothesis that MOE did not differ with bolt position within individual regeneration methods could not be rejected.

Table 15. Summary of analysis of variance components for modulus of elasticity.

Source	d.f.	Sum of Squares	Mean Square	$F_{calculated}$	$F_{critical(0.05)}$	Sig.[a]
Stand	3	9.332E+06	3.111E+06	0.543	3.49	
Plot(Stand)	12	6.873E+07	5.727E+06	2.942	2.07	*
Tree(Stand*Plot)	32	6.229E+07	1.947E+06			
Bolt	2	2.171E+06	1.085E+06	3.288	3.4	
Stand*Bolt	6	4.212E+06	7.019E+05	2.126	2.51	
Bolt*Plot(Stand)	24	7.923E+06	3.301E+05	1.331	1.70	
Bolt*Tree(Stand*Plot)	64	1.588E+07	2.481E+05			
Error	0	0				

[a] - * indicates significance at 0.05 level

From the results of ANOVA model, a significant difference between plots within regeneration methods was found. The Tukey HSD test was performed to determine which plots were significantly different at the 0.05 level (Figure 16). Through multiple comparisons of plot means eight homogeneous subsets of plots were formed. With respect to MOE, the post-hoc test revealed that plots within the same regeneration method were significantly different. For example, within the aerial seeded stand, plots 3 and 4 were significantly different from plot 2 while plot 1 was not significantly different from the other three. The planted stand had the least variability with only plot 11 significantly different from the remaining three plots. Within the Bräcke seeded stand,

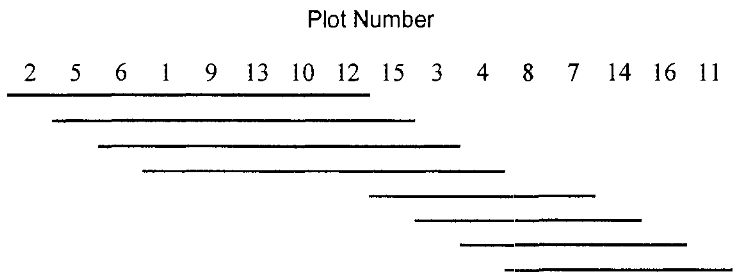


Figure 16. Tukey's HSD test homogeneous subsets (solid lines) for plots based on modulus of elasticity. Plots are ranked from smallest to largest. Aerial seeded: plots 1 – 4; Bräcke seeded: 5 – 8; planted: 9 – 12; natural: 13 – 16.

plots 5 and 6 were significantly different from plots 7 and 8. This pattern was also present in the natural stand. The variability of mean plot MOE within each regeneration method is graphically displayed in Figure 17.

4.1.2. Treatment Effect on Modulus of Rupture

A statistical summary of the mean MOR values for each regeneration method is presented in Table 16. The natural stand had the highest mean MOR value of 63.5 MPa while the aerial seeded stand had the lowest MOR value of 58.9 MPa. The Bräcke seeded and planted stand had similar mean MOR values of 60.7 MPa and 60.2 MPa, respectively. During the exploration of the MOR data, a Shapiro-Wilk test indicated that the aerial and Bräcke seeded stands were not normally distributed. It was determined that a natural log transformation of the MOR data would achieve a normal distribution

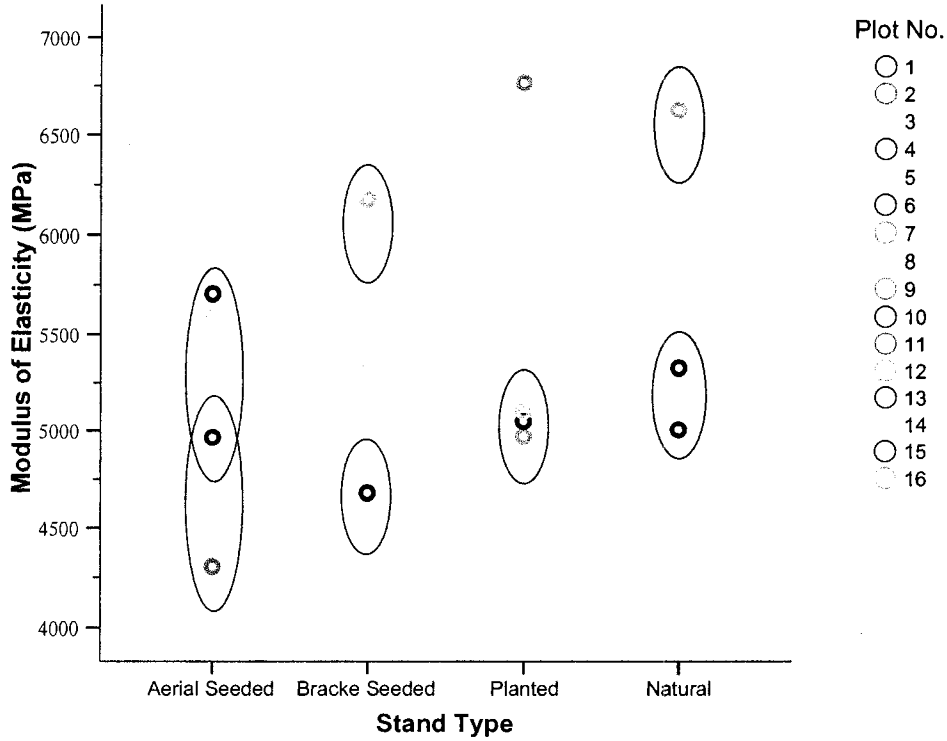


Figure 17. Bending modulus of elasticity by regeneration method and plot number. Markers found within the same ellipses signify plots within each method that were not significantly different.

for all stands. Thus for MOR, statistical analyses was performed using natural log transformed data. Comparative boxplots of MOR for each stand type are displayed in Figure 18. Similar to the boxplots displayed in Figure 14 for MOE, the dispersion of MOR data was least for the Bräcke seeded stand and most for the natural stand (Figure 18).

Table 16. Modulus of rupture statistical summary of the regeneration methods: aerial seeded, Bräcke seeded, planted and natural.

Stand Type	Plot No.	Bolt Position[a]			Mean
		Bolt 1	Bolt 2	Bolt 3	
Aerial Seeded	1	59.1[b] (3[c]–4.1[d]–7[e])	59.5 (3–5.8–10)	53.3 (3–2.2–4)	**57.3** (9–4.8–8)
	2	58.2 (3–2.0–3)	54.6 (3–1.9–3)	51.6 (3–1.0–2)	**54.8** (9–3.2–6)
	3	63.1 (3–4.2–7)	63.3 (3–6.7–11)	60.6 (3–5.5–9)	**62.3** (9–5.0–8)
	4	66.1 (3–6.9–10)	57.5 (3–8.6–15)	59.9 (3–8.8–15)	**61.2** (9–8.0–13)
	Mean	**61.6** (12–5.2–8)	**58.7** (12–6.3–11)	**56.3** (12–6.1–11)	**58.9** (36–6.1–10)
Bräcke Seeded	5	57.0 (3–3.4–6)	58.6 (3–4.4–8)	54.4 (3–2.1–4)	**56.7** (9–3.5–6)
	6	56.1 (3–2.4–4)	56.6 (3–2.3–4)	57.2 (3–2.0–3)	**56.6** (9–2.0–3)
	7	64.0 (3–2.2–3)	63.0 (3–4.1–7)	64.3 (3–3.7–6)	**63.8** (9–3.0–5)
	8	66.5 (3–1.8–3)	62.7 (3–5.0–8)	62.4 (3–3.6–6)	**63.9** (9–3.8–6)
	Mean	**60.9** (12–5.1–8)	**60.5** (12–4.5–7)	**59.0** (12–4.8–8)	**60.7** (36–4.7–8)
Planted	9	58.4 (3–2.9–5)	55.9 (3–3.1–5)	59.5 (3–3.7–6)	**58.0** (9–3.2–6)
	10	57.9 (3–5.6–10)	53.5 (3–5.1–9)	57.8 (3–7.2–12)	**56.4** (9–5.6–10)
	11	68.7 (3–2.8–4)	68.3 (3–4.5–7)	68.7 (3–5.7–8)	**68.6** (9–3.9–6)
	12	58.1 (3–6.2–11)	59.3 (3–5.9–10)	56.8 (3–4.7–8)	**58.0** (9–5.0–9)
	Mean	**60.8** (12–6.2–10)	**59.3** (12–7.1–12)	**60.7** (12–6.8–11)	**60.2** (36–6.6–11)
Natural	13	63.3 (3–1.8–3)	59.5 (3–1.9–3)	54.7 (3–4.2–8)	**59.2** (9–4.5–8)
	14	72.8 (3–8.8–12)	67.7 (3–4.5–7)	63.5 (3–6.0–9)	**68.0** (9–7.1–10)
	15	63.0 (3–6.9–11)	56.8 (3–3.1–5)	58.1 (3–5.3–9)	**59.3** (9–5.4–9)
	16	70.1 (3–3.7–5)	70.7 (3–10.8–15)	61.6 (3–11.0–18)	**67.5** (9–9.1–13)
	Mean	**67.3** (12–6.8–10)	**63.7** (12–7.9–12)	**59.5** (12–7.0–12)	**63.5** (36–7.7–12)

a – centre point of bolts one, two and three are located at one, two and four metres, respectively, from base to top of tree, b – mean value, c – number of samples, d – standard deviation and e – coefficient of variation (%)

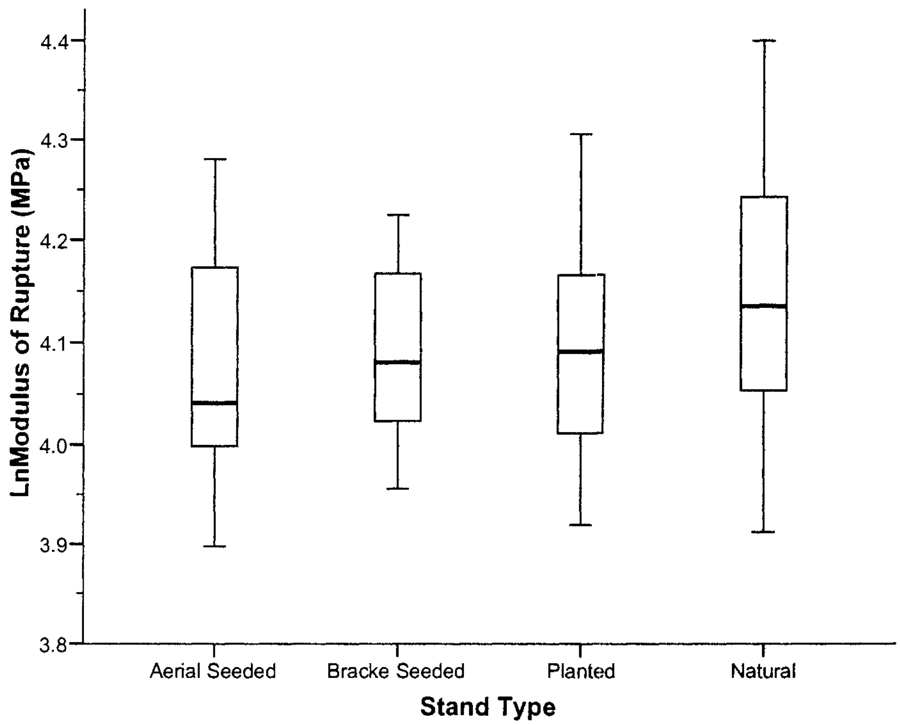


Figure 18. Comparative boxplots of the natural log of modulus of rupture for each regeneration method.

Similar to the plot mean MOE values, the plot mean MOR values exhibited variability within each stand (Table 16). Within the aerial seeded stand, plots 3 and 4 had greater mean MOR values than plots 1 and 2, with plot 2 having the lowest value of 54.8 MPa. Plots 7 and 8 within the Bräcke seeded stand had much greater mean MOR values than plots 5 and 6. Plot 11 had the greatest mean MOR value within the planted stand, while the remaining three plots had similar values that were much lower. Lastly, the natural stand contained two plots with large values, plots 14 and 16, and two plots with smaller values, plots 13 and 15. The dispersion of the MOR data within each plot is displayed in Figure 19. Outliers were found in plots 1 and 13. Overall, plot 16 had the greatest dispersion, plot 1 had the least dispersion excluding outliers, while plot 6 had the least dispersion with no outliers.

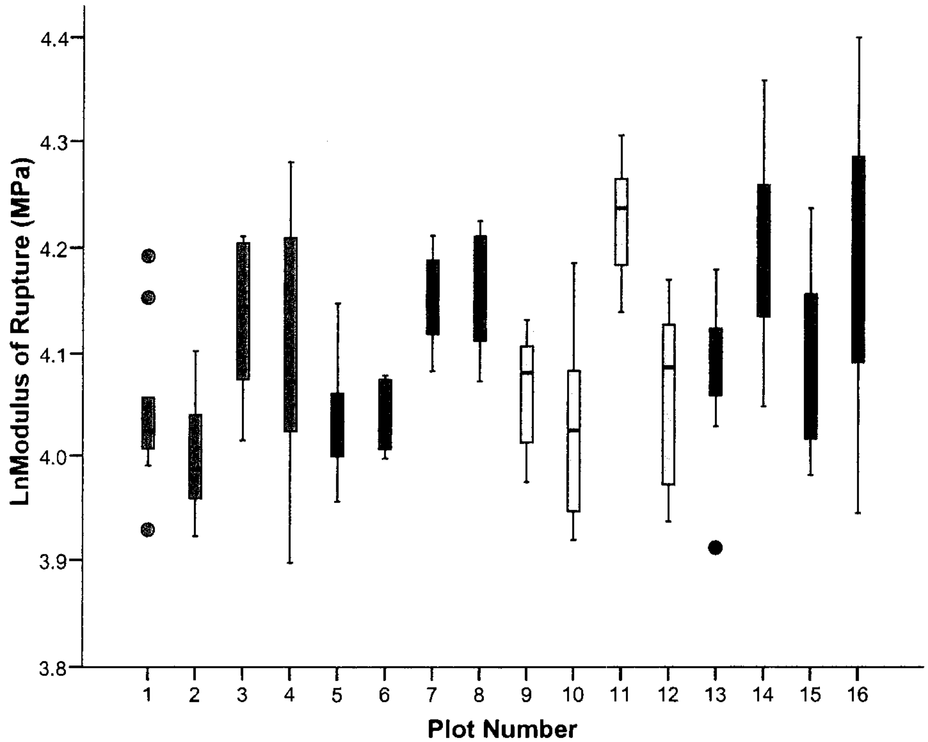


Figure 19. Natural log modulus of rupture comparative boxplots for each plot. Aerial seeded: plots 1 – 4; Bräcke seeded: 5 – 8; planted: 9 – 12; natural: 13 – 16.

The mean MOR values of the aerial seeded, Bräcke seeded and natural stands follow the pattern of decreasing MOR with increasing height (Table 16). In contrast, while bolt 1 had the greatest MOE value for the planted stand, bolt 3 was slightly greater than bolt 2.

The ANOVA generated to test the null hypothesis a) that regeneration method had no effect on mean MOR values and b) vertical position within individual regeneration methods had no effect on mean MOR values is displayed in Table 17. As previously mentioned, a difference in mean MOR was found between stands, but from the ANOVA (Table 17) this difference was not significant at the alpha 0.05 level. The null hypothesis that regeneration method had no effect on MOR was accepted.

Table 17. Summary of analysis of variance components for the natural log of modulus of rupture.

Source	d.f.	Sum of Squares	Mean Square	$F_{calculated}$	$F_{critical(0.05)}$	Sig.[a]
Stand	3	0.102	0.034	0.692	3.49	
Plot	12	0.591	0.049	2.776	2.07	*
Tree(Stand*Plot)	32	0.529	0.017			
Bolt	2	0.088	0.044	12.993	3.4	*
Stand*Bolt	6	0.065	0.011	3.211	2.51	*
Bolt*Plot(Stand)	24	0.081	0.003	1.561	1.70	
Bolt*Tree(Stand*Plot)	64	0.138	0.002			
Error	0					

[a] - * indicates significance at 0.05 level

A difference in mean MOR was found with vertical position (Table 16), and from the ANOVA (Table 17) and this difference was found to be significant. The null hypothesis that vertical position did not influence mean MOR within individual regeneration methods was rejected and the alternative hypothesis that vertical position influenced mean MOR within individual regeneration methods was accepted.

Tukey's HSD test was first performed for each stand-bolt interaction to determine where the significant difference ($\alpha = 0.05$) in MOR with respect to bolt position was occurring. The tests revealed that within the aerial seeded and natural stands, bolts 1 and 3 were significantly different. Contrast to this, bolt position within the Bräcke seeded and planted stands did not significantly differ in mean MOR (Figure 20).

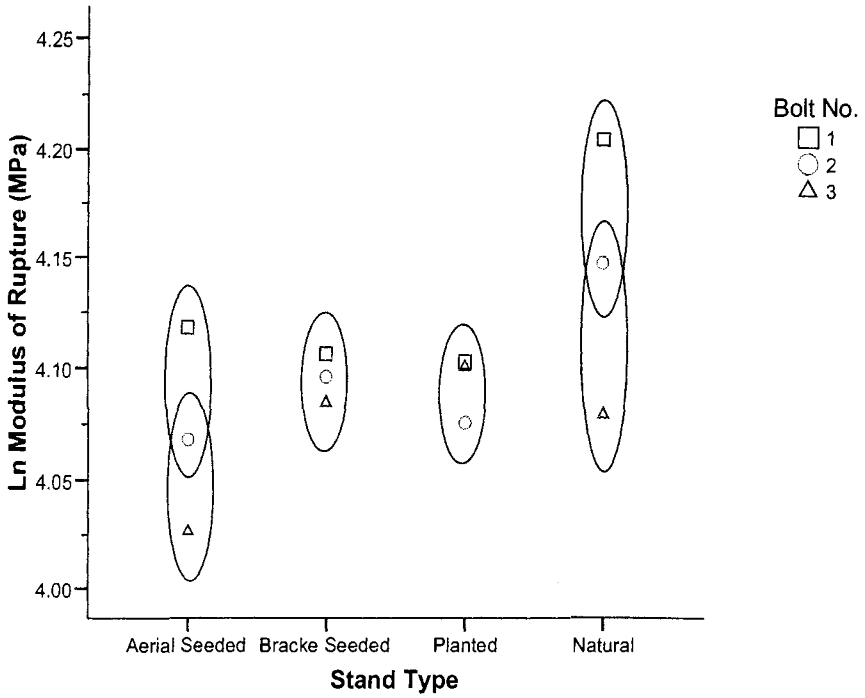


Figure 20. Mean natural log of modulus of rupture for each bolt position categorized by regeneration method. Markers found within the same ellipses signify bolts within each regeneration method that were not significantly different in MOR. Bolts 1, 2 and 3 were located at approximately 1, 2 and 4 m from the base of each tree.

From Table 17, it is evident that the factor Bolt was also significantly different in MOR; however, from the bolt-stand interaction post-hoc test it was determined that only the aerial seeded and natural stands exhibited this significant difference (Figure 20).

From Table 17, it was found that plots within regeneration methods were also significantly different in MOR. A Tukey's HSD test created a total of five homogeneous subsets of plots (Figure 21). Similar to the MOE post-hoc analysis, plots within individual regeneration methods were found to vary in MOR. Within the

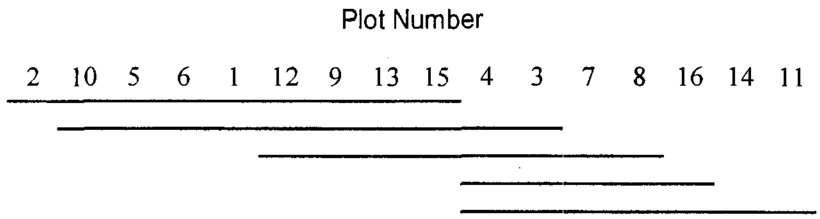


Figure 21. Tukey's HSD test homogeneous subsets for plots based on the natural log of modulus of rupture. Plots are ranked based on smallest to largest mean. Aerial seeded: plots 1 – 4; Bräcke seeded: 5 – 8; planted: 9 – 12; natural: 13 – 16.

aerial seeded stand, plots 3 and 4 were found to be significantly different from plot 2 in MOR. The planted stand had the least variation with plot 11 MOR significantly different from the other three plots. Plots 5 and 6 significantly differed in MOR from plots 7 and 8 within the Bräcke seeded stand. Similarly, within the natural stand two plots 13 and 15 were statistically different from plots 14 and 16. Between stands, no discernable pattern in differences between plots could be determined (Figure 22).

4.1.3. Treatment Effect on Specific Gravity

A statistical summary of the mean specific gravity values for each regeneration method is presented in Table 18. The planted stand had the highest mean specific gravity value of 0.40, whereas the aerial seeded stand had the lowest value of 0.38. Both the Bräcke seeded and natural stands had the same mean specific gravity value of 0.39. Comparative boxplots of specific gravity for each stand is displayed in Figure 23. Both the aerial seeded and planted stands contain an outlier. The median of the planted stand is greater than the others. With respect to dispersion, all stands have similar variability.

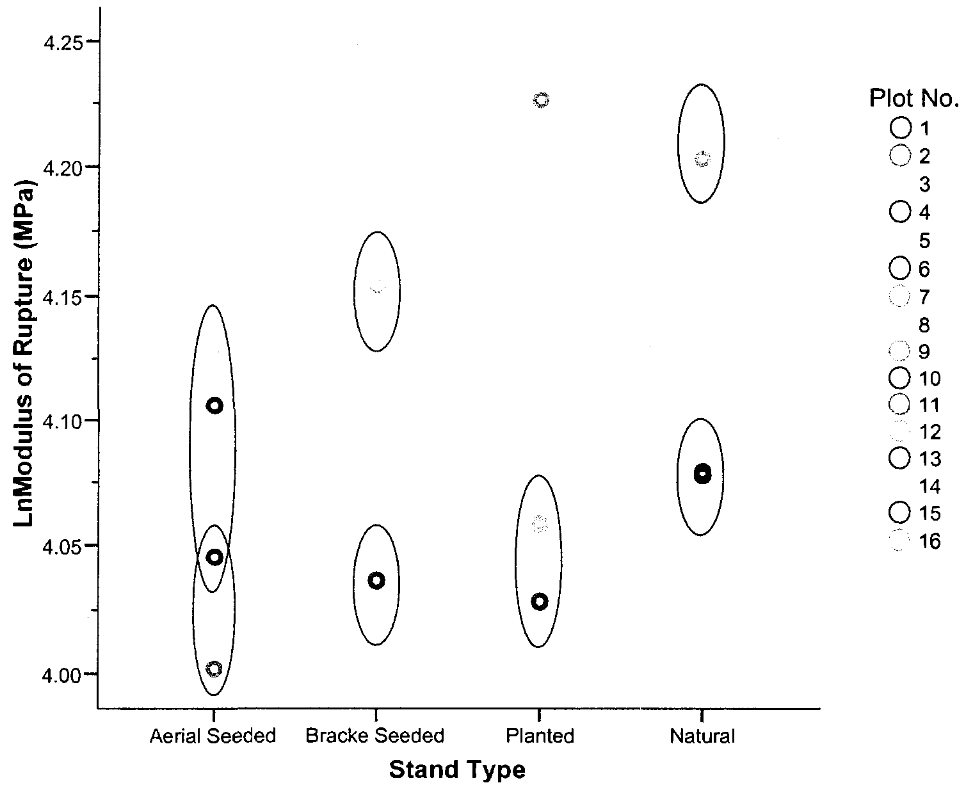


Figure 22. Mean plot natural log modulus of rupture categorized by regeneration method. Markers found within the same ellipses signify plots within each stand type that were not significantly different.

Mean specific gravity values between plots within each regeneration method did not greatly vary (Table 18). The largest difference in specific gravity within a stand was found between plots 11 and 12 within the planted stand with a difference of 0.04. Comparative boxplots of plot specific gravity is displayed in Figure 24. Outliers were found within plots 4, 9 and 15. Although mean specific gravity did not vary greatly between and within regeneration methods, some plots exhibited a larger spread of data, such as plots 7, 10 and 14, while others had much smaller dispersion, such as plots 2, 6 and 9.

Table 18. Specific gravity statistical summary of the four stands: aerial seeded, Bräcke seeded, planted and natural.

Stand Type	Plot No.	Bolt Position[a]			Mean
		Bolt 1	Bolt 2	Bolt 3	
Aerial Seeded	1	0.39[b] (3[c]–0.007[d]–2[e])	0.39 (3–0.014–4)	0.36 (3–0.005–1)	**0.38** (9–0.017–4)
	2	0.37 (3– 0.008–2)	0.36 (3–0.011–3)	0.36 (3–0.009–3)	**0.36** (9–0.009–3)
	3	0.39 (3–0.019–5)	0.39 (3–0.022–6)	0.37 (3–0.022–6)	**0.38** (9–0.020–5)
	4	0.40 (3–0.042–10)	0.38 (3–0.016–4)	0.37 (3–0.038–10)	**0.38** (9–0.032–8)
	Mean	**0.39** (12–0.02–6)	**0.38** (12–0.02–5)	**0.37** (12–0.02–6)	**0.38** (36–0.02–6)
Bräcke Seeded	5	0.38 (3–0.011–3)	0.37 (3–0.006–2)	0.36 (3–0.006–2)	**0.37** (9–0.01–3)
	6	0.37 (3–0.015–4)	0.37 (3–0.008–2)	0.36 (3–0.010–3)	**0.36** (9–0.011–3)
	7	0.41 (3–0.009–2)	0.40 (3–0.021–5)	0.37 (3–0.028–7)	**0.39** (9–0.026–7)
	8	0.40 (3–0.008–2)	0.38 (3–0.009–2)	0.36 (3–0.005–1)	**0.38** (9–0.016–4)
	Mean	**0.40** (12–0.02–5)	**0.38** (12–0.02–4)	**0.36** (12–0.01–4)	**0.39** (36–0.02–5)
Planted	9	0.41 (3–0.025–6)	0.39 (3–0.008–2)	0.40 (3–0.006–1)	**0.40** (9–0.016–4)
	10	0.41 (3–0.050–12)	0.39 (3–0.037–9)	0.40 (3–0.035–9)	**0.40** (9–0.037–9)
	11	0.42 (3–0.019–4)	0.41 (3–0.023–6)	0.41 (3–0.017–4)	**0.42** (9–0.018–4)
	12	0.39 (3–0.027–7)	0.38 (3–0.030–8)	0.37 (3–0.022–6)	**0.38** (9–0.025–7)
	Mean	**0.41** (12–0.03–7)	**0.39** (12–0.03–7)	**0.40** (12–0.03–7)	**0.40** (36–0.03–7)
Natural	13	0.40 (3–0.012–3)	0.37 (3–0.005–1)	0.37 (3–0.010–3)	**0.38** (9–0.015–4)
	14	0.43 (3–0.033–8)	0.40 (3–0.029–7)	0.39 (3–0.035–9)	**0.41** (9–0.032–8)
	15	0.40 (3–0.011–3)	0.37 (3–0.002–1)	0.37 (3–0.008–2)	**0.38** (9–0.014–4)
	16	0.43 (3–0.020–5)	0.41 (3–0.037–9)	0.39 (3–0.034–9)	**0.41** (9–0.032–8)
	Mean	**0.41** (12–0.02–6)	**0.39** (12–0.03–7)	**0.38** (12–0.02–6)	**0.39** (36–0.03–7)

a – centre point of bolts one, two and three are located at one, two and four metres, respectively, from base to top of tree, b – mean value, c – number of samples, d – standard deviation and e – coefficient of variation (%)

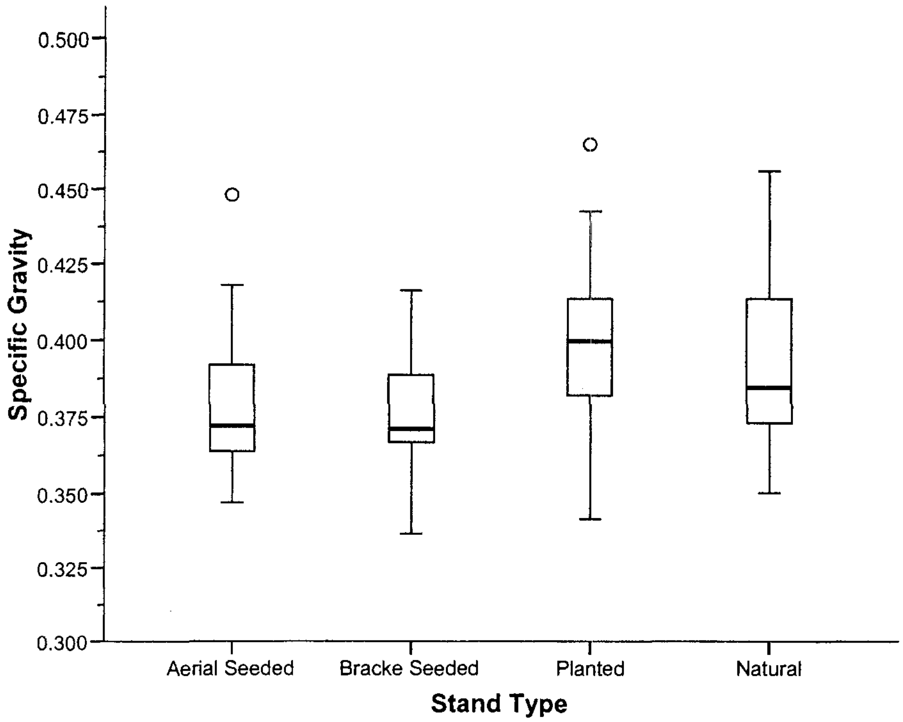


Figure 23. Comparative boxplots of specific gravity for each regeneration method.

The mean specific gravity values for bolt position decreased with height for the aerial seeded, Bräcke seeded and natural stands (Table 18). The planted stand mean specific gravity decreased from bolt 1 to 2, but bolt 3 was slightly higher than bolt 2.

The slight difference in mean specific gravity between stands was not significantly different at the alpha 0.05 level (Table 19); therefore, the null hypothesis that regeneration method had no effect on specific gravity was accepted. From Table 19, the ANOVA determined that bolt position as well as the interaction of bolt position and stand was significant. In this case, the null hypothesis was rejected and the alternative hypothesis that specific gravity was affected by vertical position within individual stands was accepted.

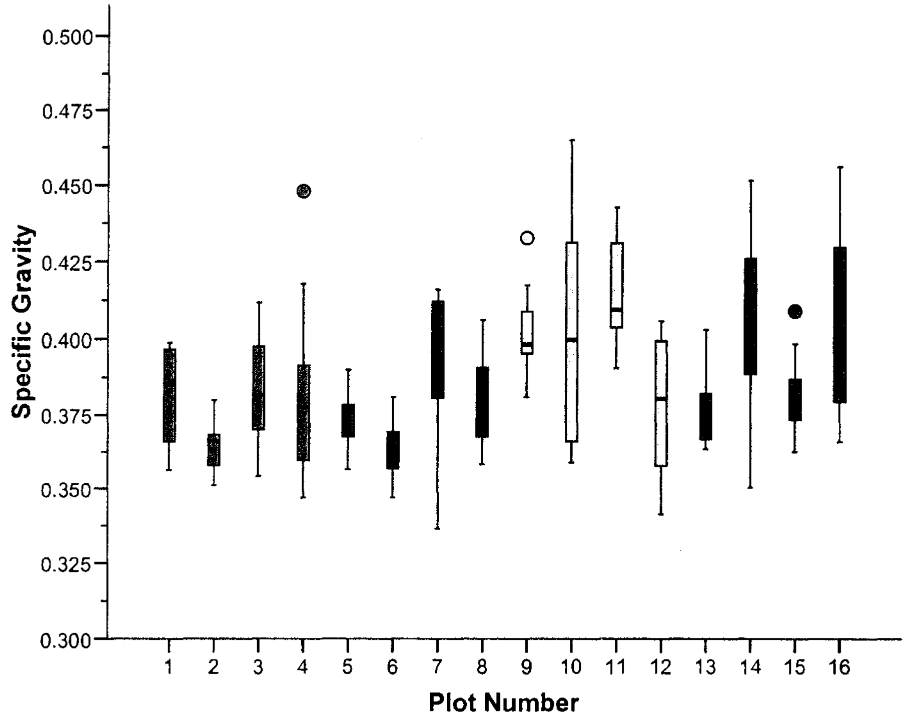


Figure 24. Comparative boxplots of specific gravity for each plot. Aerial seeded: plots 1 – 4; Bräcke seeded: 5 – 8; planted: 9 – 12; natural: 13 – 16.

Tukey HSD tests were first performed on the stand-bolt interaction to determine which bolt positions were significantly different with respect to specific gravity within each regeneration method. The test revealed that bolts 1 and 3 differed in mean specific gravity for the aerial seeded, Bräcke seeded and natural stands. Unlike these three stands, the mean specific gravity between bolts within the planted stand did not significantly differ (Figure 25).

Bolt position alone was determined to be significantly different (Table 19). But from the analysis of the stand-bolt interaction it is known that this significant difference is found within the aerial seeded, Bräcke seeded and natural stands, but not found within the planted stand.

Table 19. Summary of analysis of variance components for specific gravity.

Source	d.f.	Sum of Squares	Mean Square	$F_{calculated}$	$F_{critical(0.05)}$	Sig.[a]
Stand	3	1.391E-02	4.637E-03	2.702	3.49	
Plot(Stand)	12	2.060E-02	1.716E-03	1.346	2.07	
Tree(Stand*Plot)	32	4.080E-02	1.275E-03			
Bolt	2	1.309E-02	6.547E-03	54.784	3.4	*
Stand*Bolt	6	2.006E-03	3.343E-04	2.797	2.51	*
Bolt*Plot(Stand)	24	2.868E-03	1.195E-04	1.439	1.70	
Bolt*Tree(Stand*Plot)	64	5.315E-03	8.304E-05			
Error	0					

[a] - * indicates significance at 0.05 level

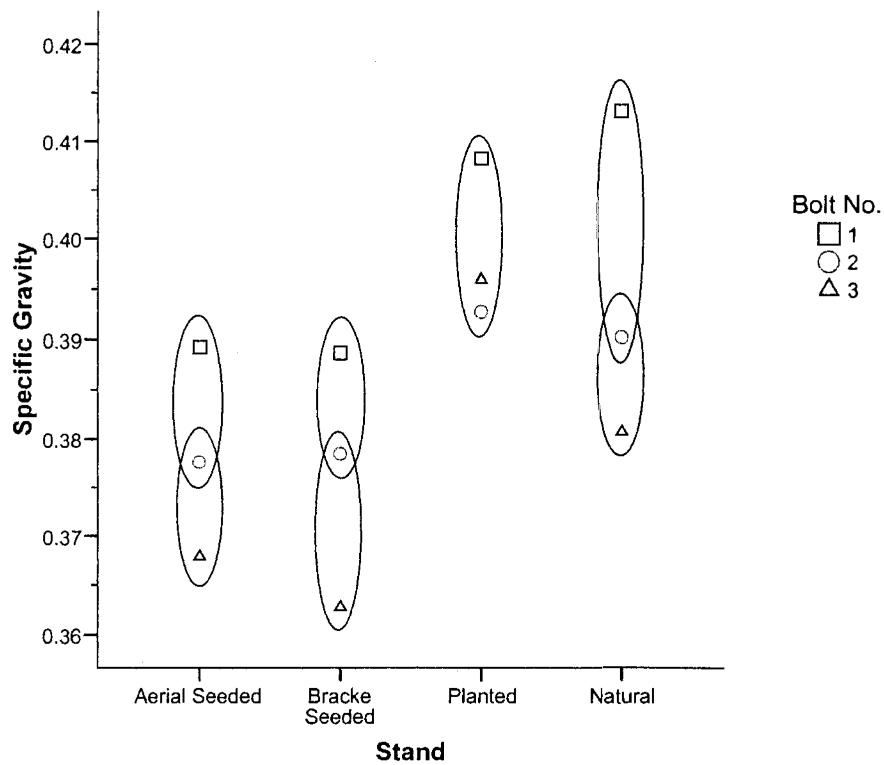


Figure 25. Mean specific gravity for each bolt position categorized by regeneration method. Markers found within the same ellipses signify bolts within each regeneration method that are not significantly different. Bolts 1, 2 and 3 were located at approximately 1, 2 and 4 m, respectively.

4.2. MECHANICAL PROPERTIES AS RELATED TO SPECIFIC GRAVITY

From Shapiro-Wilks' tests of normality it was determined that transformations were not necessary to achieve normality (Appendix II). The assumption of homogeneity of variance also holds true in most cases (Appendix III). However, the results must be reviewed with caution, since not all bolt positions for MOR and MOE were normally distributed due to small sample size.

From the preliminary analyses, a few outliers were observed. For the MOR data an outlier was observed within the aerial seeded bolt 2 scatter plot. In addition, one outlier within the analysis of all aerial seeded samples combined from each bolt position was observed. For the MOE data one outlier was found from the regression analyses of aerial seeded bolt 1 and for all aerial seeded samples combined. An outlier was also observed in the natural stands of bolts 1 and 3. Furthermore, two outliers were found for the analyses of all bolt samples combined for the natural stand MOE data. The observed outliers were removed before conducting regression analyses.

The mean, standard deviation, minimum and maximum values and the coefficient of variation for specific gravity and MOR for each regeneration method, separated by bolt position, are displayed in Table 20. These same statistics are presented in Table 21 for specific gravity and MOE. All wood properties were adjusted to 12 percent moisture content.

4.2.1. Linear vs. Curvilinear Regression Equations

The linear and curvilinear equation coefficients and coefficients of determination for specific gravity as a function of MOR and as a function of MOE are presented in Table 22 and Table 23, respectively. The relationships are plotted in Appendix IV. Both regression methods found a significant positive relationship ($\alpha = 0.05$) between specific gravity and mechanical properties (MOR and MOE) for all bolt positions and for each regeneration method. Consequently, the null hypothesis, that the slope equals zero, was rejected for both linear and curvilinear relationships.

Table 20. Summary of test results for specific gravity and modulus of rupture (MPa) for four regeneration methods based on stem location (bolt 1, 2 and 3 were situated at 1, 2 and 4 m, respectively).

Stand Type	Statistic[a]	Specific Gravity[b]				Modulus of Rupture[b] (MPa)			
		Bolt 1	Bolt 2	Bolt 3	Mean	Bolt 1	Bolt 2	Bolt 3	Mean
Aerial Seeded	No.	89	76	62	227	89	76	62	227
	Mean	0.39	0.38	0.37	0.38	61.5	58.4	57.6	59.4
	Std. Dev.	0.03	0.02	0.03	0.03	7.3	8.6	7.8	8.1
	Min.	0.33	0.34	0.33	0.33	48.3	41.2	45.0	41.2
	Max.	0.49	0.44	0.45	0.49	81.0	85.6	79.3	85.6
	C.V. %	8.0	5.5	7.4	7.4	11.9	14.7	13.6	13.6
Bräcke Seeded	No.	94	79	61	234	94	79	61	234
	Mean	0.39	0.38	0.36	0.38	61.4	60.3	60.3	60.8
	Std. Dev.	0.03	0.02	0.02	0.03	8.1	7.2	7.3	7.6
	Min.	0.32	0.33	0.32	0.32	43.4	44.8	44.5	43.4
	Max.	0.46	0.44	0.41	0.46	80.2	77.9	77.3	80.2
	C.V. %	7.8	6.2	5.4	7.3	13.2	12.0	12.1	12.5
Planted	No.	123	109	85	317	123	109	85	317
	Mean	0.40	0.39	0.39	0.40	59.9	59.6	61.1	60.1
	Std. Dev.	0.04	0.03	0.03	0.04	9.1	8.5	9.1	8.9
	Min.	0.32	0.33	0.32	0.32	43.6	43.3	42.5	42.5
	Max.	0.51	0.47	0.46	0.51	83.5	85.9	86.6	86.6
	C.V. %	10.1	8.7	8.3	9.3	15.2	14.2	14.9	14.8
Natural	No.	97	80	57	234	97	80	57	234
	Mean	0.41	0.39	0.38	0.40	66.3	63.2	59.7	63.6
	Std. Dev.	0.04	0.03	0.03	0.03	9.9	9.4	8.9	9.8
	Min.	0.34	0.33	0.33	0.33	48.2	41.1	40.9	40.9
	Max.	0.52	0.49	0.45	0.52	95.4	85.3	79.3	95.4
	C.V. %	8.6	8.4	7.6	8.8	14.9	14.8	14.9	15.4

[a]No., number of samples; Std. Dev., standard deviation; Min., minimum value; Max., maximum value; C.V., coefficient of variation expressed as a percentage
[b]Values adjusted to 12% moisture content

Table 21. Summary of test results for specific gravity and modulus of elasticity (MPa) for four regeneration methods based on stem location (bolt 1, 2 and 3 were situated at 1, 2 and 4 m, respectively).

Stand Type	Statistic[a]	Specific Gravity[b]				Modulus of Elasticity[b] (MPa)			
		Bolt 1	Bolt 2	Bolt 3	Mean	Bolt 1	Bolt 2	Bolt 3	Mean
Aerial Seeded	No.	89	76	62	227	89	76	62	227
	Mean	0.39	0.38	0.37	0.38	5466	5090	5042	5224
	Std. Dev.	0.03	0.02	0.03	0.03	1221	1272	1217	1247
	Min.	0.33	0.34	0.33	0.33	2796	2790	2789	2789
	Max.	0.49	0.44	0.45	0.49	8575	8675	8685	8685
	C.V. %	8.0	5.5	7.4	7.4	22.3	25.0	24.1	23.9
Bräcke Seeded	No.	94	79	61	234	94	79	61	234
	Mean	0.39	0.38	0.36	0.38	5440	5522	5567	5501
	Std. Dev.	0.03	0.02	0.02	0.09	1447	1276	1129	1308
	Min.	0.32	0.33	0.32	0.32	2482	2381	2831	2381
	Max.	0.46	0.44	0.41	0.46	10286	8742	8474	10286
	C.V. %	7.8	6.2	5.4	7.3	26.6	23.1	20.3	23.8
Planted	No.	123	109	85	317	123	109	85	317
	Mean	0.40	0.39	0.39	0.40	5335	5432	5653	5454
	Std. Dev.	0.04	0.03	0.03	0.04	1493	1273	1493	1422
	Min.	0.32	0.33	0.32	0.32	2015	2827	2372	2015
	Max.	0.51	0.47	0.46	0.51	9014	8998	9089	9089
	C.V. %	10.1	8.7	8.3	9.3	28.0	23.4	26.4	26.1
Natural	No.	96	80	56	232	96	80	56	232
	Mean	0.41	0.39	0.38	0.40	5998	5835	5546	5833
	Std. Dev.	0.03	0.03	0.03	0.03	1669	1388	1525	1546
	Min.	0.34	0.33	0.33	0.33	1410	1909	2461	1410
	Max.	0.50	0.49	0.45	0.50	9823	8757	8825	9823
	C.V. %	8.2	8.4	7.3	8.5	27.8	23.8	27.5	26.5

[a]No., number of samples; Std. Dev., standard deviation; Min., minimum value; Max., maximum value; C.V., coefficient of variation expressed as a percentage
[b]Values adjusted to 12% moisture content

Table 22. The linear and curvilinear regression coefficients and coefficients of determination for modulus of rupture as related to specific gravity for each regeneration method (Source: Appendix IV).

Stand Type	Bolt No.	No. of Samples	Modulus of Rupture[a]					
			Linear[b]			Curvilinear		
			a	b	R^2	α	β	R^2
Aerial Seeded	Bolt 1	89	- 0.05	158.14	0.457	160.53	1.021	0.452
	Bolt 2	76	- 28.19	229.98	0.307	237.63	1.445	0.291
	Bolt 3	62	- 32.20	241.91	0.725	256.93	1.513	0.709
	All	227	- 15.86	198.00	0.476	202.89	1.276	0.466
Bräcke Seeded	Bolt 1	94	- 21.27	210.97	0.627	219.33	1.364	0.637
	Bolt 2	79	- 8.67	181.21	0.346	181.10	1.144	0.341
	Bolt 3	61	- 10.53	194.91	0.269	195.48	1.167	0.273
	All	234	- 5.31	173.53	0.406	174.66	1.099	0.407
Planted	Bolt 1	123	- 3.87	157.62	0.494	155.86	1.063	0.507
	Bolt 2	109	0.84	150.03	0.363	148.65	0.982	0.369
	Bolt 3	85	- 7.16	173.57	0.386	166.73	1.084	0.362
	All	317	- 1.06	154.08	0.406	152.32	1.013	0.407
Natural	Bolt 1	97	- 12.55	192.72	0.469	195.17	1.216	0.470
	Bolt 2	80	- 26.22	229.69	0.643	241.33	1.427	0.624
	Bolt 3	57	- 10.13	182.66	0.360	177.18	1.139	0.328
	All	234	- 17.39	204.70	0.528	207.61	1.284	0.513
	Mean		-12.48	189.61	0.454	192.09	1.20	0.447

[a]A significant relationship ($\alpha = 0.05$) between specific gravity and MOR was found for all bolts and bolts combined for each stand type following both linear and curvilinear relationships

[b]All slope coefficients are significant at 5% level

Table 23. The linear and curvilinear regression coefficients and coefficients of determination for modulus of elasticity as related to specific gravity for each regeneration method (Source: Appendix IV).

Stand Type	Bolt No.	No. of Samples	Modulus of Elasticity[a]					
			Linear			Curvilinear		
			a	b	R^2	α	β	R^2
Aerial Seeded	Bolt 1	89	- 5182.68	27346.14	0.487	36880	2.046	0.446
	Bolt 2	76	- 9897.26	39820.88	0.419	80725	2.855	0.392
	Bolt 3	62	- 7541.26	33897.69	0.593	52726	2.391	0.515
	All	227	- 6601.14	31113.92	0.490	46472	2.283	0.449
Bräcke Seeded	Bolt 1	94	- 9143.41	37202.30	0.611	72059	2.790	0.591
	Bolt 2	79	- 9219.64	38712.48	0.510	73959	2.711	0.473
	Bolt 3	61	- 5454.20	30315.99	0.273	42937	2.037	0.276
	All	234	- 5860.11	29834.22	0.406	41803	2.126	0.379
Planted	Bolt 1	123	- 5352.05	26419.65	0.519	33570	2.068	0.471
	Bolt 2	109	- 2198.43	19494.48	0.271	19110	1.364	0.258
	Bolt 3	85	- 5532.27	28430.23	0.384	34126	1.961	0.322
	All	317	- 3972.53	23741.19	0.377	26558	1.745	0.339
Natural	Bolt 1	97	- 6895.18	31623.27	0.398	42845	2.238	0.238
	Bolt 2	80	- 6153.59	30783.37	0.527	39011	2.040	0.427
	Bolt 3	57	- 7333.88	33793.50	0.378	45154	2.213	0.260
	All	234	- 5955.78	29844.23	0.421	36512	2.012	0.301
	Mean		-6393.34	30773.35	0.442	45278	2.18	0.384

[a]A significant relationship (α = 0.05) between specific gravity and MOR was found for all bolts and bolts combined for both the linear and curvilinear relationships
[b]All slope coefficients are significant at 5% level

5.0 DISCUSSION

This study was designed to compare the effects of four regeneration methods on three wood properties of jack pine, along different vertical positions of the tree, grown in northwestern Ontario. The investigations were based on small clear wood samples. Implementing a regeneration method is the initial stage of controlling the stand density, which has been found to have a powerful effect for manipulating wood yield and quality (Larson 1969). Different regeneration methods and available growing space influence both tree form and growth characteristics (Ralston 1953; Janas and Brand 1988; Van Damme and McKee 1990). It was thought that changes in tree characteristics brought about by regeneration method would consequently result in changes in wood properties.

Data indicating the initial stem density of these particular stands were unavailable. However, the common practices of regenerating jack pine within northwestern Ontario during the time these stands were established were known. In general, aerial seeding of jack pine was implemented in areas that were site prepared with disc trenchers and seeded at a rate of 10,000 to 15,000 stems/ha with variable results. Bräcke seeding was implemented at 8,000 stems/ha while planting targets were approximately 2,200 stems/ha [L. Van Damme (per. comm., July 21, 2008)]. Natural regeneration following fire has been documented to result on average, 25,000 stems/ha (Van Damme and McKee 1990). Within this study, approximately 25 years after establishment, the Bräcke seeded stand contained the most stems/ha followed by the natural, aerial seeded and planted stands (Table 12). Although these regeneration methods have produced differing numbers of stems/ha, the average tree diameters were similar. This observation is interesting since, in general, the greater the number of initial stems/ha the greater the competition for resources. This, in turn, influences tree growth, i.e. more competition results in slower growth. For example, in Tong and Zhang's (2005) study of different initial planting spacings of mature jack pine (5 by 5, 7 by 7 and 9 by 9 feet) they found that these spacings were significantly different ($p < 0.05$) in diameter, branch size, taper, crown length and crown width. They observed that as initial spacing increased these tree attributes also increased. In our study, the stands studied were established around 1980 and establishment success rates may have varied between them leading to the observed similarities in average diameter.

In addition to similar average diameters between regeneration methods, trees selected in this study for the sampling of wood properties - MOE and MOR in static bending and specific gravity - were found to be similar in diameter and crown characteristics (Table 13). Similarities in the measured characteristics were primarily due to the sample design. Sample trees were selected at random based on a minimum 10 cm dbh and free from visual defect. As the stands were established around 1980, the selection of trees greater or equal to 10 cm dbh was limiting for all four stands. Consequently, trees sampled within this study were representative of the largest trees within each established plot. From visual observations, these trees tended to have more growing space. They tended to be classed as co-dominate or dominate. Also, because they were generally the largest, they were not necessarily representative of the whole plot. This was an aspect that could not have been avoided because of the size requirements of the wood samples for static bending tests.

5.1. TREATMENT EFFECTS ON WOOD PROPERTIES

5.1.1. Treatment Effects on Modulus of Elasticity and Modulus of Rupture

5.1.1.1. Between Regeneration Methods

It was hypothesized that the differing regeneration methods would result in different mechanical property values due to differing initial stem densities. The results of ANOVA models for comparison of both mechanical properties – MOR and MOE – revealed that these properties were not statistically different ($\alpha \leq 0.05$) for the four regeneration methods. The lack of significance in mechanical properties may have been due to sample tree characteristics and juvenile wood content.

As described above, the trees had similar diameter and crown characteristics as well as similar crown classes. Dominate and co-dominate trees generally possess large, vigorous crowns with relatively wide bands of earlywood produced along the bole of the tree (Larson 1962). Since the majority of trees sampled were within the co-dominate crown class and had similar crown characteristics (Table 12), overall property differences may not have been identified because trees were in a similar stage of development and dominance. For example, Amarasekara and Denne (2002) observed that crown class influenced MOR and MOE for Corsican pine (*Pinus nigra* var. maritime). They found that MOR and MOE from small clear samples decreased as crown class went from dominate to co-dominate to suppressed.

If lumber sized samples were tested, rather than small clear samples, a significant difference in MOE and MOR in static bending may have been observed. Full sized lumber contains various growth defects including knots. Knots reduce the strength of structural sized lumber. For example, in a study of white spruce (*Picea glauca* (Moench) Voss) bending properties of full sized lumber, Zhou and Smith (1991) found that knots accounted for 73% of failure in bending.

In addition to similar tree attributes, the presence of juvenile wood most likely contributed to a lack of significant difference of MOE and MOR between the four regeneration methods. Jack pine juvenile wood production has been observed to extend from 12 to 18 years of age (Bodie 1988) or up to 20 years of age (Hatton and Hunt 1993). Trees sampled within this study were established around 1980. Therefore, the wood samples tested were comprised of juvenile wood. It is unlikely that mature wood was present because a zone of transition wood exists between juvenile and mature wood. Also, outer growth rings would have been removed during the bolt processing stages. Within the juvenile zone, wood properties rapidly change from pith to bark (Figure 4). For example, Seth (1981) observed that the lengths of first formed earlywood tracheids of blue pine (*Pinus wallichiana* A. B. Jackson) were found to rapidly increase from pith radially towards the bark up to the 10th ring, then more slowly up to the 40th ring. After this point tracheid length levelled off. The authors referred to these zones of growth as juvenile, transition and mature, respectively. In a review of MFA, Barnett and Bonham (2004) described that MFA in softwoods rapidly decrease from pith to bark which eventually stabilizes. These two examples are in accordance with the schematic diagram in Figure 4 describing property variations between juvenile and mature wood. For this present study, the jack pine wood samples for the determination of MOE and MOR in static bending would have contained rapidly changing cell characteristics similar to those displayed in Figure 4 because the samples were composed of juvenile wood. As a result, variability in MOE and MOR was present within each regeneration method. This was evident by the significant difference observed between plots within regeneration methods. Due to this significant difference, a wide dispersion of MOE and MOR data occurred within each regeneration method. Consequently, an overlap of MOE and MOR data occurred across all regeneration methods, which in turn resulted in a lack of significance in MOE and MOR between the four regeneration methods. Within the planted stand, one plot had very high values of MOE and MOR. This plot was found within an area dominated by bedrock and contained the least amount of trees. Disks were removed from these trees for another study and it was found that these were several years older than 25 years. These trees were either naturally regenerated or were planted previously. Being older, these trees contained more mature wood, thus leading to higher mechanical property values.

The variability in plots within each regeneration method may have been due to different growth conditions, such as growing space and soil moisture, and tree form characteristics. Studies comparing MOE and MOR values between trees with varying initial planting densities have shown that wider the spacing, lower the mechanical property. For example, Middleton and Monroe (2001) studied the effect of stand density on second-growth western hemlock tree and wood characteristics at age 90 years. Three stands from Vancouver Island were selected for study: two from the north at stand densities of 580 and 930 stems/ha and one 500 km south also with 930 stems/ha. They found that tree MOE and MOR values from small clear wood specimens obtained from the more dense stands were significantly higher than values obtained from the less dense stand. Zhang *et al.* (2005) studied MOE and MOR in static bending for jack pine lumber obtained from the oldest jack pine initial spacing trials established in Wellston, Michigan in 1941. The spacings of interest were 5 × 5 (1.52 × 1.52 m), 7 × 7 (2.13 ×

2.13 m), and 9 × 9 (2.74 by 2.74 m) feet. Overall, MOE was greater for the smaller spacing (9218 MPa) compared to the larger spacing (8538 MPa). The same pattern was found for MOR. Although this study examined four regeneration methods, trees selected for sampling in one plot may have had more growing space compared to another plot. This would cause variations in the juvenile cell characteristics, which would have influenced MOE and MOR.

With respect to tree form characteristics, the height to live crown between plots (Table 13) within each regeneration method was variable. Larson (1969) explains that the type of wood formed (juvenile, transition or mature) is influenced by the developmental stages of the tree and the proximity of the wood to the live crown. A young tree is comprised primarily of crown. It is known that earlywood formation is favoured by close proximity to foliage organs; therefore, young trees tend to have a greater portion of earlywood. As a tree matures, crown size diminishes and extends upwards with height growth. The stem wood found within the crown area still produces wood of predominately earlywood and juvenile characteristics because of its close proximity to foliage, but wood found downward in the stem which is further from the growth centres, will begin to exhibit more latewood and mature characteristics. Since the height to live crown was variable within each regeneration method, MOE and MOR would also have been variable because of the crown influences on cell characteristics.

If the trees were older and contained a greater portion of mature wood, differences in MOE and MOR may have been found. Eriksson *et al.* (2006) demonstrated that silviculture regime does influence wood properties of Scots pine. Direct seeded trees, 85 years of age subjected to several thinnings throughout the stands life, were 150% stiffer and 70% stronger in bending compared to seed-tree sheltered planted trees, 56 years of age subjected to several cleanings. The difference in strength properties were attributed to the lack of mature wood in the planted stand. The direct seeded trees began to produce strong wood at 20 years of age while the planted trees had yet to produce mature wood. Eriksson *et al.* (2006) clearly demonstrated that silviculture regime influences wood strength. In summary, the findings of this present jack pine study indicated that MOE and MOR are highly variable in static bending during the juvenile stage of development.

Both the mean MOE and MOR values from all four regeneration methods were low compared to published values presented by Jessome (1977) and Porter (1981). Values presented by these two authors were most likely based on mature trees that were naturally grown as opposed to planted or artificially seeded. Trees sampled within this study were primarily composed of juvenile wood, which has been demonstrated to be much weaker in strength than mature wood (Bendtsen 1978; Bendtsen and Senft 1986; Kretschmann and Bendtsen 1992; Bao *et al.* 2001; Passialis and Kiriazakos 2004). For example, Bendtsen and Senft (1986) demonstrated an approximate fivefold increase in MOE for pine from early juvenile wood to mature wood and an approximate threefold increase in MOR. In both plantation and naturally grown trees, Boa *et al.* 2001 found that juvenile wood was weaker than mature wood. Differences in strength between juvenile and mature wood can be attributed to the differing cell characteristics (Figure 4). In addition to juvenile wood content, compression wood may have been a contributing factor resulting in lower mechanical strength values. Juvenile wood tends to contain compression wood, which is weaker than normal wood (Panshin and de Zeeuw 1980; Dhubhain *et al.* 1988). When a tree is young, its stem is quite flexible and often the presence of wind induces the production of compression wood to maintain a fixed vertical position. With age, the mechanical properties of the trees within these stands are expected to increase due to the production of mature wood.

5.1.1.2. Vertical Variation

For all four regeneration methods, MOE was not significantly different as distance from stump increased. Although a significant difference was not found, the aerial seeded and natural stands followed the expected pattern of decreased MOE with increased distance from stump. The decrease in MOE with distance from stump has been observed in planted slash pine subjected to various thinnings (MacPeak *et al.* 1990), planted jack pine (Zhang et al. 2005) and seeded Scots pine subject to various thinnings (Eriksson *et al.* 2006). In contrast, the Bräcke seeded and planted stands did not exhibit this pattern. The Bräcke seeded stand demonstrated the opposite pattern of increasing MOE with height. In this case, the average lower stiffness value at the base may have been due to compression wood, which is a common occurrence at and below breast height. The difference in stiffness between bolt 2 and 3 are minimal. Presence of extractives further up the tree may have contributed to this. Similarly, greater stiffness in the average planted bolt 3 compared to bolt 1 and 2 was most likely due to resin content. This pattern has been observed in planted loblolly pine at age 35 years by Biblis *et al.* (1995); however, the authors did not provide any reason for the difference.

Vertical variation in MOR was observed to be significantly different between bolts 1 and 3 for the aerial seeded and natural stands. The Bräcke seeded stand followed the pattern of decreasing MOR with distance from base, but the differences were very minimal. Also, the planted stand followed this pattern, except bolt 3 was marginally greater than bolt 2. The lack of significant difference and similar uniformity in MOR with height for the Bräcke seeded and planted stands may be attributed to crown differences. On average, the height to live crown for the aerial seeded and natural stands were approximately 4.5 m; thus, top bolts within these stands were removed just below live crown. In contrast, the height to live crown for the Bräcke seeded and planted stands was greater by approximately 1 m (Table 13). As previously discussed, cell characteristics are influenced by proximity to live crown and cambial age. Further from the crown, the amount of cells exhibiting latewood characteristics, such as thicker cell walls, increase because of an older cambium and a larger distance from growth centres. These cells are stronger than earlywood cells, which are found in greater proportions closer to and within the crown; therefore, wood produced higher within the tree tends to be weaker than wood produced downwards along the bole. Also, the aerial seeded and natural stands might have begun production of transition wood at the base of the stem. This would create differences in earlywood and latewood proportions, MFA, specific gravity and cell length, which could have contributed to differences in MOR between bolts 1 and 3.

5.1.2. Specific Gravity

5.1.2.1. Between Regeneration Methods

Specific gravity was not significantly different among the four regeneration methods studied. Also, unlike the analyses of MOE and MOR, plots were not found to be significantly different. The average nominal specific gravity values of the regeneration methods were 0.38, 0.39, 0.40 and 0.39, for the aerial seeded, Bräcke seeded, planted and natural stands, respectively. A lack of significant difference may be due to the strong jack pine heritability of specific gravity (Okwuagwu and Guries 1980; Villeneuve *et al.* 1987). Also, a significant difference may not have been observed as the trees were in a juvenile stage of development. Larocque and Marshall (1995) studied the influence of seven initial planting spacings on red pine wood relative density. They found that stand density strongly effects wood density. At young ages, less than 20 years old, the relative wood densities did not differ much between initial spacings, but as the stands grew older relative wood density increased. They also found that the closer the initial spacings the faster the wood relative densities increased.

These specific gravity values are much lower than the nominal specific gravity of 0.44 for jack pine reported by Porter (1981). This higher value is most likely based on trees containing mature wood, while the smaller specific gravity values observed within our study are primarily from juvenile wood. For hard pines, it has been documented that as growth ring number increases from pith to bark, specific gravity increases (Spurr and Hsiung 1954; Megraw 1985; Zobel and van Buijtenen 1989). Thus, as trees within these stands increase in age, specific gravity will correspondingly increase as more mature wood is produced.

5.1.2.2. Vertical Variation

The aerial seeded, Bräcke seeded and natural stands exhibited a decrease in specific gravity with height. Similar differences have been observed by Megraw (1985) for loblolly pine, Mackes *et al.* (2005) for ponderosa pine and Duchesne (2006) for jack pine. Within these three stands, bolt positions 1 and 3 were significantly different in specific gravity. The planted stand did not exhibit these differences in bolt position as bolt 3 was greater in specific gravity compared to bolt 2. Larson (1962) attributed an increase in specific gravity within the upper crown to the presence of knots and branches. Within this study, these characteristics were avoided within the samples; however, an increase in resin content and disoriented grain caused by compression wood produced near branches may have led to an increase in specific gravity within bolt 3. Taras and Saucier (1996) observed that determining specific gravity from unextracted increment cores for the southern pines resulted in overestimations of 6 to 7%.

5.2. MECHANICAL PROPERTIES AS RELATED TO SPECIFIC GRAVITY

5.2.1. Linear vs. Curvilinear Equations

Within this study, a significant relationship was observed for the linear and curvilinear relationships between specific gravity and MOR for jack pine. Most researchers, at a species level, have measured this relationship following the linear relationship (Pearson and Gilmore 1971; Pearson and Gilmore 1980; Bendtsen and Senft 1986). In contrast, Zhang (1997) found that a curvilinear relationship at a species level was better suited. From this study, based on the coefficient of determination, the linear and curvilinear methods were consistent in describing the amount of variation in MOR explained by specific gravity. In contrast, the linear equation consistently accounted for more variation in MOE expressed by specific gravity.

With respect to vertical variation, within each regeneration method variation in the mechanical properties (MOR or MOE) explained by specific gravity was not consistent. Trends may not have been evident because of the variable nature of juvenile wood characteristics. Also, there may have been instances where data from an individual tree distorted the variation.

Percentage of variability in MOR or MOE explained by specific gravity has been observed to be greater within other studies (Pearson and Gilmore 1971; Bendsten and Senft 1986; Deresse *et al.* 2003) as compared to the results of our study (Table 22 and Table 23). This difference was most likely due to the fact that sample trees were primarily composed of juvenile wood, which has variable properties. If the trees had a greater proportion of mature wood, the cell characteristics would have been more uniform, thereby resulting in a stronger relationship between MOR or MOE and specific gravity.

5.2.2. Mechanical Property - Specific Gravity Relationships Compared Between Regeneration Methods

The mechanical property (MOR or MOE) slope coefficients between the aerial seeded, Bracke seed and natural stands were similar. This indicated that the relationship between MOR or MOE and specific gravity were similar between these three regeneration methods. In contrast the mechanical property (MOE or MOR) slope coefficient of the planted stand was lower than the other regeneration methods. A weaker relationship may be, in part, due to a lower stem density. With a greater amount of growing space, the changes in juvenile wood characteristics with age may have been slower.

6.0 CONCLUSION

The effects of regeneration method on static bending properties of small clear wood specimens and wood specific gravity of juvenile jack pine were investigated in this study. It was hypothesized that different regeneration methods would produce different wood properties because of differences in initial stand density. With respect to MOE and MOR in static bending and specific gravity, significant differences were not found between different regeneration methods. However, variability of these properties within each regeneration method was found. This indicates that wood properties of jack pine within the juvenile stage of development are quite variable, regardless of regeneration method.

All four regeneration methods did not significantly differ along the stem for MOE. With respect to MOR and specific gravity, the aerial seeded and natural stands were the only regeneration methods that exhibited a significant difference between the bottom and top bolts. The planted stand produced the least variability along the bole; all three properties were not significantly different between the three vertical positions. The Bräcke seeded stand was similar to the planted stand, except for a significant difference in specific gravity between the bottom and top bolts. These results indicate that in future, there may be potential in dividing jack pine logs along the stem for various uses, based on regeneration method. For example, the top portions of logs from the aerial seeded and natural stands may be more suitable for pulp production, while the bottom log may be utilized as lumber. This sorting method would add more value to the utilization of jack pine.

Specific gravity – mechanical property relationships were also investigated and it was found that a significant relationship existed between MOR and specific gravity, and MOE and specific gravity following both linear and curvilinear functions for all four regeneration methods. The variability in MOR explained by specific gravity was similar for both the linear and curvilinear functions; however a difference was found for MOE. On average the linear method accounted for more of the variation in MOE explained by specific gravity compared to the curvilinear method. Therefore, the use of linear method is recommended to describe the relationship of specific gravity and MOR or MOE for juvenile wood of jack pine.

A limitation of this study is that the wood properties of jack pine were investigated only for juvenile wood for all regeneration methods. This limitation occurred because Bräcke seeding was first introduced to northwestern Ontario in the 1970s. Correspondingly, stands representing the other regeneration methods of interest were selected based on similar age of the Bräcke seeded stand. It is recommended that further research should investigate these properties from mature jack pine grown under these four regeneration methods. Further analysis of mature wood produced under varying regeneration methods would determine whether, from a wood quality perspective, the sorting method recommended for juvenile wood holds true for mature wood also. In future, differences in these wood properties may be found because the regeneration methods may influence the timing of transition from juvenile into mature wood production. Moreover, studying mature trees would allow for the comparisons of trees from varying diameter classes and crown classes; unlike this study where trees were limited to 10 cm dbh or greater and crown closure had yet to occur. In addition, samples from dimensional lumber would be of interest as branching characteristics may vary between regeneration methods leading to variations in lumber grade and hence value.

Ideally, controlled experiments should be implemented whereby a complete stand history is available and influencing factors, such as soil type, are removed. In the interim, it is recommended that these sites be revisited 30 to 40 years from present to investigate these three wood properties in the mature stage of development.

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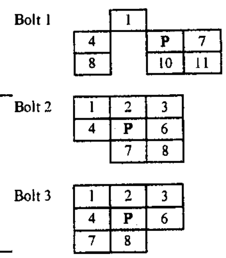
APPENDICES

APPENDIX I:

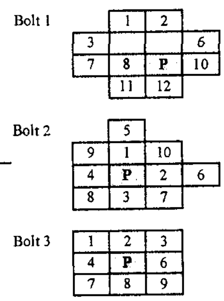
INDIVIDUAL TREE ATTRIBUTES
AND WOOD PROPERTIES OF
SAMPLE TREES

Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
Aerial Seeded	1	14.2	10.95	4.7	6.25	2.875	Bolt 1	3.7	A1.1_1	4190	54.2	0.37
									A1.1_4	4915	53.2	0.37
									A1.1_7	6230	62.1	0.40
									A1.1_8	5793	61.2	0.40
									A1.1_10	3697	52.3	0.38
									A1.1_11	4122	51.1	0.38
							Bolt 2	2.7	A1.2_1	5753	62.8	0.38
									A1.2_2	4266	52.8	0.40
									A1.2_3	4711	52.2	0.38
									A1.2_4	6649	65.8	0.39
									A1.2_6	4030	51.9	0.36
									A1.2_7	4504	51.8	0.34
									A1.2_8	5526	58.5	0.35
							Bolt 3	0.7	A1.3_1	3434	51.5	0.37
									A1.3_2	3263	52.9	0.35
									A1.3_3	3688	52.8	0.36
									A1.3_4	3827	52.5	0.35
									A1.3_6	4212	55.4	0.37
									A1.3_7	5123	60.5	0.37
									A1.3_8	4143	52.9	0.38
Aerial Seeded	2	13.1	9.65	4.3	5.35	3.525	Bolt 1	3.3	A2.1_1	5602	63.4	0.39
									A2.1_2	3191	53.0	0.36
									A2.1_3	5196	61.1	0.41
									A2.1_6	4590	55.8	0.38
									A2.1_7	5941	59.1	0.40
									A2.1_8	5065	61.1	0.42
									A2.1_10	5137	56.2	0.42
									A2.1_11	6164	59.7	0.40
									A2.1_12	5277	50.9	0.40
							Bolt 2	2.3	A2.2_2	4452	55.0	0.38
									A2.2_3	4160	53.2	0.39
									A2.2_4	5955	63.1	0.39
									A2.2_5	5542	62.5	0.40
									A2.2_6	4516	54.8	0.38
									A2.2_7	3367	48.0	0.48
									A2.2_8	4710	59.8	0.39
									A2.2_9	3897	56.9	0.39
									A2.2_10	3346	49.8	0.39
							Bolt 3	0.3	A2.3_1	4103	52.3	0.37
									A2.3_2	4737	55.7	0.36
									A2.3_3	3521	49.9	0.35
									A2.3_4	5239	54.4	0.36
									A2.3_6	4569	56.8	0.37
									A2.3_7	5464	57.3	0.36
									A2.3_8	4959	56.5	0.35
									A2.3_9	4696	56.9	0.37
Aerial Seeded	3	11	9	4.4	4.6	2.075	Bolt 1	3.4	A3.1_1	7214	72.4	0.41
									A3.1_2	5941	61.8	0.38
									A3.1_3	6001	62.1	0.40
									A3.1_4	5835	56.9	0.40
									A3.1_6	6653	64.6	0.39
									A3.1_7	6212	61.4	0.40
									A3.1_8	6747	66.5	0.40
							Bolt 2	2.5	A3.2_1	5792	60.0	0.40
									A3.2_2	5217	64.3	0.38
									A3.2_4	6853	73.8	0.40
									A3.2_6	6531	68.7	0.38
									A3.2_7	7117	70.8	0.40
									A3.2_8	4548	60.1	0.37
									A3.2_9	5953	65.7	0.41
							Bolt 3	0.3	A3.3_1	4648	53.9	0.36
									A3.3_2	4534	52.0	0.40
									A3.3_3	4003	49.5	0.34
									A3.3_5	4647	52.3	0.35
									A3.3_6	3444	48.6	0.36
									A3.3_7	4110	48.8	0.33

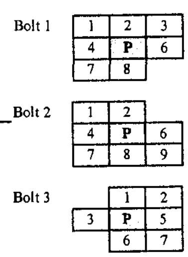
Aerial Seeded Tree 1



Aerial Seeded Tree 2

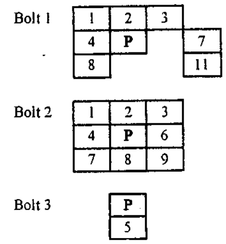


Aerial Seeded Tree 3

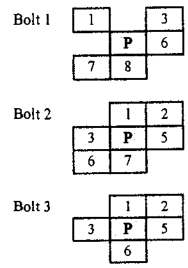


Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									A4.1_1	5016	56.7	0.37
									A4.1_2	4179	52.8	0.36
									A4.1_3	5263	60.5	0.38
							Bolt 1	2.9	A4.1_4	5134	58.1	0.37
									A4.1_7	4816	52.4	0.36
									A4.1_8	5706	66.5	0.38
									A4.1_11	3902	53.9	0.36
Aerial Seeded	4	12.3	8.5	3.85	4.65	2.3			A4.2_1	4670	58.6	0.37
									A4.2_2	4748	60.3	0.37
									A4.2_3	4890	55.8	0.36
							Bolt 2	1.9	A4.2_4	4148	53.6	0.34
									A4.2_6	4066	50.9	0.35
									A4.2_7	3425	50.6	0.34
									A4.2_8	4098	54.1	0.35
									A4.2_9	3230	41.2	0.35
							Bolt 3	-0.3	A4.3_5	2789	50.5	0.36
									A5.1_1	4242	52.6	0.37
									A5.1_3	3997	52.9	0.36
							Bolt 1	3.8	A5.1_6	5308	60.8	0.37
									A5.1_7	3183	57.7	0.36
									A5.1_8	2896	60.0	0.37
									A5.2_1	4553	60.6	0.37
									A5.2_2	4162	57.9	0.36
Aerial Seeded	5	11.5	9.9	4.75	5.15	1.9	Bolt 2	2.6	A5.2_5	3450	48.2	0.35
									A5.2_6	3406	52.6	0.35
									A5.2_7	2974	50.1	0.35
									A5.3_1	3535	47.9	0.35
									A5.3_2	2910	45.0	0.33
							Bolt 3	0.9	A5.3_3	5625	60.0	0.36
									A5.3_5	4001	52.0	0.34
									A5.3_6	5702	56.9	0.37
									A6.1_1	6875	70.4	0.39
									A6.1_2	4804	56.5	0.35
									A6.1_3	5723	60.5	0.39
							Bolt 1	2.9	A6.1_4	6301	64.0	0.41
									A6.1_6	4736	48.3	0.34
									A6.1_7	6387	62.4	0.41
Aerial Seeded	6	10.9	10.2	3.9	6.3	1.85			A6.1_8	6078	61.5	0.38
									A6.2_1	4751	51.2	0.38
									A6.2_2	4863	60.1	0.39
							Bolt 2	1.8	A6.2_3	5138	61.8	0.38
									A6.2_6	4205	53.3	0.36
									A6.2_7	5624	56.9	0.38
							Bolt 3	-0.2	A6.3_3	4367	56.2	0.37
									A6.3_5	4013	47.7	0.36
									A7.1_1	4305	55.4	0.37
									A7.1_2	5612	60.3	0.38
									A7.1_3	3450	55.5	0.35
									A7.1_5	5327	69.5	0.38
							Bolt 1	3.35	A7.1_6	5304	61.9	0.37
									A7.1_7	4022	58.2	0.37
									A7.1_8	2796	49.0	0.37
									A7.1_9	5447	62.2	0.39
									A7.1_11	4398	58.9	0.38
									A7.1_12	5222	57.6	0.37
									A7.2_1	5443	58.7	0.37
Aerial Seeded	7	14	9.6	4.45	5.15	3.2			A7.2_2	5253	55.9	0.35
									A7.2_4	5458	55.4	0.37
							Bolt 2	2.25	A7.2_5	3749	50.8	0.37
									A7.2_6	3518	52.6	0.37
									A7.2_7	4573	53.4	0.36
									A7.2_8	3513	53.5	0.36
									A7.2_9	6066	63.7	0.37
									A7.3_2	4415	52.0	0.35
									A7.3_3	4807	56.9	0.36
							Bolt 3	0.25	A7.3_5	4018	54.5	0.36
									A7.3_6	4958	55.3	0.35
									A7.3_7	5410	58.4	0.36

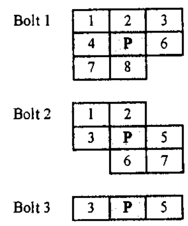
Aerial Seeded Tree 4



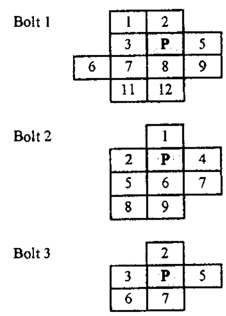
Aerial Seeded Tree 5



Aerial Seeded Tree 6

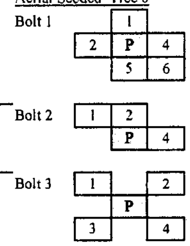


Aerial Seeded Tree 7

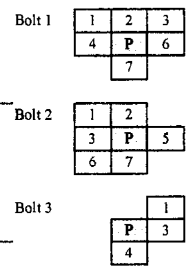


Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
Aerial Seeded	8	10.1	8.4	4.2	4.2	2.7	Bolt 1	2.8	A8.1_1	4880	59.7	0.41
									A8.1_2	5745	62.5	0.39
									A8.1_4	5796	64.0	0.38
									A8.1_5	5823	62.6	0.39
									A8.1_6	5757	66.9	0.37
							Bolt 2	1.8	A8.2_1	5297	62.3	0.38
									A8.2_2	6812	66.5	0.38
									A8.2_4	7947	72.1	0.39
							Bolt 3	0.2	A8.3_1	4791	54.5	0.37
									A8.3_2	5234	58.9	0.37
									A8.3_3	6225	67.2	0.37
									A8.3_4	5257	59.4	0.37
Aerial Seeded	9	11.4	9.1	3.8	5.3	2.5	Bolt 1	2.8	A9.1_1	5729	69.8	0.41
									A9.1_2	3850	53.9	0.37
									A9.1_3	5152	64.8	0.40
									A9.1_4	5707	69.0	0.39
									A9.1_6	7609	75.1	0.46
									A9.1_7	7454	71.1	0.43
							Bolt 2	1.8	A9.2_1	6004	70.6	0.39
									A9.2_2	6564	65.6	0.41
									A9.2_3	4398	57.5	0.37
									A9.2_5	7165	60.6	0.44
									A9.2_6	7167	76.4	0.41
									A9.2_7	7614	73.8	0.43
							Bolt 3	0.2	A9.3_1	6654	67.7	0.40
									A9.3_3	6442	70.0	0.41
									A9.3_4	5937	61.3	0.38
Aerial Seeded	10	12.8	10.4	5.1	5.3	2.88	Bolt 1	4.1	A10.1_1	5976	67.2	0.38
									A10.1_2	5558	68.9	0.41
									A10.1_3	4813	55.1	0.36
									A10.1_4	3743	50.9	0.36
									A10.1_5	4705	51.9	0.37
									A10.1_6	5640	63.1	0.40
									A10.1_7	5591	65.8	0.38
									A10.1_9	3326	53.2	0.33
									A10.1_10	6000	62.8	0.37
									A10.1_11	4043	51.8	0.34
									A10.1_12	5035	59.7	0.36
									A10.1_13	4632	54.0	0.37
							Bolt 2	3.1	A10.2_1	3817	51.3	0.36
									A10.2_3	3764	42.5	0.36
									A10.2_5	4315	55.8	0.35
									A10.2_6	4243	46.3	0.38
									A10.2_7	4487	48.4	0.37
									A10.2_8	4538	54.9	0.35
									A10.2_9	4200	45.8	0.36
							Bolt 3	1.1	A10.3_1	4632	54.0	0.35
									A10.3_2	5058	58.3	0.36
									A10.3_4	4091	51.9	0.33
									A10.3_5	4382	51.8	0.34
									A10.3_6	4862	54.7	0.35
									A10.3_7	4546	51.9	0.35
Aerial Seeded	11	12.7	11.1	5.2	5.9	1.725	Bolt 1	4.5	A11.1_1	6446	66.2	0.46
									A11.1_2	7645	76.3	0.35
									A11.1_3	5614	65.6	0.41
									A11.1_5	6729	68.9	0.48
									A11.1_8	7291	69.9	0.46
									A11.1_9	8575	80.1	0.49
									A11.1_10	7622	75.6	0.45
									A11.1_11	6721	68.5	0.45
									A11.1_12	7875	79.3	0.48
							Bolt 2	3.2	A11.2_1	6827	67.4	0.39
									A11.2_2	6594	65.9	0.39
									A11.2_3	6431	74.4	0.37
									A11.2_5	8675	85.6	0.42
									A11.2_6	5325	60.1	0.38
									A11.2_7	4772	57.0	0.38
									A11.2_8	4756	54.1	0.41

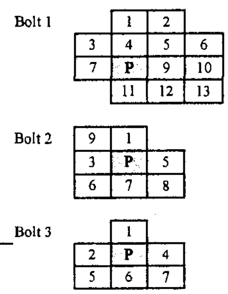
Aerial Seeded Tree 8



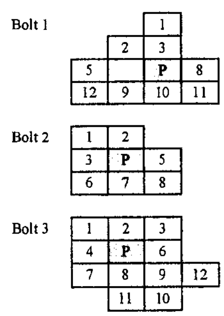
Aerial Seeded Tree 9



Aerial Seeded Tree 10

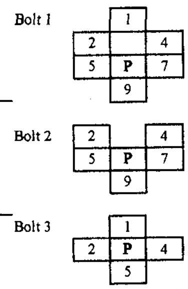


Aerial Seeded Tree 11

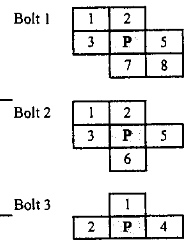


Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									A11.3_1	6428	61.9	0.39
									A11.3_2	6336	64.9	0.38
									A11.3_3	6921	69.8	0.41
									A11.3_4	7461	79.3	0.44
									A11.3_6	6027	64.5	0.41
							Bolt 3	1.1	A11.3_7	7283	74.6	0.45
									A11.3_8	5763	60.5	0.42
									A11.3_9	7000	69.8	0.44
									A11.3_10	7067	74.2	0.41
									A11.3_11	7008	72.0	0.42
									A11.3_12	8685	78.0	0.43
									A12.1_1	8120	81.0	0.41
									A12.1_2	6477	68.5	0.37
							Bolt 1	3.7	A12.1_4	5425	58.9	0.38
									A12.1_5	5943	62.8	0.38
									A12.1_7	7136	65.3	0.38
									A12.1_9	6132	67.3	0.39
									A12.2_2	5280	45.8	0.40
Aerial Seeded	12	11.8	11.8	4.7	7.1	1.795			A12.2_4	6566	70.2	0.38
							Bolt 2	2.7	A12.2_5	7144	68.5	0.38
									A12.2_7	2790	42.0	0.37
									A12.2_9	5383	58.5	0.36
									A12.3_1	5449	53.0	0.36
							Bolt 3	0.4	A12.3_2	5268	52.9	0.35
									A12.3_4	5662	65.7	0.38
									A12.3_5	5207	52.0	0.35
									B1.1_1	3935	59.3	0.40
									B1.1_2	5195	58.0	0.40
							Bolt 1	5.94	B1.1_3	3214	52.4	0.39
									B1.1_5	4490	49.8	0.36
									B1.1_7	5333	56.9	0.38
									B1.1_8	5125	56.6	0.38
Bracke Seeded	1	10.3	10.04	6.94	3.1	2.675			B1.2_1	5330	58.6	0.38
									B1.2_2	5153	59.2	0.36
							Bolt 2	4.69	B1.2_3	7448	69.4	0.39
									B1.2_5	6373	65.7	0.39
									B1.2_6	6501	63.7	0.38
									B1.3_1	5039	53.4	0.36
							Bolt 3	2.94	B1.3_2	5305	58.5	0.37
									B1.3_4	4996	57.5	0.38
									B2.1_2	4581	56.5	0.37
									B2.1_3	2625	43.4	0.33
									B2.1_4	4156	54.0	0.38
									B2.1_5	5849	70.4	0.40
							Bolt 1	5.3	B2.1_6	4229	58.5	0.40
									B2.1_8	2617	45.5	0.33
									B2.1_9	3780	51.8	0.37
									B2.1_10	2482	44.5	0.34
									B2.1_11	4614	57.2	0.37
									B2.1_12	5794	63.9	0.39
									B2.2_1	4458	56.3	0.37
Bracke Seeded	2	13.5	11.46	6.2	5.26	2.9			B2.2_3	4392	57.1	0.38
									B2.2_4	4667	55.0	0.38
							Bolt 2	4.05	B2.2_6	4161	51.4	0.35
									B2.2_7	4987	59.0	0.37
									B2.2_8	4735	54.2	0.38
									B2.2_9	3426	49.0	0.34
									B2.3_1	4506	54.7	0.37
									B2.3_2	4105	52.4	0.37
							Bolt 3	2.05	B2.3_3	2831	44.5	0.33
									B2.3_5	5499	58.3	0.37
									B2.3_6	4101	50.9	0.34
									B2.3_7	4528	52.6	0.36
Bracke Seeded	3	12.1	10.04	6.2	3.84	1.835	Bolt 1	5.2	B3.1_1	5620	66.3	0.41
									B3.1_2	3500	57.1	0.37
									B3.1_3	4720	61.7	0.40
									B3.1_4	4273	55.9	0.40
									B3.1_6	2561	54.5	0.36

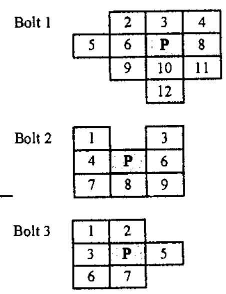
Aerial Seeded Tree 12



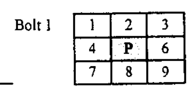
Bracke Seeded Tree 1



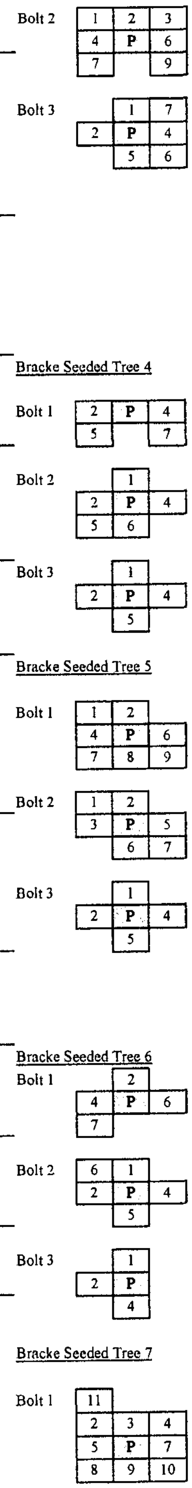
Bracke Seeded Tree 2



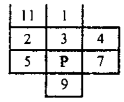
Bracke Seeded Tree 3

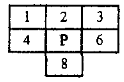


Regen Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									B3.1_7	6275	73.0	0.43
									B3.1_8	4169	58.9	0.36
									B3.1_9	4563	60.0	0.38
							Bolt 2	4.2	B3.2_1	5353	64.5	0.38
									B3.2_2	4046	53.2	0.38
									B3.2_3	3574	51.9	0.34
									B3.2_4	3799	55.7	0.35
									B3.2_6	5510	66.6	0.37
									B3.2_7	4641	60.9	0.38
									B3.2_9	3233	53.8	0.39
							Bolt 3	2.2	B3.3_1	4835	58.9	0.36
									B3.3_2	3796	53.2	0.34
									B3.3_4	4594	56.1	0.36
									B3.3_5	4350	55.1	0.37
									B3.3_6	4819	53.0	0.39
									B3.3_7	4042	51.0	0.35
Bracke Seeded	4	10.1	10.7	5.5	5.2	2.45	Bolt 1	4.5	B4.1_2	4295	54.3	0.36
									B4.1_4	6721	68.1	0.38
									B4.1_5	4089	53.8	0.35
									B4.1_7	5336	59.2	0.38
							Bolt 2	3.5	B4.2_1	5194	59.3	0.35
									B4.2_2	5048	59.5	0.36
									B4.2_4	3816	50.3	0.34
									B4.2_5	5719	67.4	0.39
									B4.2_6	5361	58.4	0.36
							Bolt 3	1.5	B4.3_1	4724	53.3	0.36
									B4.3_2	4816	57.3	0.34
									B4.3_4	5591	60.6	0.36
									B4.3_5	4229	49.4	0.37
Bracke Seeded	5	11.5	11.05	5.45	5.6	1.975	Bolt 1	4.45	B5.1_1	3843	54.9	0.38
									B5.1_2	4798	58.3	0.34
									B5.1_4	4821	55.7	0.33
									B5.1_6	3126	47.6	0.34
									B5.1_7	4195	56.0	0.38
									B5.1_8	4207	53.4	0.32
									B5.1_9	4655	56.0	0.37
							Bolt 2	3.35	B5.2_1	3740	54.6	0.37
									B5.2_2	3646	51.3	0.39
									B5.2_3	4962	57.9	0.37
									B5.2_5	4951	54.7	0.35
									B5.2_6	5109	59.3	0.37
									B5.2_7	5205	60.2	0.35
							Bolt 3	1.3	B5.3_1	6158	62.0	0.34
									B5.3_2	3935	54.9	0.32
									B5.3_4	4549	55.9	0.34
									B5.3_5	5803	63.5	0.38
Bracke Seeded	6	10.5	10	6.2	3.8	2.3	Bolt 1	5.1	B6.1_2	5436	64.9	0.41
									B6.1_4	4402	54.5	0.37
									B6.1_6	4406	55.8	0.41
									B6.1_7	2512	44.6	0.33
							Bolt 2	4.15	B6.2_1	4752	58.6	0.37
									B6.2_4	4643	53.7	0.39
									B6.2_5	4521	60.3	0.38
									B6.2_6	2381	45.3	0.36
							Bolt 3	2.05	B6.3_1	4156	53.4	0.37
									B6.3_2	5989	62.1	0.38
									B6.3_4	4641	56.8	0.36
Bracke Seeded	7	12.1	11.4	4.5	6.9	1.85	Bolt 1	3.5	B7.1_2	7133	73.4	0.43
									B7.1_3	5733	60.7	0.39
									B7.1_4	6488	63.8	0.41
									B7.1_5	5062	56.3	0.38
									B7.1_7	4922	57.1	0.37
									B7.1_8	6981	68.6	0.41
									B7.1_9	6348	59.1	0.40
									B7.1_10	3781	48.3	0.37
									B7.1_11	7093	66.3	0.42
							Bolt 2	2.6	B7.2_1	4995	55.1	0.36
									B7.2_2	4452	53.1	0.35

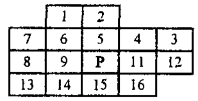


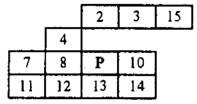
Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									B7.2_4	5643	63.4	0.38
									B7.2_5	5061	57.8	0.38
									B7.2_7	6163	63.7	0.39
									B7.2_9	7233	68.0	0.40
									B7.2_11	6700	68.7	0.39
									B7.3_1	5538	60.4	0.34
									B7.3_2	4408	50.0	0.32
							Bolt 3	0.5	B7.3_3	6615	68.9	0.35
									B7.3_4	5111	52.5	0.33
									B7.3_6	6706	69.9	0.35
									B7.3_8	5917	58.6	0.33
									B8.1_1	6033	64.8	0.42
									B8.1_2	5908	66.2	0.41
									B8.1_3	5789	62.4	0.41
									B8.1_4	4863	59.9	0.38
									B8.1_5	4306	54.0	0.36
									B8.1_6	5638	61.8	0.38
									B8.1_7	6537	72.9	0.41
							Bolt 1	1.5	B8.1_8	6727	63.2	0.43
									B8.1_9	4979	49.7	0.35
									B8.1_11	5140	61.3	0.38
									B8.1_12	7252	76.0	0.45
									B8.1_13	8299	77.5	0.46
									B8.1_14	10286	71.2	0.46
									B8.1_15	7091	68.3	0.46
									B8.1_16	7948	77.8	0.44
									B8.2_2	7591	68.2	0.41
									B8.2_3	8742	74.5	0.44
									B8.2_4	6400	47.1	0.40
Bracke Seeded	8	16	12.1	2.5	9.6	3.2			B8.2_7	7610	68.5	0.41
									B8.2_8	4500	53.9	0.35
							Bolt 2	0.5	B8.2_10	7652	54.1	0.41
									B8.2_11	5734	58.8	0.38
									B8.2_12	6574	64.9	0.38
									B8.2_13	6693	56.0	0.40
									B8.2_14	6746	65.9	0.41
									B8.2_15	8062	73.7	0.44
									B8.3_1	5648	59.2	0.35
									B8.3_2	5442	55.6	0.37
									B8.3_3	7129	71.8	0.37
									B8.3_4	6646	72.1	0.37
									B8.3_5	6229	66.7	0.36
							Bolt 3	-1.5	B8.3_6	8055	77.3	0.40
									B8.3_8	6725	68.5	0.38
									B8.3_10	6155	63.0	0.41
									B8.3_11	6303	66.4	0.39
									B8.3_12	7720	70.4	0.40
									B8.3_13	6755	65.1	0.39
Bracke Seeded	9	12.4	11.1	6.1	5	1.85			B9.1_1	6219	68.6	0.44
									B9.1_2	4531	53.4	0.41
									B9.1_3	5727	62.5	0.40
									B9.1_4	6283	64.8	0.40
									B9.1_5	6909	68.8	0.42
							Bolt 1	5.1	B9.1_6	4037	56.5	0.37
									B9.1_8	6183	58.8	0.41
									B9.1_9	6881	69.9	0.43
									B9.1_10	7361	70.3	0.44
									B9.1_11	6438	67.6	0.42
									B9.1_12	6639	69.6	0.43
									B9.2_1	5237	62.2	0.38
									B9.2_2	5904	68.8	0.40
									B9.2_3	7382	76.6	0.41
							Bolt 2	4.2	B9.2_4	5481	50.1	0.42
									B9.2_6	6057	73.2	0.43
									B9.2_7	6271	70.3	0.40
									B9.2_8	7701	70.9	0.44
							Bolt 3	2.1	B9.3_1	6639	73.9	0.40
									B9.3_2	7109	66.9	0.39

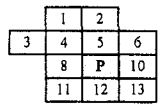
Bolt 2


Bolt 3


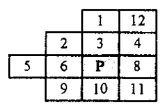
Bracke Seeded Tree 8

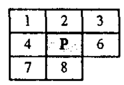
Bolt 1


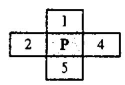
Bolt 2


Bolt 3


Bracke Seeded Tree 9

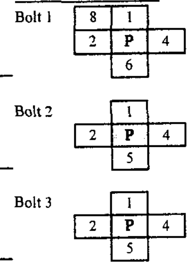
Bolt 1


Bolt 2


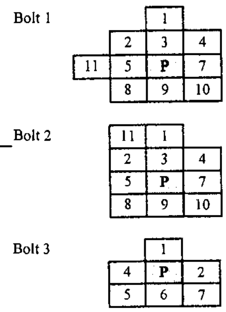
Bolt 3


Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									B9.3_4	5610	65.2	0.37
									B9.3_5	4950	57.8	0.38
Bracke Seeded	10	10.3	9.9	4.75	5.15	1.39	Bolt 1	3.75	B10.1_2	7961	79.1	0.41
									B10.1_4	5306	62.5	0.40
									B10.1_6	6309	68.0	0.42
									B10.1_8	5121	60.1	0.40
							Bolt 2	2.75	B10.2_1	6653	68.9	0.39
									B10.2_2	7708	77.9	0.38
									B10.2_4	6414	61.8	0.38
									B10.2_5	6805	64.8	0.38
							Bolt 3	0.75	B10.3_1	6515	67.2	0.35
									B10.3_2	5854	62.5	0.37
									B10.3_4	5775	55.4	0.35
									B10.3_5	6154	64.8	0.35
Bracke Seeded	11	10.3	10.3	4.6	5.7	2.415	Bolt 1	3.65	B11.1_1	6998	69.8	0.39
									B11.1_2	4586	56.7	0.38
									B11.1_3	5714	60.6	0.38
									B11.1_4	6734	71.1	0.43
									B11.1_5	4040	51.7	0.38
									B11.1_7	6934	69.1	0.41
									B11.1_8	6735	68.9	0.41
									B11.1_9	7025	67.4	0.40
									B11.1_10	6499	65.1	0.38
									B11.1_11	5753	64.1	0.41
							Bolt 2	2.6	B11.2_1	6654	62.7	0.39
									B11.2_2	5563	61.1	0.37
									B11.2_3	4551	55.2	0.36
									B11.2_4	6322	59.7	0.39
									B11.2_5	4912	54.5	0.35
									B11.2_7	6073	65.8	0.40
									B11.2_8	6611	67.4	0.39
									B11.2_9	6608	65.6	0.40
									B11.2_10	5279	61.4	0.40
									B11.2_11	5303	57.5	0.40
							Bolt 3	0.7	B11.3_1	8474	76.3	0.37
									B11.3_2	5641	57.6	0.36
									B11.3_4	7525	74.9	0.37
									B11.3_5	5576	63.1	0.36
									B11.3_6	5947	63.0	0.37
									B11.3_7	5496	60.6	0.37
Bracke Seeded	12	13	10.5	4.7	5.8	2.09	Bolt 1	3.7	B12.1_1	5376	65.0	0.40
									B12.1_2	4967	60.2	0.37
									B12.1_3	6595	71.8	0.39
									B12.1_5	8054	80.2	0.40
									B12.1_6	6385	67.2	0.40
									B12.1_7	6191	61.7	0.38
							Bolt 2	2.8	B12.2_1	5631	60.8	0.36
									B12.2_2	5178	57.9	0.37
									B12.2_3	5891	64.9	0.36
									B12.2_5	5115	59.0	0.39
									B12.2_7	4218	51.0	0.36
							Bolt 3	0.8	B12.3_1	6333	61.9	0.39
									B12.3_2	4638	53.1	0.35
									B12.3_4	6422	62.9	0.37
									B12.3_5	5895	57.2	0.36
Planted	1	12.2	11.1	6.1	5	2.65	Bolt 1	5.1	P1.1_1	6118	64.2	0.40
									P1.1_2	3847	57.4	0.39
									P1.1_3	4124	58.6	0.43
									P1.1_4	2384	44.2	0.32
									P1.1_5	2257	47.4	0.36
									P1.1_6	3511	54.1	0.39
									P1.1_7	3751	50.3	0.34
									P1.1_9	5244	57.8	0.43
									P1.1_10	4937	57.5	0.39
									P1.1_11	5177	60.0	0.38
							Bolt 2	4.3	P1.2_1	4574	57.0	0.39
									P1.2_2	4820	56.7	0.41
									P1.2_3	5433	59.9	0.39

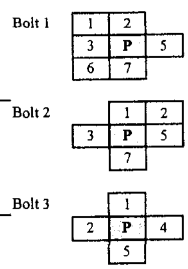
Bracke Seeded Tree 10



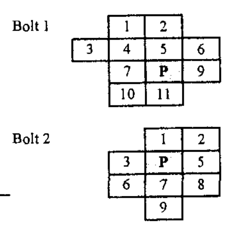
Bracke Seeded Tree 11



Bracke Seeded Tree 12

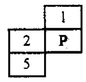


Planted Tree 1



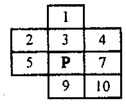
Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									P1.2_6	4968	57.2	0.37
									P1.2_8	2827	45.1	0.35
									P1.2_9	4564	56.4	0.38
									P1.3_1	6553	68.0	0.40
							Bolt 3	2.4	P1.3_2	3478	49.5	0.42
									P1.3_5	3344	48.4	0.41
									P2.1_1	6813	66.0	0.45
									P2.1_2	4370	52.8	0.39
									P2.1_3	5331	58.1	0.45
									P2.1_4	3841	51.2	0.39
							Bolt 1	5.7	P2.1_5	7115	77.7	0.46
									P2.1_7	3449	50.8	0.43
									P2.1_9	6214	56.2	0.46
									P2.1_10	5650	61.7	0.44
									P2.2_1	4148	54.1	0.42
Planted	2	11.3	10.7	6.7	4	1.9			P2.2_2	4570	55.6	0.40
							Bolt 2	4.6	P2.2_3	3991	51.4	0.36
									P2.2_6	4188	50.5	0.39
									P2.2_7	4846	54.5	0.40
									P2.3_1	3211	53.9	0.39
									P2.3_2	4621	54.2	0.38
									P2.3_3	3352	57.8	0.39
							Bolt 3	2.9	P2.3_5	4449	79.0	0.42
									P2.3_6	4253	58.8	0.40
									P2.3_7	6265	62.2	0.40
									P3.1_1	5033	51.9	0.44
									P3.1_2	5475	57.4	0.37
							Bolt 1	6.6	P3.1_3	7416	66.9	0.44
									P3.1_6	7657	76.4	0.48
									P3.1_7	4860	56.0	0.39
									P3.1_8	5184	56.2	0.37
									P3.2_1	6003	60.7	0.40
									P3.2_2	5027	53.0	0.35
									P3.2_4	5612	55.8	0.37
							Bolt 2	5.3	P3.2_5	5315	52.0	0.35
Planted	3	12	12.3	7.5	4.8	2.05			P3.2_6	3998	48.6	0.44
									P3.2_7	6635	68.3	0.40
									P3.2_8	7029	68.5	0.41
									P3.2_9	6241	66.9	0.43
									P3.3_1	6188	59.9	0.41
									P3.3_2	5520	56.0	0.40
									P3.3_3	5493	59.7	0.38
							Bolt 3	3.4	P3.3_5	4673	59.7	0.40
									P3.3_6	5945	63.6	0.46
									P3.3_7	7317	71.2	0.41
									P3.3_8	5993	66.3	0.39
Planted	4	15.3	11	2.02	8.98	4.35			P4.1_1	7805	74.7	0.50
									P4.1_2	6057	56.1	0.44
									P4.1_3	6071	59.8	0.47
									P4.1_4	6030	66.8	0.42
									P4.1_7	5869	62.8	0.45
									P4.1_11	6418	51.3	0.42
							Bolt 1	1.02	P4.1_12	7596	68.8	0.50
									P4.1_13	4989	56.1	0.42
									P4.1_14	4874	57.5	0.44
									P4.1_15	6453	70.2	0.49
									P4.1_16	7642	76.0	0.50
									P4.1_17	7560	75.4	0.51
									P4.1_18	6728	58.4	0.50
							Bolt 2	0.12	P4.2_1	4999	59.8	0.46
									P4.2_3	4220	48.4	0.42
									P4.2_4	4193	55.0	0.45
									P4.2_5	5692	64.8	0.41
									P4.2_7	4475	55.9	0.39
									P4.2_8	5396	59.0	0.41
									P4.2_9	7654	73.0	0.44
									P4.2_10	6038	63.7	0.42
									P4.2_12	3738	52.3	0.44

Bolt 3

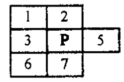


Planted Tree 2

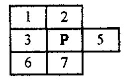
Bolt 1



Bolt 2

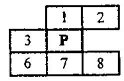


Bolt 3

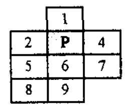


Planted Tree 3

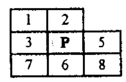
Bolt 1



Bolt 2

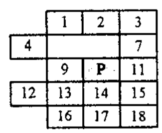


Bolt 3

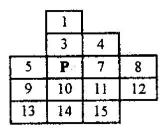


Planted Tree 4

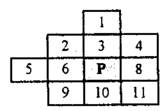
Bolt 1



Bolt 2



Bolt 3



Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									P4.2_13	5600	62.1	0.46
									P4.2_14	4783	57.0	0.43
									P4.2_15	5984	61.0	0.46
									P4.3_1	7789	68.7	0.45
									P4.3_2	7003	67.9	0.43
									P4.3_3	6172	65.1	0.41
									P4.3_4	6395	60.7	0.42
							Bolt 3	-0.198	P4.3_5	7335	66.4	0.42
									P4.3_6	7248	60.8	0.43
									P4.3_8	7273	65.6	0.41
									P4.3_9	6506	69.3	0.43
									P4.3_10	6789	62.5	0.45
									P4.3_11	7737	70.6	0.45
									P5.1_1	4469	57.1	0.43
									P5.1_2	4815	59.7	0.43
							Bolt 1	2.45	P5.1_3	5372	57.6	0.39
									P5.1_5	5201	60.8	0.40
									P5.1_6	3813	47.2	0.37
									P5.1_8	4720	55.5	0.38
Planted	5	10.8	10.1	3.45	6.65	2.3			P5.2_1	5295	57.9	0.38
									P5.2_2	3596	44.8	0.34
							Bolt 2	1.45	P5.2_3	4358	55.4	0.39
									P5.2_4	3847	43.3	0.37
									P5.2_7	4167	52.7	0.43
									P5.3_2	4624	50.9	0.42
							Bolt 3	-0.55	P5.3_5	3459	49.5	0.40
									P5.3_6	4824	54.8	0.40
									P6.1_1	5291	63.5	0.38
									P6.1_2	5303	57.0	0.38
									P6.1_3	3970	50.5	0.36
									P6.1_4	3425	47.0	0.35
									P6.1_5	2794	49.1	0.36
							Bolt 1	2.8	P6.1_6	4761	54.9	0.38
									P6.1_7	3718	50.6	0.33
									P6.1_9	3564	49.5	0.33
									P6.1_10	3998	52.6	0.37
									P6.1_11	3756	51.0	0.35
									P6.1_12	4309	54.8	0.37
									P6.1_13	5391	59.1	0.41
Planted	6	13	9.68	3.8	5.88	2.7			P6.2_1	3853	48.7	0.35
									P6.2_3	4687	46.6	0.36
									P6.2_5	4614	50.5	0.35
							Bolt 2	1.8	P6.2_7	4317	49.4	0.35
									P6.2_8	4039	50.6	0.36
									P6.2_10	4395	48.8	0.36
									P6.2_11	4748	53.9	0.37
									P6.2_12	4234	54.4	0.37
									P6.3_1	6227	66.1	0.36
									P6.3_2	5996	67.9	0.38
							Bolt 3	-0.3	P6.3_3	3705	46.5	0.38
									P6.3_4	3974	48.9	0.34
									P6.3_6	4441	50.3	0.35
Planted	7	13.7	14	7.6	6.4	1.7			P7.1_1	6206	68.8	0.41
									P7.1_3	4945	63.7	0.40
									P7.1_4	5289	64.5	0.41
							Bolt 1	6.7	P7.1_5	6604	71.0	0.43
									P7.1_7	5409	64.0	0.41
									P7.1_8	7367	76.6	0.43
									P7.1_9	7695	77.9	0.43
									P7.2_1	6643	68.4	0.41
									P7.2_2	6093	64.0	0.42
									P7.2_3	5911	62.1	0.38
							Bolt 2	5.4	P7.2_5	7229	72.4	0.42
									P7.2_6	6668	70.6	0.41
									P7.2_7	7163	69.6	0.41
									P7.3_1	7232	73.1	0.41
							Bolt 3	3.9	P7.3_2	5827	62.3	0.40
									P7.3_3	7132	74.6	0.41

Planted Tree 5

Bolt 1

	1	2
3	P	5
6	7	8

Bolt 2

1	2	3
4	P	
	7	

Bolt 3

	2	
	P	5
	6	

Planted Tree 6

Bolt 1

	1	2	
3	4	5	6
7	P	9	10
11	12	13	

Bolt 2

1		3
5	P	7
8		10
11	12	

Bolt 3

1	2
4	P
3	6

Planted Tree 7

Bolt 1

	1	
2	3	4
5	P	7
8	9	

Bolt 2

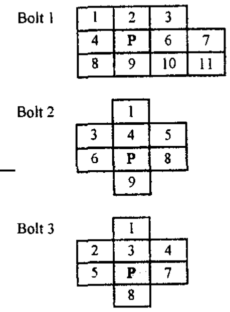
	1	2
3	P	5
	6	7

Bolt 3

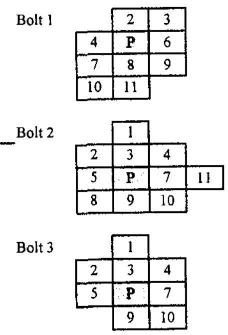
1	2	
3	P	5
	7	

Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									P7.3_5	7147	71.3	0.39
									P7.3_7	6192	64.5	0.39
									P8.1_1	6492	68.6	0.40
									P8.1_2	7472	77.8	0.43
									P8.1_3	6081	65.5	0.42
									P8.1_4	5360	62.1	0.38
							Bolt 1	4.4	P8.1_6	4793	60.3	0.40
									P8.1_7	7380	72.2	0.43
									P8.1_8	6332	65.8	0.39
									P8.1_9	4777	50.4	0.38
									P8.1_10	5542	62.6	0.39
									P8.1_11	7081	71.0	0.43
									P8.2_1	6836	68.8	0.40
Planted	8	13.8	12.7	5.4	7.3	3.15			P8.2_3	6456	62.7	0.39
									P8.2_4	5613	65.9	0.39
							Bolt 2	3.1	P8.2_5	5619	58.3	0.38
									P8.2_6	6012	60.8	0.38
									P8.2_8	6931	69.6	0.38
									P8.2_9	7353	61.7	0.41
									P8.3_1	8400	71.7	0.46
									P8.3_2	4712	52.1	0.39
									P8.3_3	6316	65.3	0.40
							Bolt 3	1.4	P8.3_4	6865	64.4	0.37
									P8.3_5	5432	48.3	0.38
									P8.3_7	5930	63.9	0.39
									P8.3_8	7618	74.1	0.44
									P9.1_2	8346	83.5	0.47
									P9.1_3	8429	76.9	0.47
									P9.1_4	5290	59.2	0.41
									P9.1_6	8589	80.3	0.47
							Bolt 1	5.1	P9.1_7	6382	59.9	0.42
									P9.1_8	4244	53.1	0.43
									P9.1_9	6956	70.7	0.45
									P9.1_10	8088	76.2	0.42
									P9.1_11	9014	80.3	0.45
									P9.2_1	7626	74.6	0.47
									P9.2_2	7862	72.8	0.43
									P9.2_3	6945	67.3	0.42
									P9.2_4	7628	74.2	0.43
Planted	9	13.6	12.9	6.4	6.5	2.2	Bolt 2	4.2	P9.2_5	7865	69.5	0.42
									P9.2_7	6239	63.0	0.42
									P9.2_8	7898	76.6	0.44
									P9.2_9	6880	67.2	0.43
									P9.2_10	8226	78.5	0.44
									P9.2_11	8998	85.9	0.46
									P9.3_1	9089	86.6	0.46
									P9.3_2	7374	75.9	0.44
									P9.3_3	6657	66.4	0.41
							Bolt 3	2.7	P9.3_4	5440	62.2	0.40
									P9.3_5	8249	76.5	0.43
									P9.3_7	6697	69.1	0.42
									P9.3_9	8166	79.6	0.45
									P9.3_10	8147	76.6	0.44
Planted	10	19.2	13.9	7.5	6.4	2.35	Bolt 1	6.5	P10.1_1	5152	58.7	0.38
									P10.1_4	4276	53.9	0.35
									P10.1_5	4687	53.1	0.36
									P10.1_6	2409	46.1	0.39
									P10.1_7	2015	43.6	0.37
									P10.1_8	4027	52.1	0.35
									P10.1_9	3757	47.4	0.35
									P10.1_10	5251	52.6	0.35
									P10.1_11	3239	50.1	0.38
									P10.1_12	4313	55.3	0.36
									P10.1_14	4565	46.8	0.35
									P10.1_15	5074	52.8	0.35
									P10.1_16	2598	45.9	0.36
									P10.1_19	3339	45.3	0.34
									P10.1_20	4817	57.0	0.37

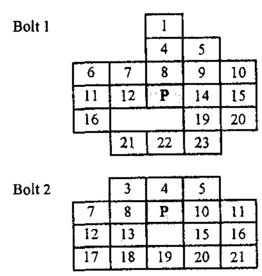
Planted Tree 8



Planted Tree 9

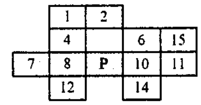


Planted Tree 10



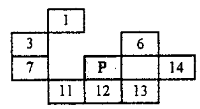
Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									P10.1_21	5001	57.7	0.35
									P10.1_22	4432	53.8	0.34
									P10.1_23	3943	49.8	0.34
									P10.2_3	5111	57.1	0.34
									P10.2_4	5463	57.2	0.35
									P10.2_5	3964	50.6	0.34
									P10.2_7	4717	51.6	0.33
									P10.2_8	4767	53.9	0.35
									P10.2_10	4160	47.4	0.33
									P10.2_11	5166	52.7	0.33
							Bolt 2	5.2	P10.2_12	5834	56.8	0.34
									P10.2_13	4441	52.0	0.35
									P10.2_15	4406	51.8	0.34
									P10.2_16	5094	54.9	0.33
									P10.2_17	3469	49.0	0.35
									P10.2_18	3167	45.0	0.35
									P10.2_19	3680	51.5	0.34
									P10.2_20	4852	56.3	0.34
									P10.2_21	5443	61.6	0.36
									P10.3_1	5324	60.4	0.34
									P10.3_2	5381	57.3	0.34
									P10.3_4	3372	48.8	0.34
									P10.3_6	4641	54.5	0.32
									P10.3_7	5446	62.3	0.36
							Bolt 3	3.2	P10.3_8	2372	43.3	0.35
									P10.3_10	3112	42.5	0.35
									P10.3_11	4793	53.7	0.33
									P10.3_12	3269	52.4	0.36
									P10.3_14	2786	45.7	0.34
									P10.3_15	5951	60.5	0.32
									P11.1_1	4878	56.7	0.39
									P11.1_3	5014	58.8	0.40
									P11.1_6	5370	58.3	0.40
							Bolt 1	6.2	P11.1_7	7084	69.7	0.42
									P11.1_11	6784	71.3	0.44
									P11.1_12	6354	65.3	0.42
									P11.1_13	5663	59.7	0.38
									P11.1_14	6455	67.3	0.39
									P11.2_1	7800	73.2	0.40
									P11.2_2	6323	64.1	0.41
									P11.2_3	6538	65.0	0.39
									P11.2_4	6632	68.5	0.38
									P11.2_5	7296	77.3	0.41
							Bolt 2	5.2	P11.2_6	5550	59.5	0.39
Planted	11	15.5	13.8	7.2	6.6	1.7			P11.2_8	7470	73.5	0.38
									P11.2_9	6354	63.5	0.42
									P11.2_10	5172	59.0	0.41
									P11.2_11	5359	60.7	0.44
									P11.2_12	5323	56.7	0.38
									P11.2_14	4898	56.3	0.38
									P11.3_2	6662	62.4	0.38
									P11.3_3	6315	64.0	0.38
									P11.3_4	5578	58.4	0.36
									P11.3_6	5540	57.1	0.36
							Bolt 3	3.4	P11.3_7	6387	62.6	0.39
									P11.3_8	5258	57.1	0.37
									P11.3_9	5247	62.0	0.39
									P11.3_10	6789	70.9	0.40
									P11.3_11	6677	66.0	0.40
									P11.3_12	5750	59.8	0.38
Planted	12	16.9	12.7	5.3	7.4	3.35	Bolt 1	4.5	P12.1_2	6085	57.2	0.41
									P12.1_4	5742	58.8	0.42
									P12.1_5	4506	57.4	0.41
									P12.1_6	3399	54.0	0.44
									P12.1_7	6078	65.5	0.42
									P12.1_8	7431	73.0	0.42
									P12.1_9	6740	60.6	0.43
									P12.1_10	2831	50.5	0.39

Bolt 3

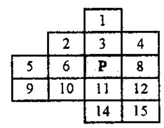


Planted Tree 11

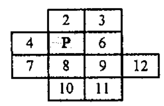
Bolt 1



Bolt 2

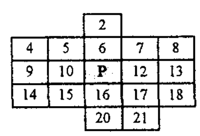


Bolt 3



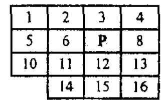
Planted Tree 12

Bolt 1

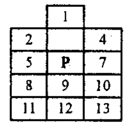


Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									P12.1_12	4260	56.6	0.40
									P12.1_13	7075	74.7	0.41
									P12.1_14	5435	59.9	0.41
									P12.1_15	4604	56.7	0.40
									P12.1_16	3846	55.0	0.37
									P12.1_17	3803	51.6	0.38
									P12.1_18	6275	65.5	0.42
									P12.1_21	4973	55.6	0.38
									P12.2_1	4483	58.6	0.38
									P12.2_2	5346	64.2	0.39
									P12.2_3	5228	64.3	0.41
									P12.2_4	6505	70.0	0.42
									P12.2_5	3976	57.9	0.38
									P12.2_6	5239	64.1	0.36
							Bolt 2	3.1	P12.2_8	5440	65.4	0.39
									P12.2_10	4490	54.4	0.39
									P12.2_11	4103	54.5	0.38
									P12.2_12	3692	49.7	0.38
									P12.2_13	4492	56.2	0.39
									P12.2_14	5240	57.3	0.39
									P12.2_15	5750	64.1	0.39
									P12.2_16	5300	60.3	0.40
									P12.3_1	6838	64.4	0.39
									P12.3_2	5493	56.0	0.39
									P12.3_4	4598	55.6	0.38
									P12.3_5	4206	55.1	0.38
							Bolt 3	1.4	P12.3_7	3711	53.5	0.38
									P12.3_8	3906	53.5	0.36
									P12.3_9	3419	47.0	0.37
									P12.3_10	4399	57.4	0.36
									P12.3_11	4957	47.6	0.39
									P12.3_12	5512	64.2	0.39
									N1.1_1	5118	57.0	0.47
									N1.1_2	4926	70.9	0.40
									N1.1_3	4319	56.3	0.34
							Bolt 1	5.4	N1.1_4	6261	70.3	0.40
									N1.1_5	4395	48.4	0.34
									N1.1_8	5096	56.4	0.35
									N1.1_9	6094	67.9	0.38
									N1.1_10	6165	67.4	0.38
									N1.2_2	4894	66.4	0.39
Natural	1	13.4	11.6	6.4	5.2	3.15			N1.2_3	5371	57.4	0.37
									N1.2_4	5682	67.4	0.41
							Bolt 2	4.3	N1.2_6	4957	54.8	0.35
									N1.2_7	5881	65.3	0.37
									N1.2_8	4177	46.1	0.33
									N1.2_9	4174	49.5	0.34
									N1.3_1	3717	50.2	0.34
									N1.3_3	2536	49.9	0.37
							Bolt 3	2.2	N1.3_4	3160	52.9	0.38
									N1.3_7	2532	47.5	0.45
									N1.3_9	2603	49.2	0.37
Natural	2	11.6	10.6	5.4	5.2	2.05			N2.1_1	4918	68.0	0.52
									N2.1_2	5378	65.2	0.38
									N2.1_3	3697	53.1	0.37
									N2.1_4	4315	50.2	0.36
							Bolt 1	4.4	N2.1_5	7230	75.9	0.40
									N2.1_6	4638	51.9	0.39
									N2.1_9	6398	66.2	0.38
									N2.1_10	7569	76.1	0.41
									N2.1_11	6399	57.3	0.41
									N2.1_13	5503	63.1	0.40
									N2.2_1	3864	54.9	0.37
									N2.2_2	5788	66.3	0.36
							Bolt 2	3.4	N2.2_3	5410	62.3	0.38
									N2.2_6	5635	57.6	0.37
									N2.2_7	4376	55.4	0.35
									N2.2_8	4835	56.3	0.36

Bolt 2

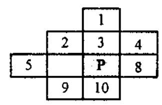


Bolt 3

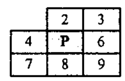


Natural Tree 1

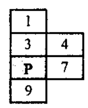
Bolt 1



Bolt 2

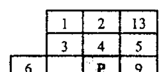


Bolt 3

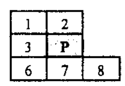


Natural Tree 2

Bolt 1



Bolt 2



Bolt 3

Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
							Bolt 3	1.4	N2.3_2	5756	60.5	0.36
									N2.3_4	3491	55.4	0.37
Natural	3	10.8	10.6	5.3	5.3	1.85	Bolt 1	4.3	N3.1_1	4888	54.9	0.39
									N3.1_2	5127	60.6	0.41
									N3.1_4	4736	61.8	0.38
									N3.1_6	6758	70.8	0.41
									N3.1_7	5754	67.1	0.41
									N3.1_8	6295	67.8	0.40
									N3.1_9	7265	74.6	0.41
							Bolt 2	3.3	N3.2_2	6316	69.5	0.40
									N3.2_4	4921	55.0	0.38
									N3.2_6	6258	64.0	0.36
									N3.2_8	5023	59.7	0.38
									N3.2_9	5429	60.1	0.36
							Bolt 3	1.5	N3.3_1	5876	59.3	0.36
									N3.3_2	5748	58.5	0.38
									N3.3_4	4612	56.2	0.35
									N3.3_5	4528	50.7	0.36
Natural	4	11	11.1	5.5	5.6	2.05	Bolt 1	4.5	N4.1_1	7682	74.8	0.46
									N4.1_2	8174	77.1	0.45
									N4.1_3	8358	82.1	0.46
									N4.1_4	8329	78.6	0.44
									N4.1_6	8197	78.0	0.46
									N4.1_7	8425	80.1	0.46
									N4.1_8	8896	83.8	0.45
									N4.1_9	7071	70.5	0.44
							Bolt 2	3.4	N4.2_1	7050	73.2	0.44
									N4.2_2	8000	73.3	0.39
									N4.2_3	7126	77.7	0.43
									N4.2_5	7742	77.0	0.43
									N4.2_6	6411	63.6	0.44
									N4.2_7	6715	64.2	0.42
									N4.2_8	6808	67.0	0.45
									N4.2_9	6891	69.8	0.42
							Bolt 3	1.7	N4.3_1	8171	75.6	0.42
									N4.3_2	7682	71.6	0.41
									N4.3_4	7130	69.4	0.42
									N4.3_5	6009	60.6	0.41
									N4.3_6	6418	69.2	0.40
Natural	5	12.8	10.8	4	6.8	2.45	Bolt 1	3	N5.1_1	9823	95.4	0.50
									N5.1_2	9740	92.5	0.48
									N5.1_3	7157	72.0	0.40
									N5.1_4	4047	48.7	0.36
									N5.1_5	6811	76.2	0.44
									N5.1_8	6435	80.4	0.45
									N5.1_9	7773	80.2	0.45
									N5.1_10	7010	78.4	0.42
									N5.1_11	7373	74.5	0.45
							Bolt 2	2	N5.2_1	7766	74.1	0.45
									N5.2_2	8020	75.8	0.46
									N5.2_3	7132	78.2	0.44
									N5.2_4	4812	53.0	0.34
									N5.2_5	6571	71.7	0.45
									N5.2_6	7416	80.6	0.42
									N5.2_8	3882	54.3	0.37
									N5.2_9	8462	80.0	0.42
									N5.2_10	6770	70.1	0.40
									N5.2_11	5767	61.3	0.39
							Bolt 3	0.2	N5.3_1	7391	75.3	0.42
									N5.3_2	5601	64.2	0.39
									N5.3_3	5439	62.0	0.42
									N5.3_4	7020	71.2	0.42
									N5.3_6	5404	59.7	0.42
									N5.3_7	5805	60.4	0.40
									N5.3_8	3266	54.4	0.39
Natural	6	13	10.7	5	5.7	2.3	Bolt 1	4	N6.1_2	6190	62.8	0.39
									N6.1_3	4663	54.2	0.37
									N6.1_4	6925	66.4	0.41

Natural Tree 3

Bolt 1

1	2	
4	P	6
7	8	9

Bolt 2

	2	
4	P	6
	8	9

Bolt 3

	1	
2	P	4
	5	

Natural Tree 4

Bolt 1

1	2	3
4	P	6
7	8	9

Bolt 2

1	2	9
3	P	5
6	7	8

Bolt 3

	1	
2	P	4
6	5	

Natural Tree 5

Bolt 1

	1	2
3	4	5
	P	8
9	10	11

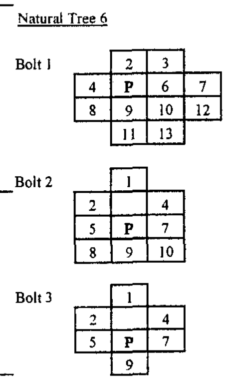
Bolt 2

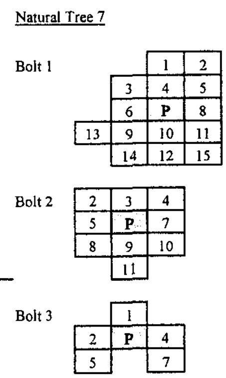
	2	1
3	4	5
6	P	8
9	10	11

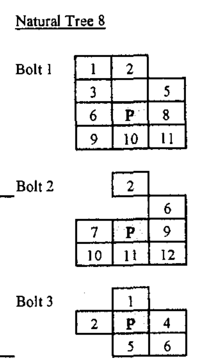
Bolt 3

1	2	3
4	P	6
7	8	

Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									N6.1_6	4035	50.5	0.35
									N6.1_7	4199	54.6	0.39
									N6.1_8	6270	66.6	0.41
									N6.1_9	5480	61.3	0.36
									N6.1_10	5905	64.9	0.37
									N6.1_11	5704	65.2	0.40
									N6.1_12	7302	72.6	0.41
									N6.1_13	5781	69.4	0.42
									N6.2_1	7472	68.1	0.39
									N6.2_2	4865	61.6	0.39
									N6.2_4	4610	55.7	0.34
							Bolt 2	3.1	N6.2_5	4354	60.1	0.38
									N6.2_7	7679	73.3	0.37
									N6.2_8	6332	67.4	0.39
									N6.2_9	5371	62.3	0.37
									N6.2_10	4124	51.3	0.35
									N6.3_1	5366	62.2	0.37
									N6.3_2	5531	61.2	0.35
							Bolt 3	1.2	N6.3_4	4553	59.2	0.36
									N6.3_5	3884	48.3	0.33
									N6.3_7	5165	57.8	0.34
									N6.3_9	4369	55.1	0.35
									N7.1_1	4120	53.6	0.39
									N7.1_3	4512	57.2	0.36
									N7.1_4	3204	54.5	0.37
									N7.1_5	4908	67.3	0.42
									N7.1_6	3937	62.6	0.39
									N7.1_8	2581	58.7	0.42
							Bolt 1	0.3	N7.1_9	2418	50.2	0.36
									N7.1_10	3926	58.4	0.36
									N7.1_11	1410	48.6	0.42
									N7.1_12	2232	48.2	0.38
									N7.1_13	2619	52.6	0.38
									N7.1_14	3511	57.5	0.39
Natural	7	14.5	10	1.3	8.7	4.35			N7.1_15	2085	52.1	0.39
									N7.2_3	1909	47.2	0.40
									N7.2_4	4566	57.7	0.39
									N7.2_5	3491	41.1	0.35
							Bolt 2	-0.7	N7.2_7	4670	56.5	0.38
									N7.2_8	4155	58.4	0.37
									N7.2_9	4270	54.8	0.35
									N7.2_10	4083	57.5	0.38
									N7.2_11	4876	57.4	0.40
									N7.3_1	2462	46.4	0.36
									N7.3_2	3487	50.3	0.36
							Bolt 3	-2.9	N7.3_4	2461	46.1	0.41
									N7.3_5	5265	58.0	0.35
									N7.3_7	6015	67.1	0.39
Natural	8	12.7	9.4	2.9	6.5	3.35			N8.1_1	7042	71.7	0.40
									N8.1_2	6837	70.5	0.39
									N8.1_3	6106	52.3	0.39
									N8.1_5	7066	65.7	0.39
							Bolt 1	1.9	N8.1_6	6339	62.0	0.40
									N8.1_8	6599	62.6	0.40
									N8.1_9	7037	65.4	0.41
									N8.1_10	6063	65.1	0.40
									N8.1_11	6087	64.2	0.41
									N8.2_2	5742	58.3	0.37
									N8.2_6	4632	54.6	0.37
									N8.2_7	5623	62.9	0.38
							Bolt 2	0.9	N8.2_9	4644	53.8	0.36
									N8.2_10	4952	52.6	0.37
									N8.2_11	5976	62.1	0.37
									N8.2_12	5179	52.4	0.39
							Bolt 3	-1.3	N8.3_1	4841	49.4	0.36
									N8.3_2	5524	57.4	0.36
									N8.3_4	5396	52.7	0.37
									N8.3_5	5479	60.7	0.35







Regen. Method	Tree No.	Diameter at dbh (cm)	Height (m)	Height to Live Crown (m)	Length of Live Crown (m)	Crown Diameter (m)	Bolt No.	Distance of Bolt Centre Point to Live Crown (m)	Sample ID	MOE Adjusted to 12 % (MPa)	MOR Adjusted to 12 % (MPa)	Specific Gravity Adjusted to 12 %
									N8.3_6	6235	63.7	0.37
Natural	9	11.4	9.3	4	5.3	2.8	Bolt 1	3	N9.1_2	6077	63.7	0.41
									N9.1_3	6457	68.9	0.41
									N9.1_4	8180	73.6	0.41
									N9.1_6	7095	75.9	0.41
									N9.1_7	8000	76.0	0.43
									N9.1_8	6383	61.9	0.39
									N9.1_9	6130	64.1	0.41
							Bolt 2	2	N9.2_2	6376	63.4	0.39
									N9.2_4	5466	52.8	0.36
									N9.2_5	6210	57.8	0.39
									N9.2_6	5345	56.5	0.34
									N9.2_7	6383	69.4	0.39
							Bolt 3	0.2	N9.3_1	7166	57.0	0.38
									N9.3_2	6047	60.8	0.37
									N9.3_4	6661	74.3	0.38
									N9.3_5	6556	63.4	0.38
									N9.3_6	6757	63.9	0.38
Natural	10	12.1	11	5.7	5.3	1.5	Bolt 1	4.7	N10.1_2	7860	82.3	0.42
									N10.1_3	7237	73.6	0.42
									N10.1_4	6875	64.0	0.42
									N10.1_6	6691	69.8	0.38
									N10.1_7	7495	75.3	0.46
									N10.1_10	6303	65.3	0.44
							Bolt 2	3.7	N10.2_1	5109	57.0	0.35
									N10.2_2	5348	56.7	0.37
									N10.2_3	5464	63.4	0.39
									N10.2_5	6950	66.9	0.40
									N10.2_6	5215	60.9	0.39
									N10.2_7	3590	49.4	0.35
									N10.2_8	6470	64.3	0.39
							Bolt 3	1.7	N10.3_1	5613	40.9	0.36
									N10.3_2	6369	61.0	0.36
									N10.3_4	5371	52.4	0.36
									N10.3_6	4519	46.1	0.35
									N10.3_7	5700	57.9	0.39
Natural	11	10.3	9.6	5.1	4.5	1.3	Bolt 1	4	N11.1_2	5479	52.4	0.44
									N11.1_4	5674	54.9	0.44
									N11.1_5	5064	48.0	0.49
									N11.1_7	6284	58.6	0.45
							Bolt 2	3.1	N11.2_1	6834	57.1	0.45
									N11.2_2	6555	57.6	0.44
									N11.2_4	7063	59.3	0.49
									N11.2_6	6461	56.4	0.43
							Bolt 3	1.1	N11.3_2	6063	53.1	0.43
									N11.3_4	7291	57.9	0.45
									N11.3_5	7190	57.3	0.44
									N11.3_6	5818	48.6	0.41
									N11.3_7	6292	51.9	0.42
Natural	12	11.1	8.7	4.2	4.5	2.15	Bolt 1	3.2	N12.1_2	6031	65.6	0.41
									N12.1_3	5752	65.6	0.45
									N12.1_8	6393	67.8	0.42
									N12.1_9	5006	68.4	0.40
									N12.1_10	5822	61.8	0.43
							Bolt 2	2.2	N12.2_2	7463	69.0	0.41
									N12.2_3	6326	70.8	0.40
									N12.2_5	7644	72.6	0.43
									N12.2_7	7215	69.6	0.39
									N12.2_8	7195	72.1	0.41
							Bolt 3	0	N12.3_2	5621	63.0	0.38
									N12.3_5	5585	58.7	0.38
									N12.3_6	5558	57.7	0.37

Natural Tree 9

Bolt 1

	2	3
4	**P**	6
7	8	9

Bolt 2

	1	
2	**P**	4
5	6	7

Bolt 3

	1	
2	**P**	4
	5	6

Natural Tree 10

Bolt 1

	2	3
4	**P**	6
7		
	10	

Bolt 2

1	2	
3	**P**	5
6	7	8

Bolt 3

	1	
2	**P**	4
	6	7

Natural Tree 11

Bolt 1

2	**P**	4
5		7

Bolt 2

	1	
2	**P**	4
		6

Bolt 3

		7
2	**P**	4
	5	6

Natural Tree 12

Bolt 1

	2	
3	**P**	
		8
	9	10

Bolt 2

	2	
3	**P**	5
	7	8

Bolt 3

2	**P**	5
		6

APPENDIX II:

SHAPIRO WILKS TEST OF NORMALITY FOR
THE WOOD PROPERTIES OF INTEREST

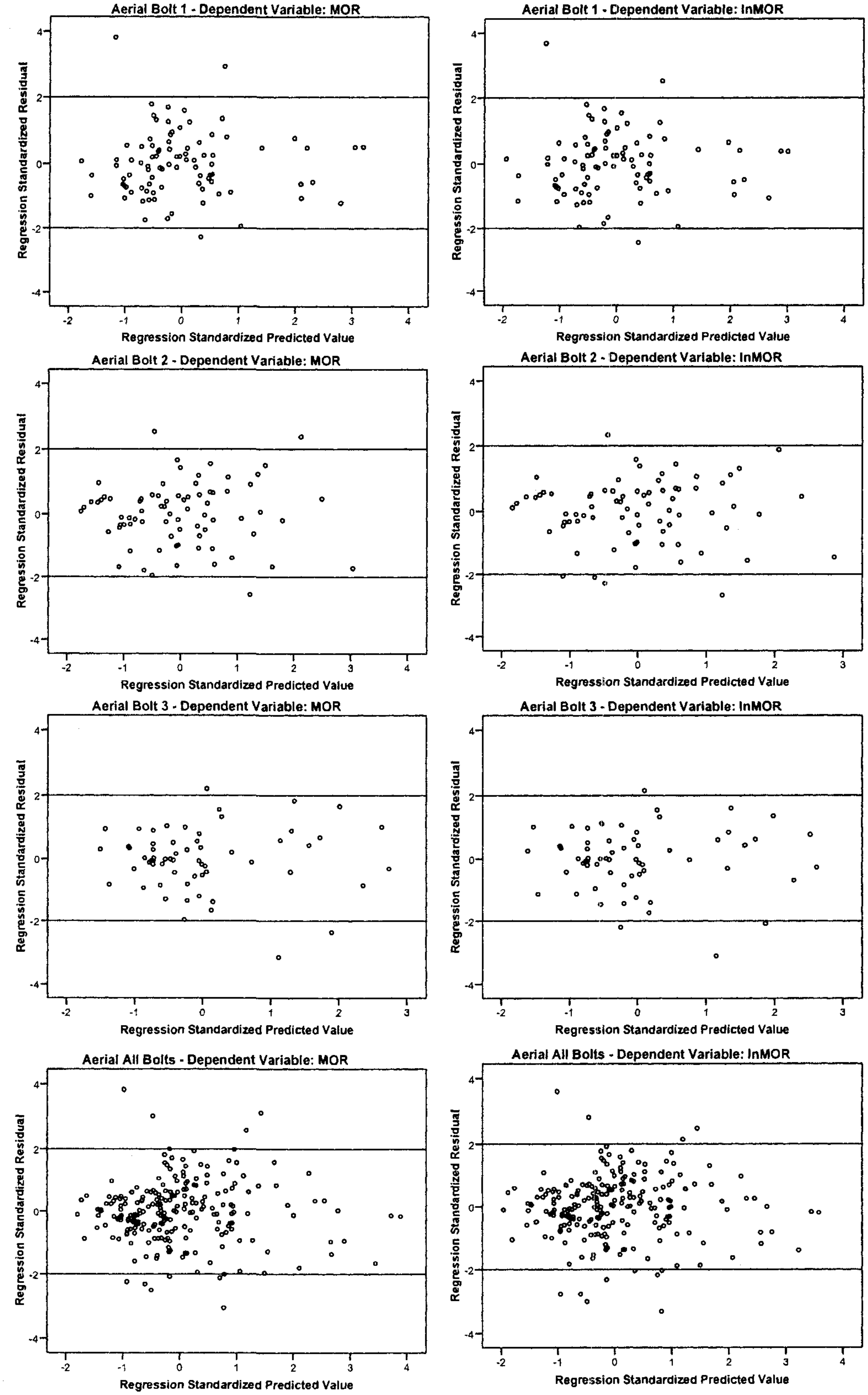
Shapiro-Wilks tests of normality for modulus of rupture, modulus of elasticity and specific gravity based on regeneration method and bolt location (Bolt 1, 2 and 3 represents bolts situated at heights of 1, 2 and 4 m).

Location	Variable	Aerial			Bräcke			Planted			Natural		
		Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.
Bolt 1	MOR	0.971	89	0.0458	0.989	94	0.6270	0.958	123	0.0007	0.981	97	0.1742
	lnMOR	0.984	89	0.3298	0.985	94	0.3398	0.977	123	0.0362	0.980	97	0.1403
Bolt 2	MOR	0.978	77	0.2029	0.989	79	0.7431	0.979	109	0.0823	0.983	80	0.3876
	lnMOR	0.993	77	0.9379	0.992	79	0.8920	0.992	109	0.7530	0.988	80	0.6609
Bolt 3	MOR	0.899	62	0.0001	0.974	61	0.2110	0.991	85	0.8301	0.977	57	0.3372
	lnMOR	0.932	62	0.0019	0.984	61	0.6270	0.990	85	0.7877	0.983	57	0.6005
All	MOR	0.974	228	0.0004	0.989	234	0.0857	0.980	317	0.0002	0.990	234	0.1134
	lnMOR	0.990	228	0.1098	0.992	234	0.2154	0.992	317	0.1035	0.994	234	0.4982
Bolt 1	MOE	0.990	89	0.7238	0.982	94	0.2170	0.990	123	0.4727	0.979	97	0.1151
	lnMOE	0.972	89	0.0497	0.960	94	0.0056	0.970	123	0.0076	0.878	97	2.20E-07
Bolt 2	MOE	0.965	77	0.0305	0.990	79	0.7747	0.971	109	0.0162	0.982	80	0.3085
	lnMOE	0.987	77	0.6387	0.976	79	0.1498	0.990	109	0.5757	0.945	80	0.0018
Bolt 3	MOE	0.972	62	0.1616	0.988	61	0.7965	0.985	85	0.4037	0.967	57	0.1204
	lnMOE	0.993	62	0.9827	0.982	61	0.5124	0.954	85	0.0045	0.909	57	0.0004
All	MOE	0.985	228	0.0158	0.993	234	0.3371	0.992	317	0.0728	0.993	234	0.3449
	lnMOE	0.991	228	0.1844	0.973	234	0.0002	0.979	317	0.0002	0.920	234	0.0000
Bolt 1	SG	0.899	89	3.94E-06	0.986	94	0.4412	0.982	123	0.0950	0.975	97	0.0557
	lnSG	0.927	89	0.0001	0.981	94	0.1900	0.989	123	0.4681	0.985	97	0.3533
Bolt 2	SG	0.929	77	0.0004	0.989	79	0.7223	0.978	109	0.0634	0.960	80	0.0136
	lnSG	0.952	77	0.0058	0.993	79	0.9482	0.978	109	0.0668	0.954	80	0.0057
Bolt 3	SG	0.891	62	4.7E-05	0.981	61	0.4466	0.983	85	0.3395	0.944	57	0.0102
	lnSG	0.911	62	0.0003	0.979	61	0.3720	0.981	85	0.2321	0.955	57	0.0324
All	SG	0.920	228	9.27E-10	0.989	234	0.0727	0.988	317	0.0080	0.972	234	0.0001
	lnSG	0.946	228	1.69E-07	0.994	234	0.4906	0.993	317	0.1300	0.985	234	0.0126

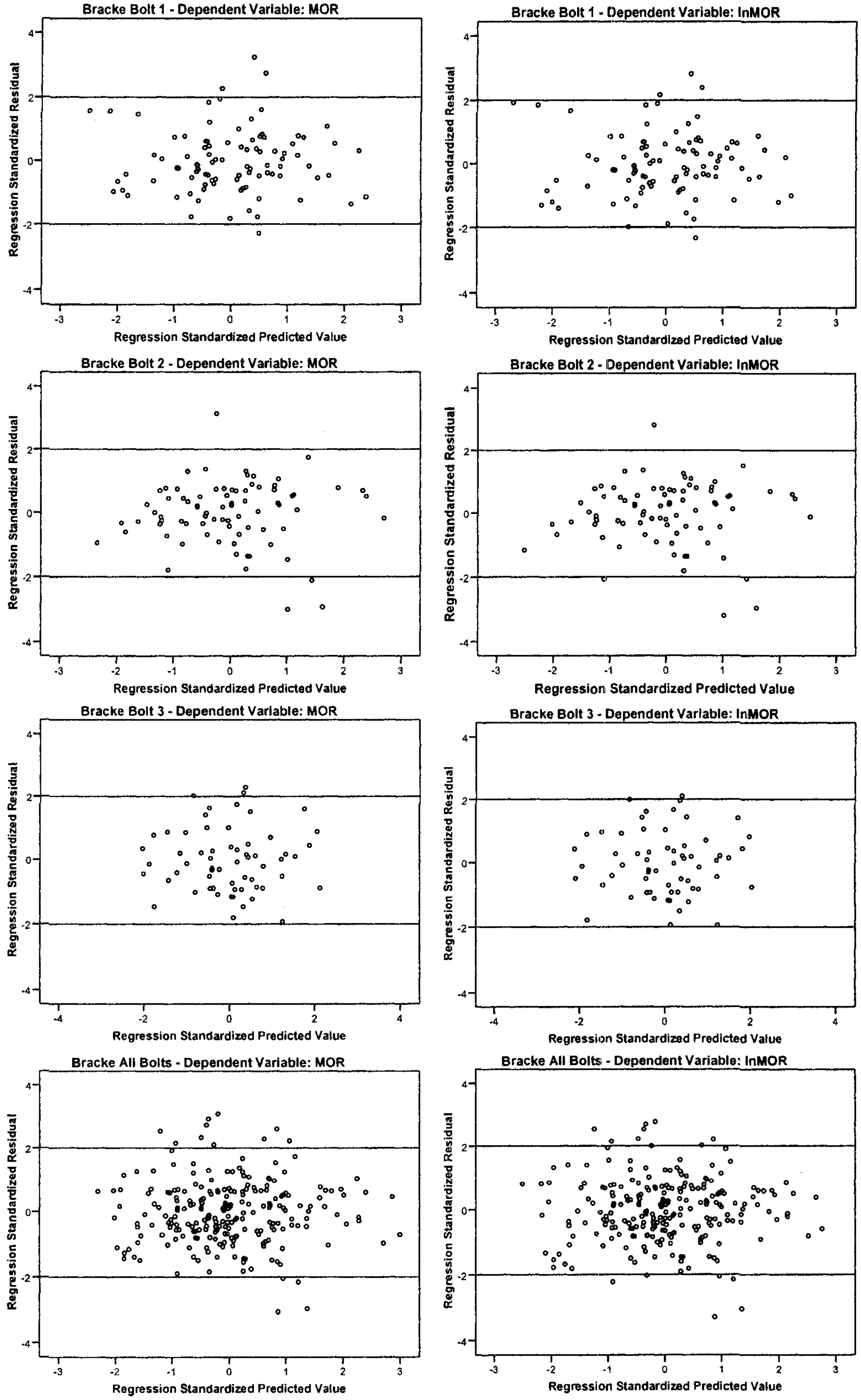
APPENDIX III:

SCATTER PLOTS OF PREDICTED
VERSUS RESIDUAL MECHANICAL
PROPERTY VALUES

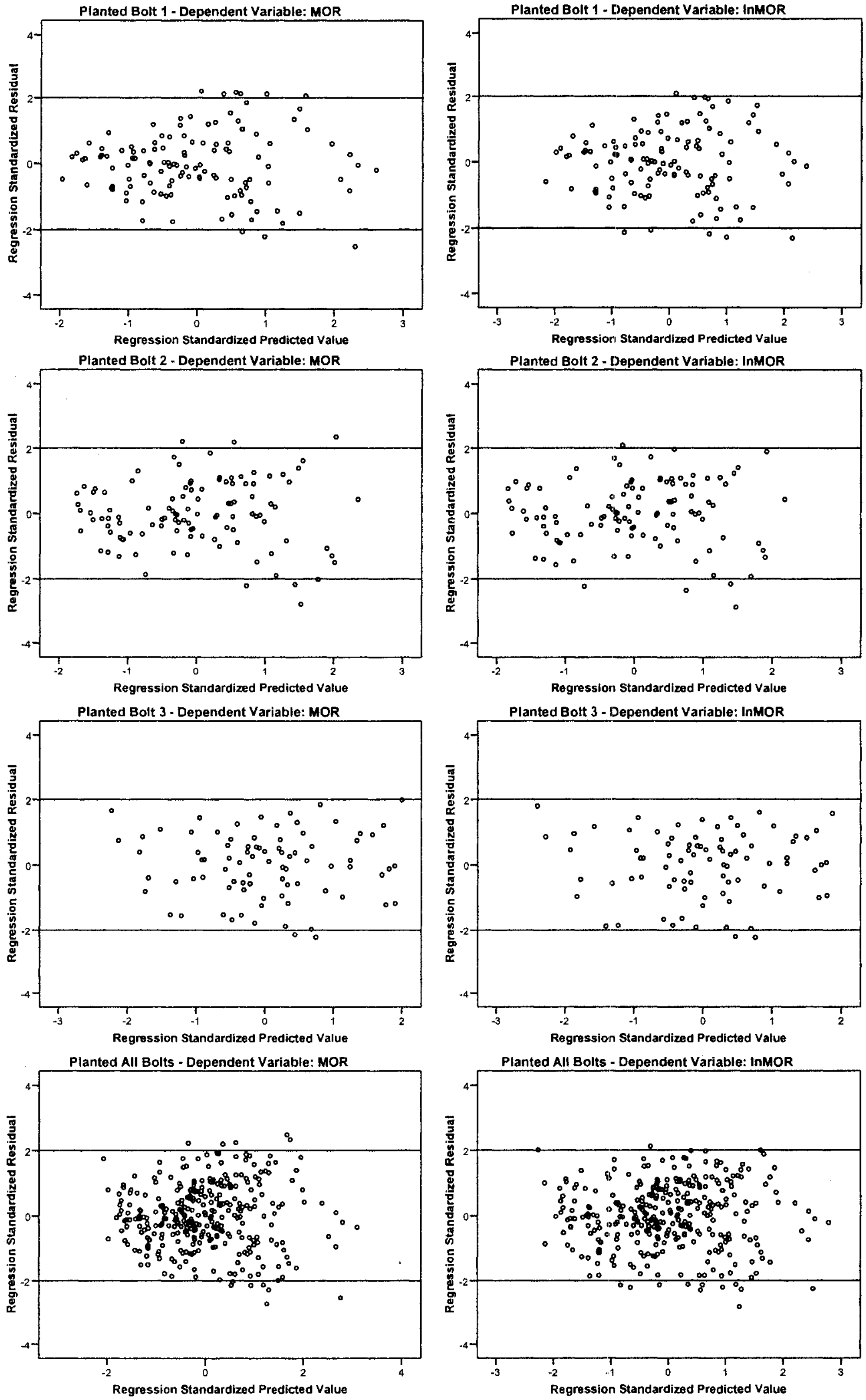
Aerial Seeded Predicted Values vs. Residual Values for MOR – Linear and Curvilinear



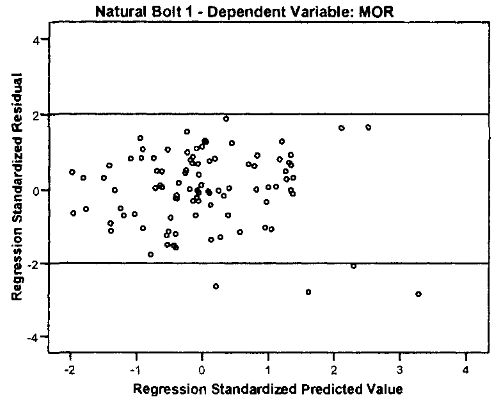
Bräcke Seeded Predicted Values vs. Residual Values for MOR – Linear and Curvilinear

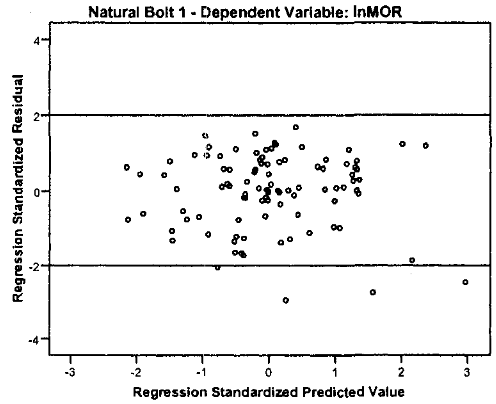


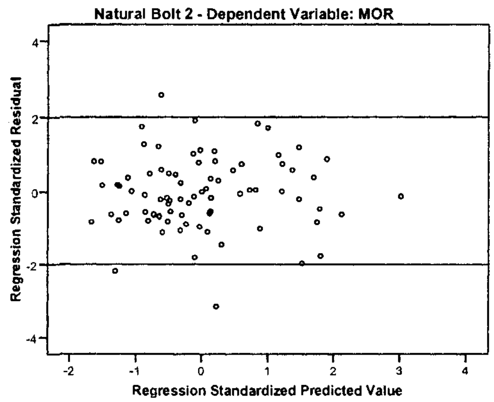
Planted Predicted Values vs. Residual Values for MOR – Linear and Curvilinear

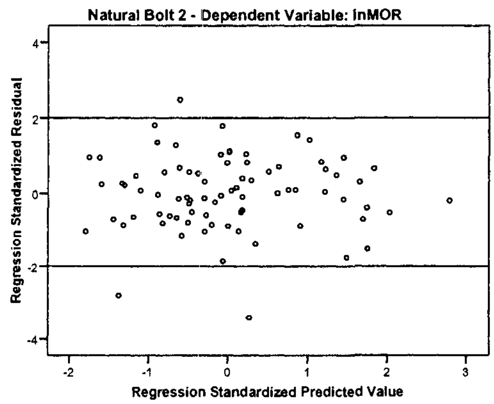


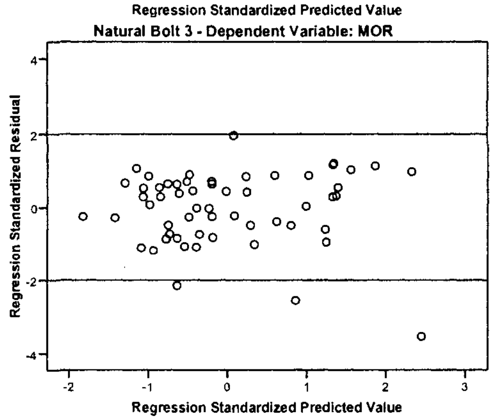
Natural Predicted Values vs. Residual Values for MOR – Linear and Curvilinear

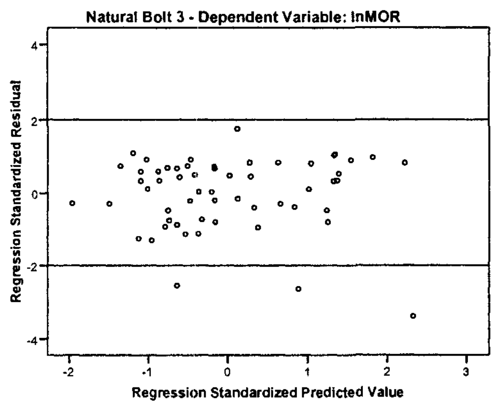


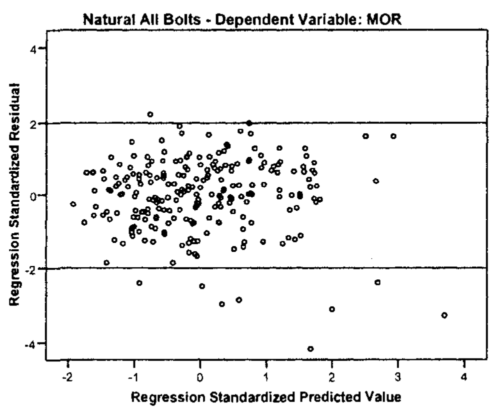


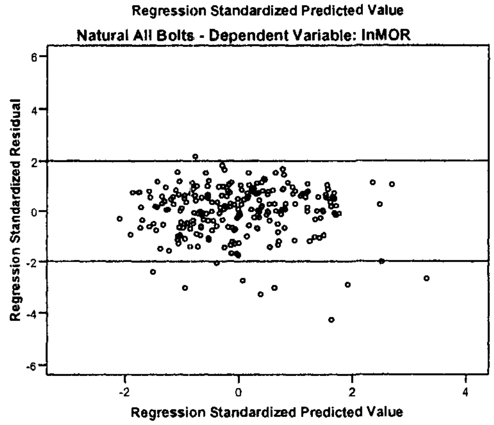




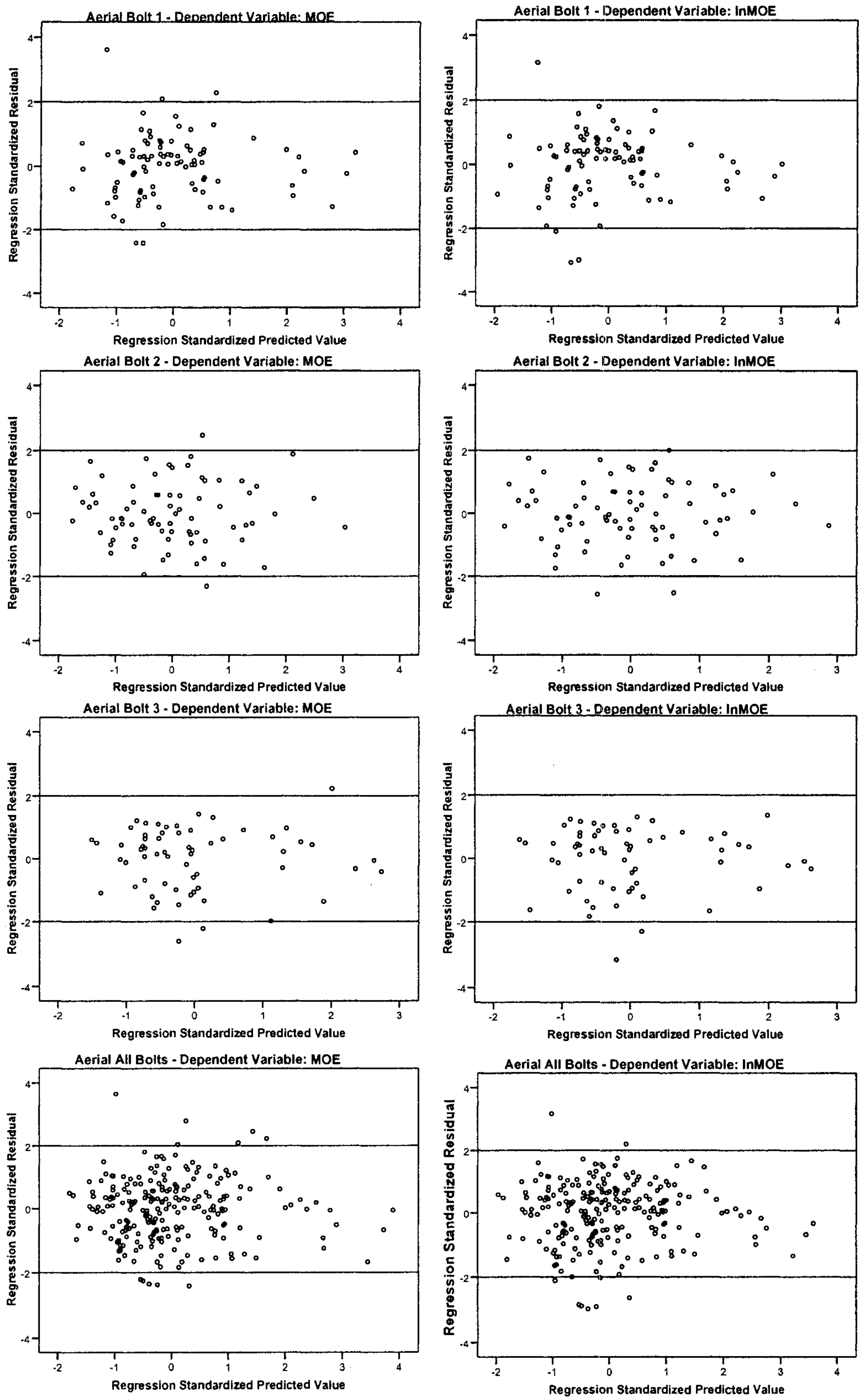




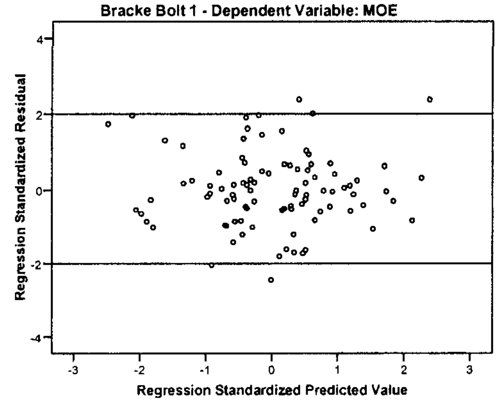


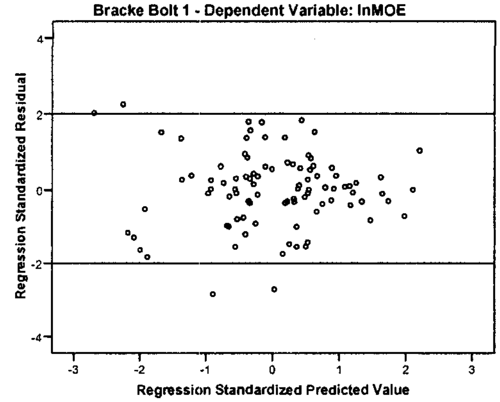


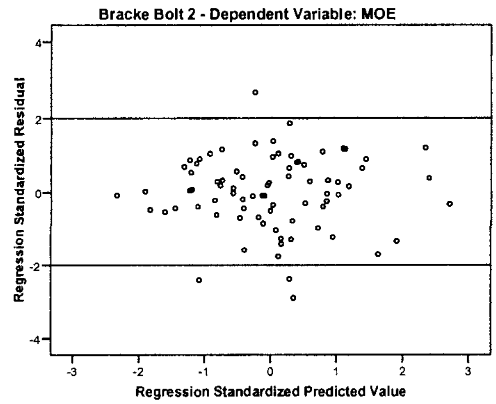
Aerial Predicted vs. Residual Scatter Plots for MOE – Linear and Curvilinear

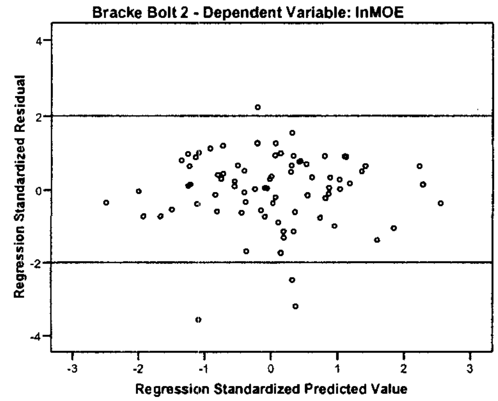


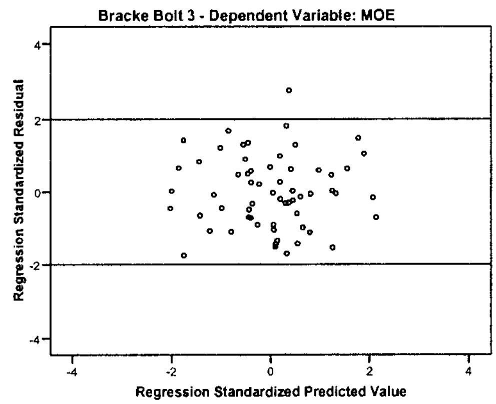
Bräcke Predicted vs. Residual Scatter Plots for MOE – Linear and Curvilinear

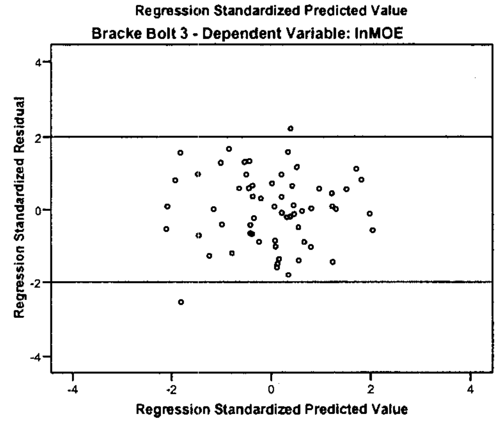


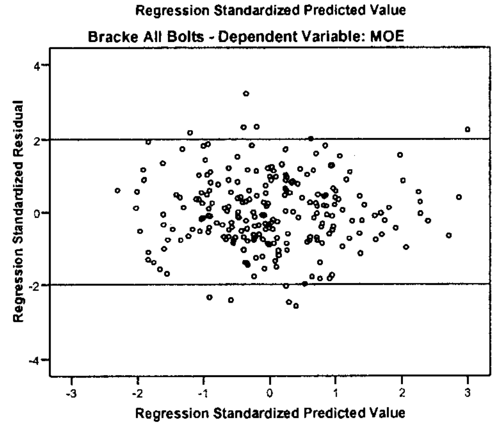


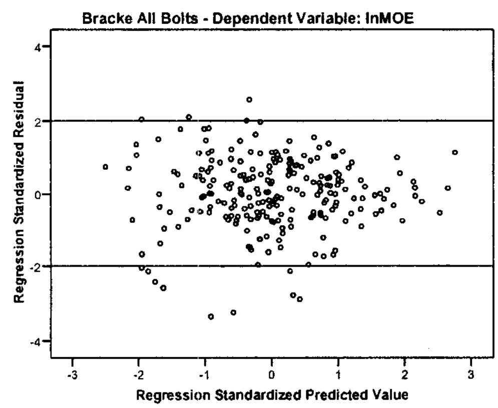






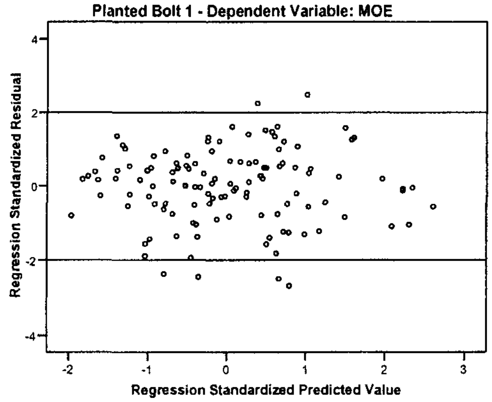




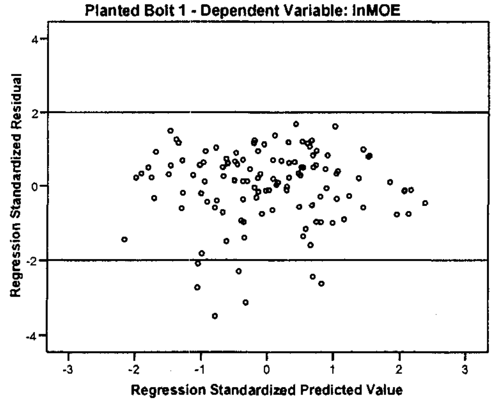


Planted Predicted vs. Residual Scatter Plots for MOE – Linear and Curvilinear

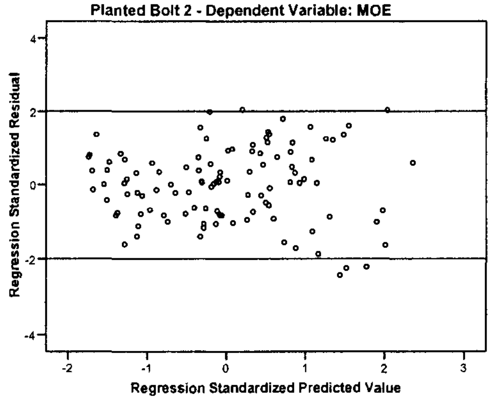
Planted Bolt 1 - Dependent Variable: MOE



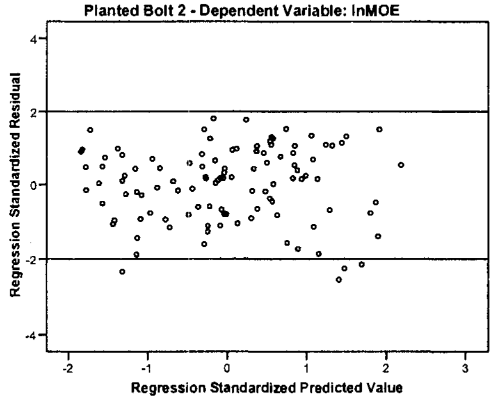
Planted Bolt 1 - Dependent Variable: lnMOE



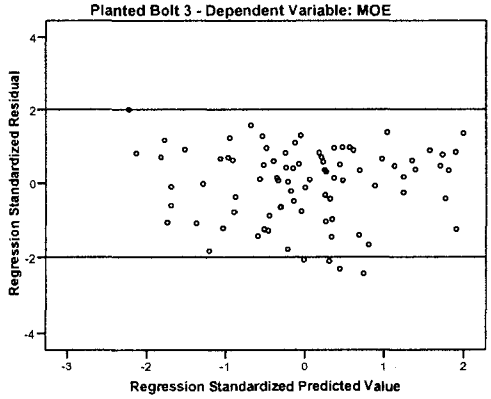
Planted Bolt 2 - Dependent Variable: MOE



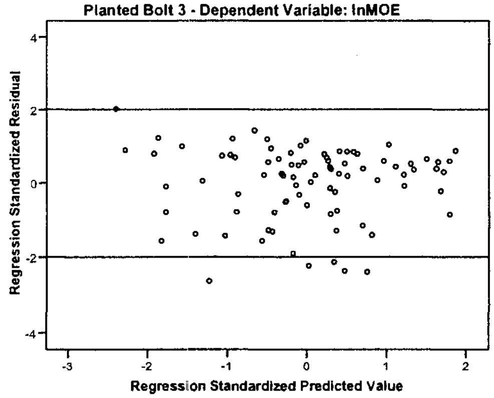
Planted Bolt 2 - Dependent Variable: lnMOE



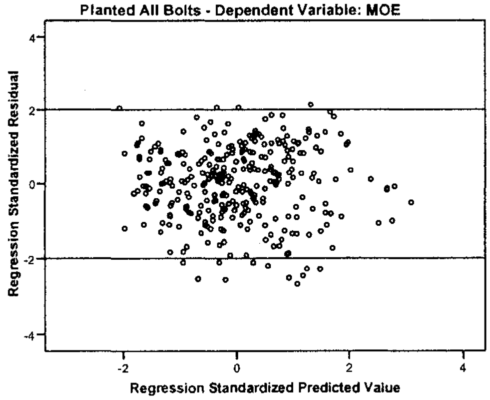
Planted Bolt 3 - Dependent Variable: MOE



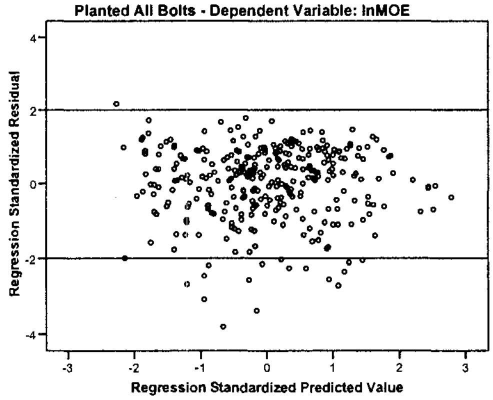
Planted Bolt 3 - Dependent Variable: lnMOE



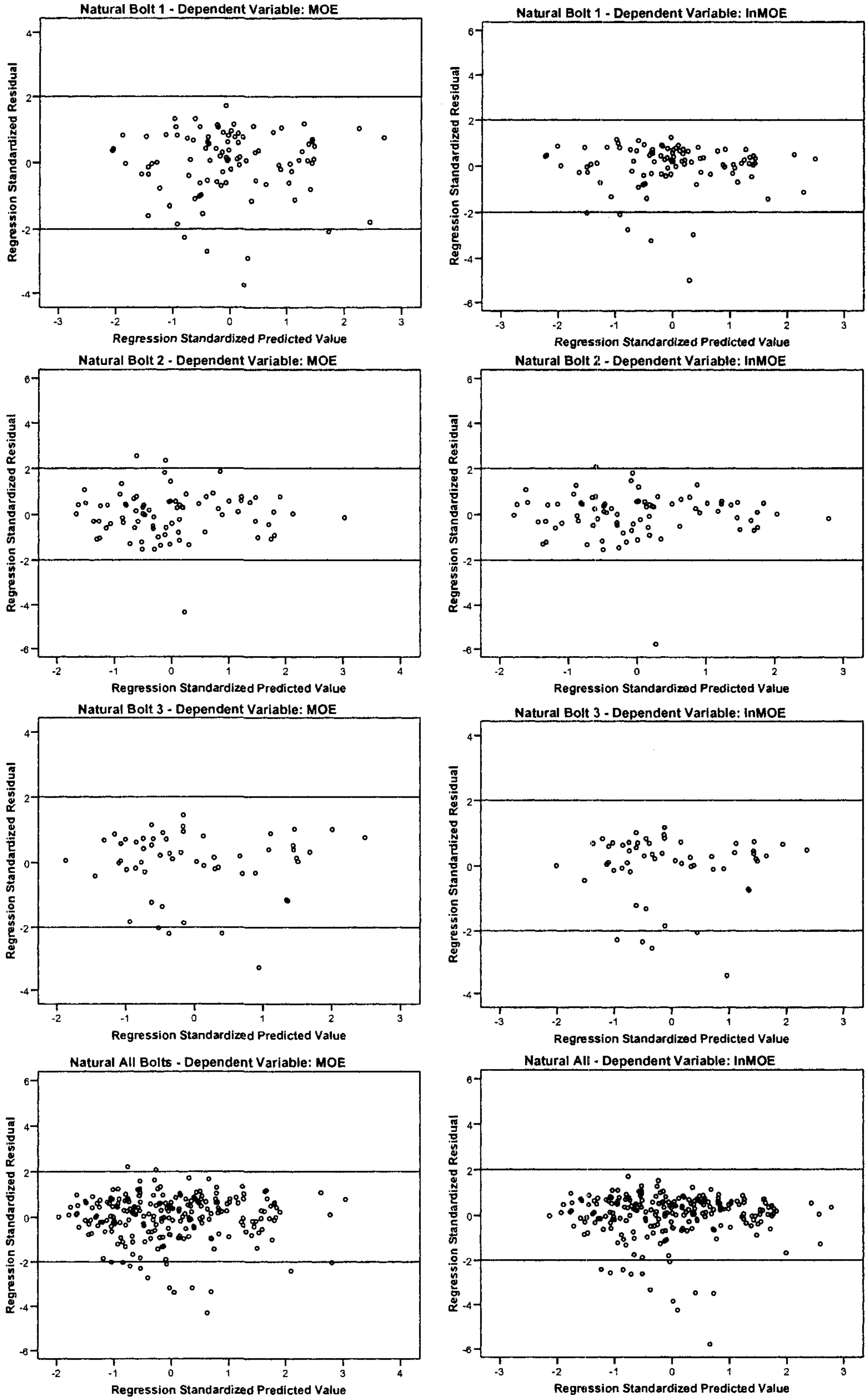
Planted All Bolts - Dependent Variable: MOE



Planted All Bolts - Dependent Variable: lnMOE



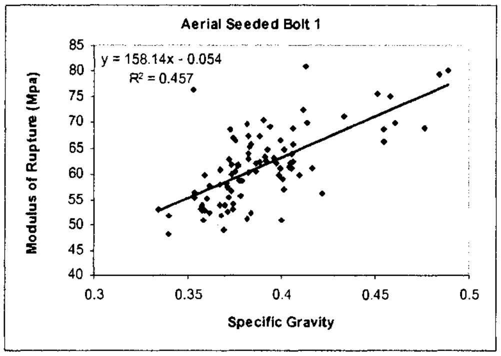
Natural Predicted vs. Residual Scatter Plots for MOE – Linear and Curvilinear

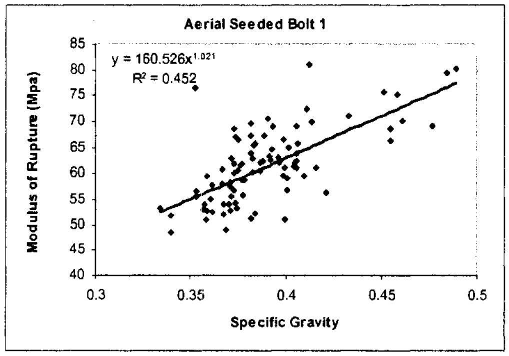


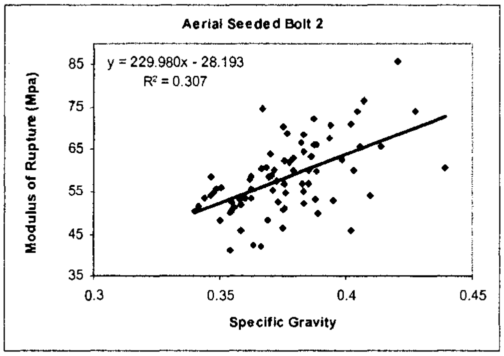
APPENDIX IV:

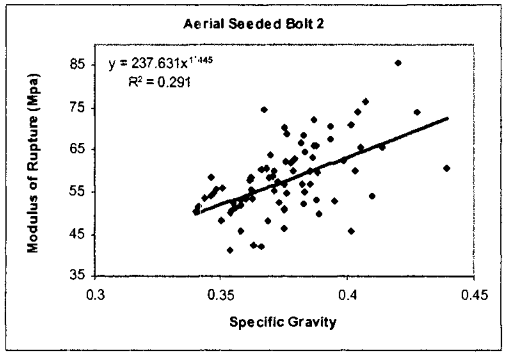
LINEAR AND CURVILINEAR RELATIONSHIPS
BETWEEN MECHANICAL PROPERTIES – MOR or MOE –
AND SPECIFIC GRAVITY

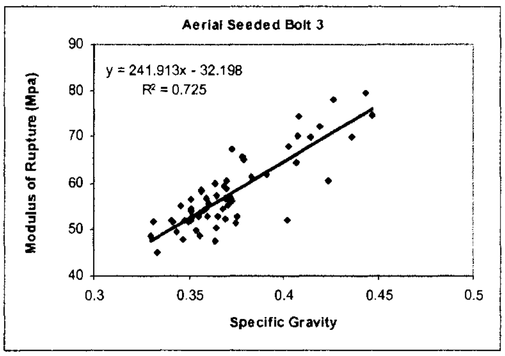
Aerial Seeded MOR Regressions: Linear and Curvilinear

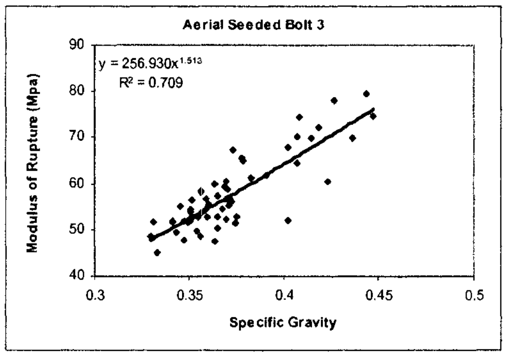


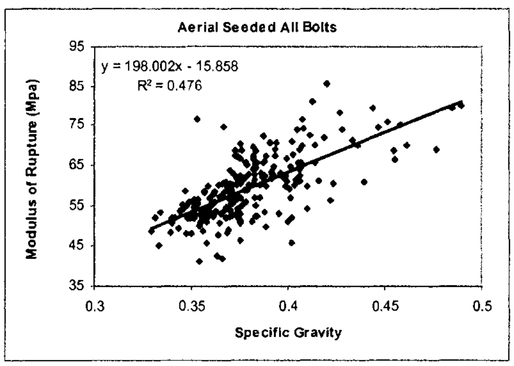


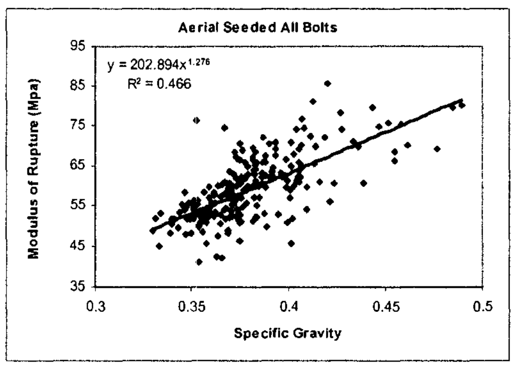




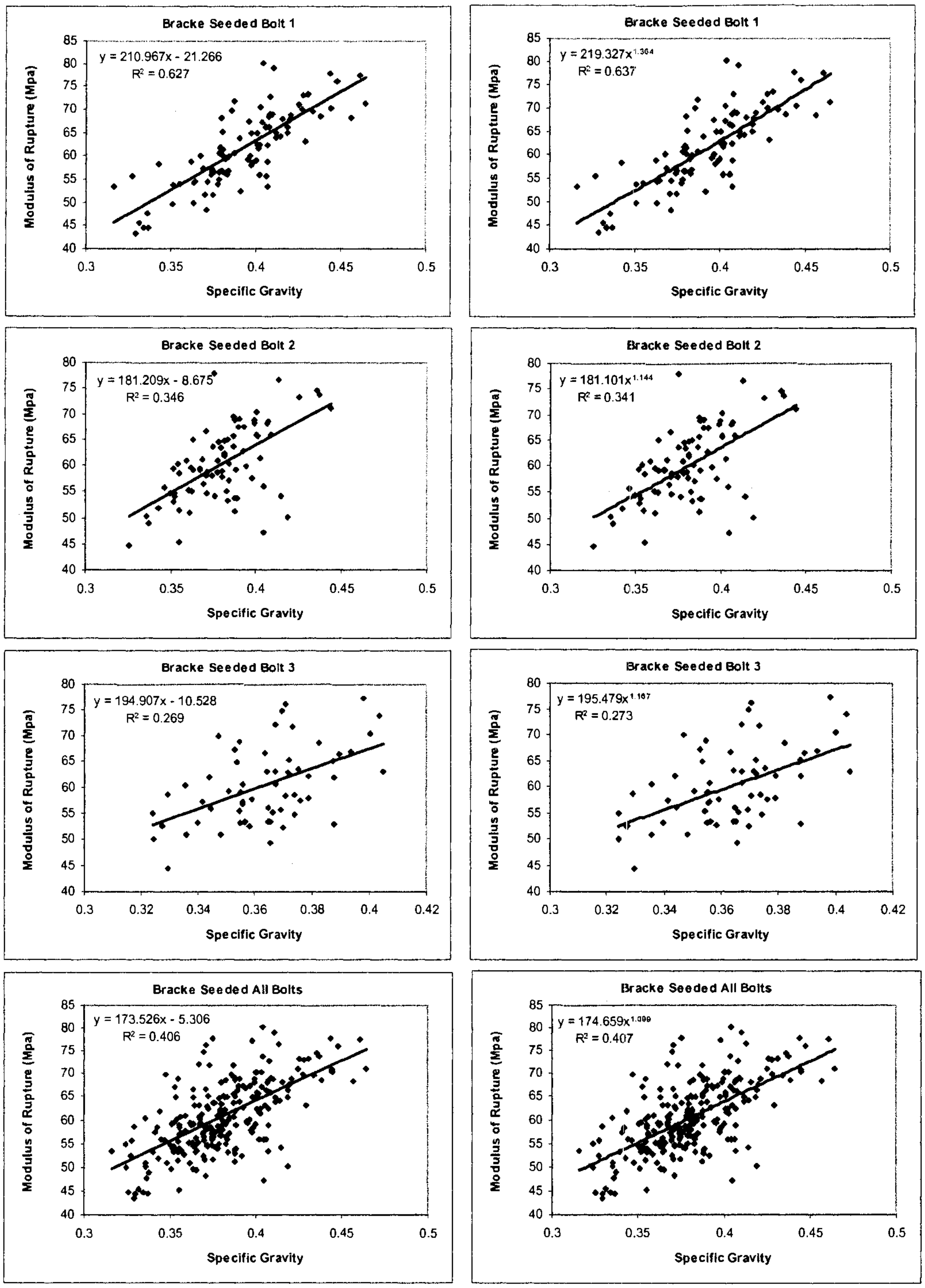




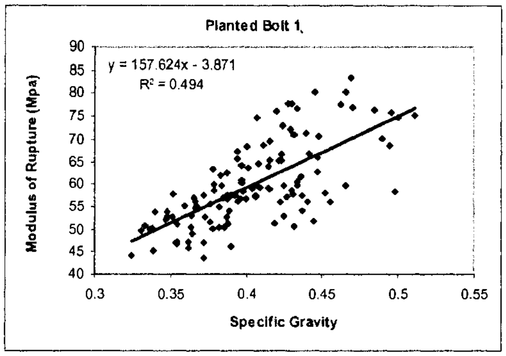


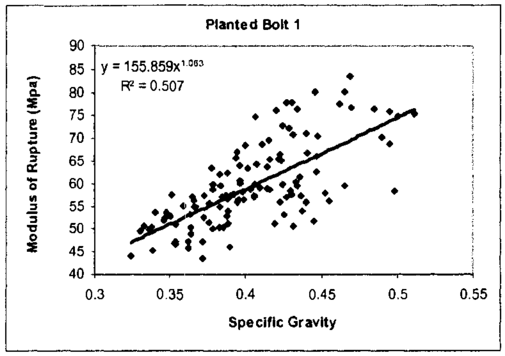


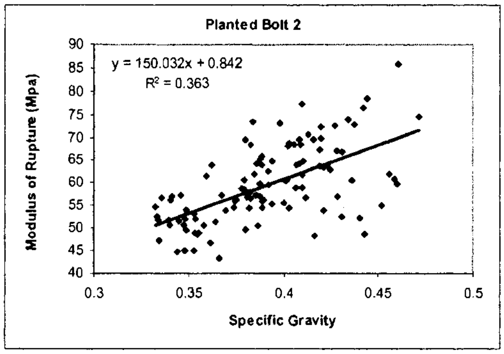
Bräcke Seeded MOR Regressions: Linear and Curvilinear

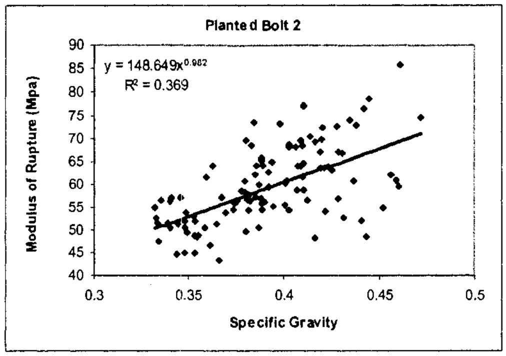


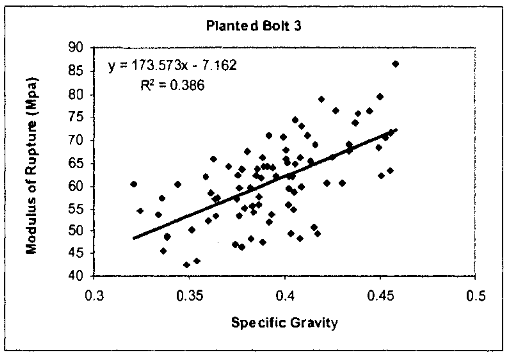
Planted MOR Regressions: Linear and Curvilinear

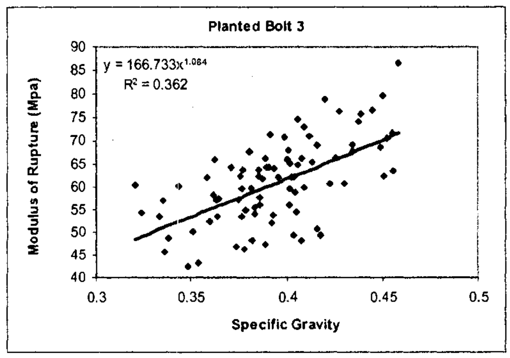


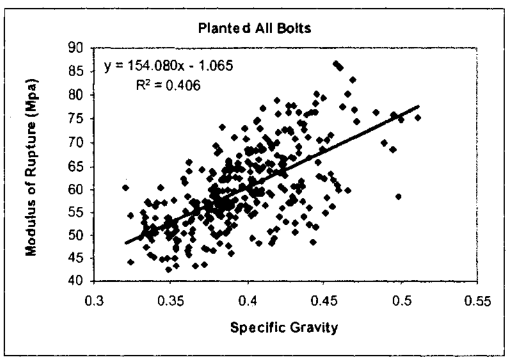


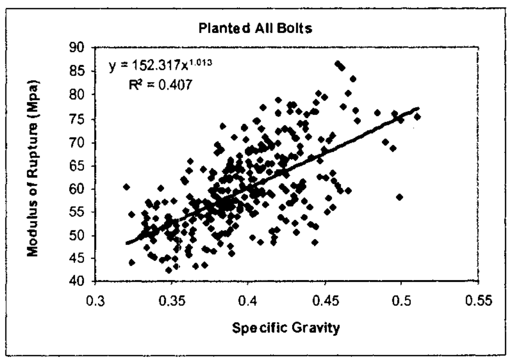




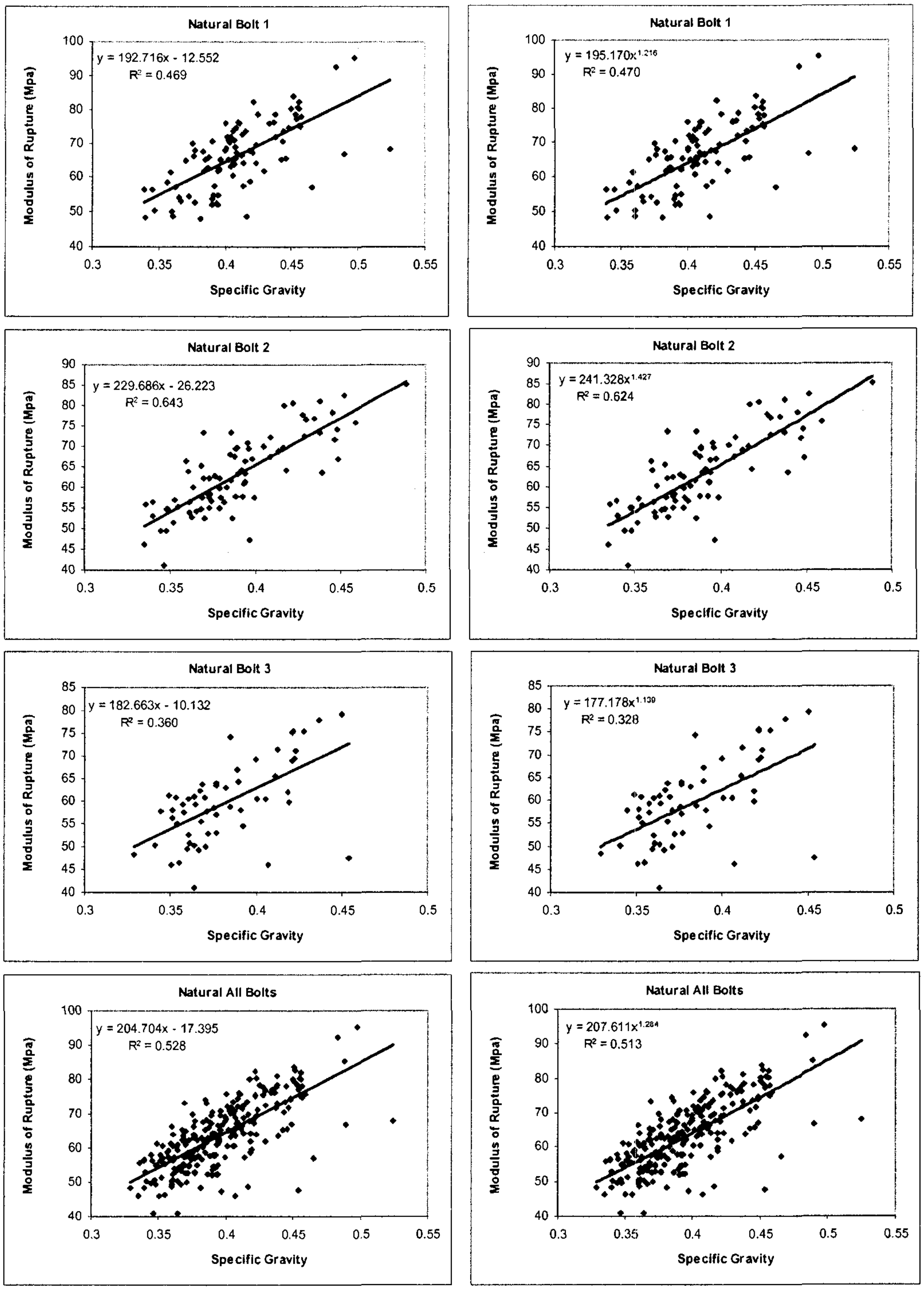




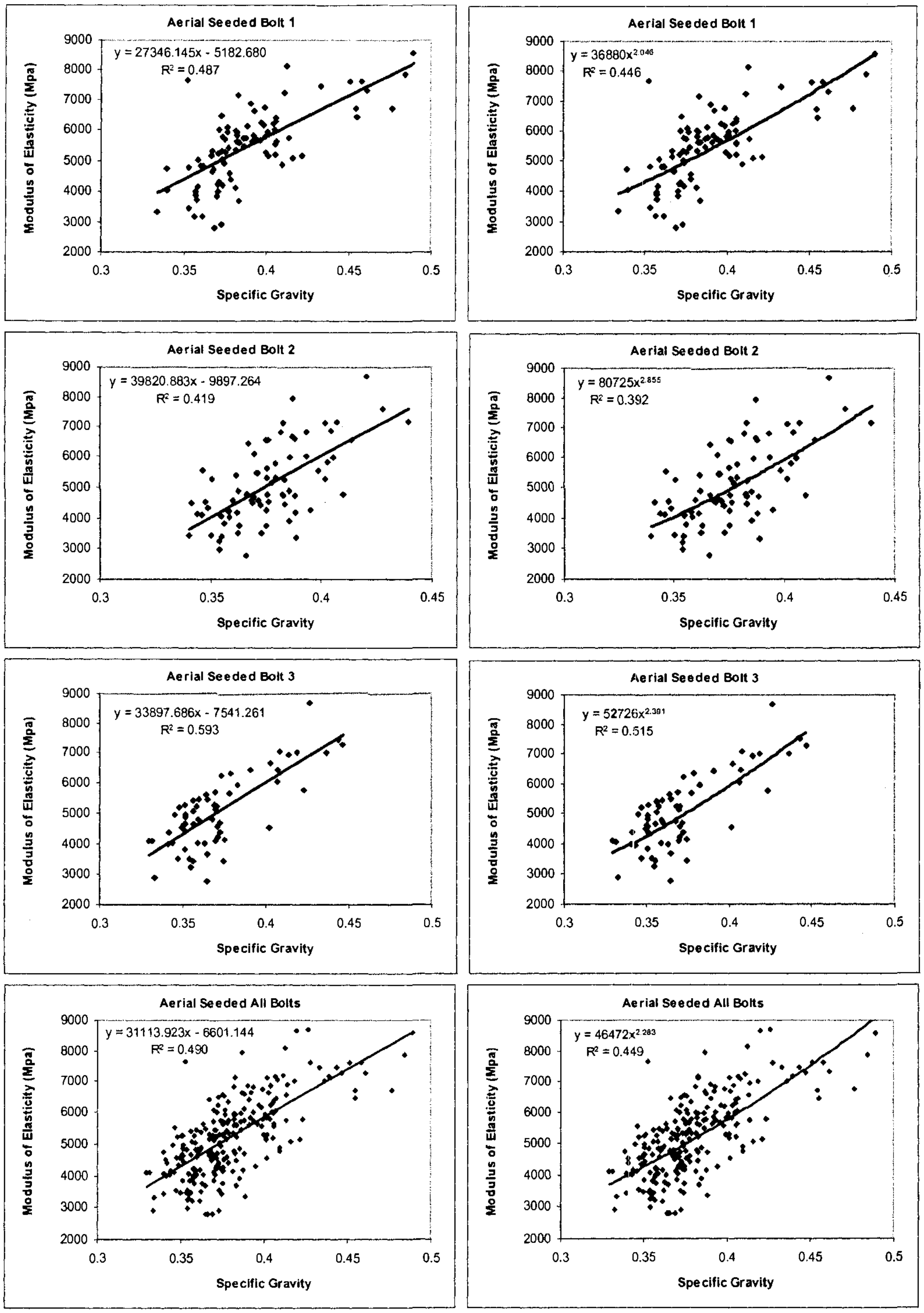




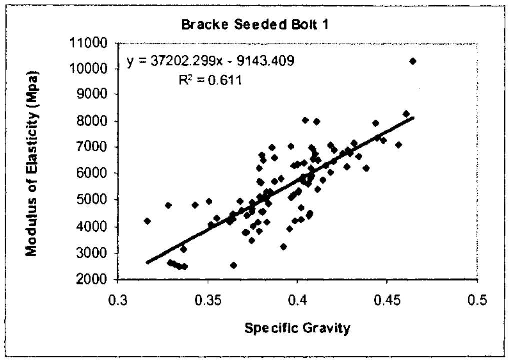
Natural MOR Regressions: Linear and Curvilinear

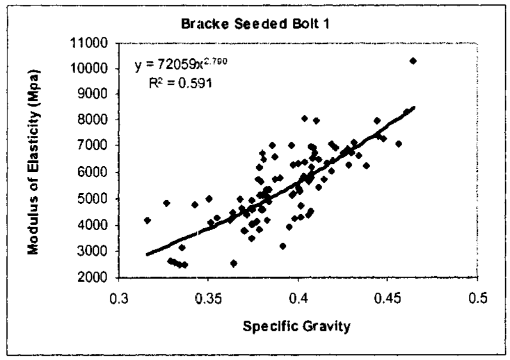


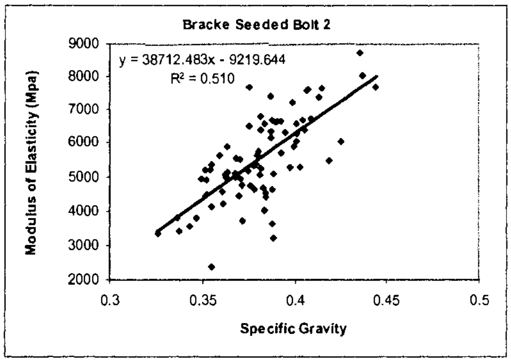
Aerial Seeded MOE Regressions: Linear and Curvilinear

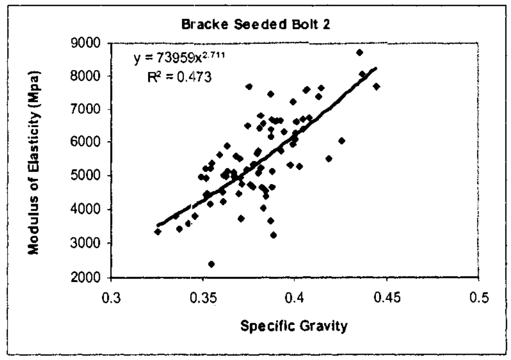


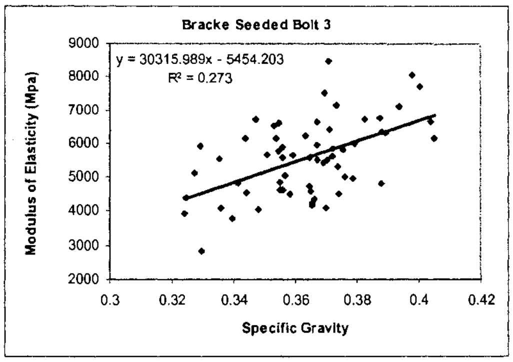
Bräcke Seeded MOE Regressions: Linear and Curvilinear

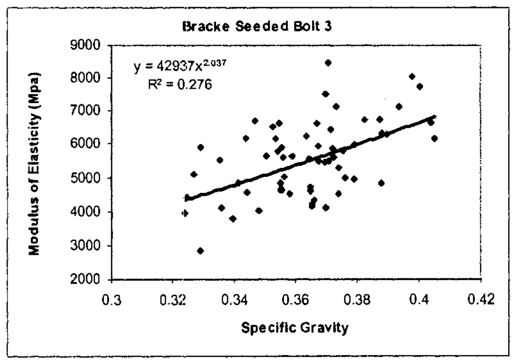


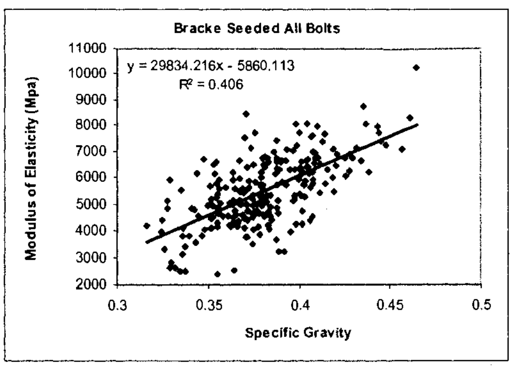


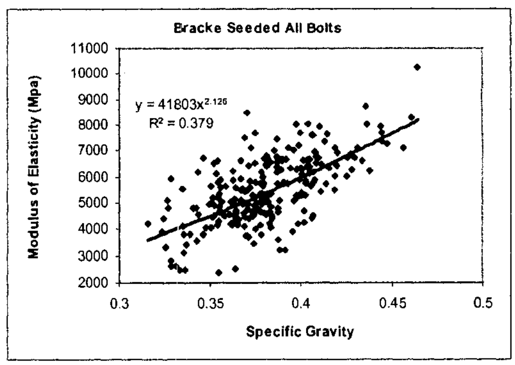




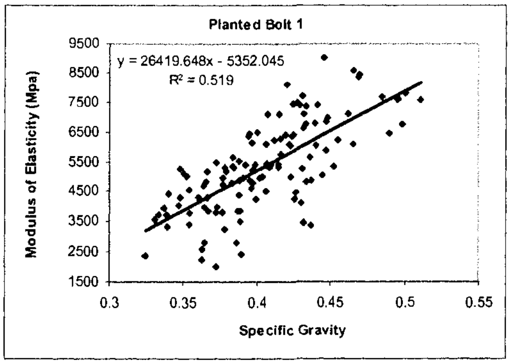


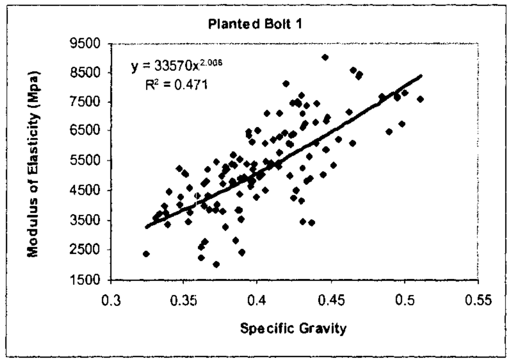


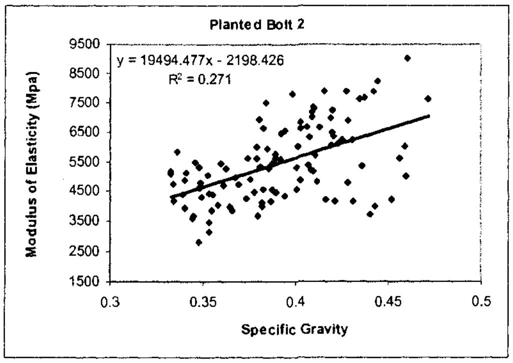


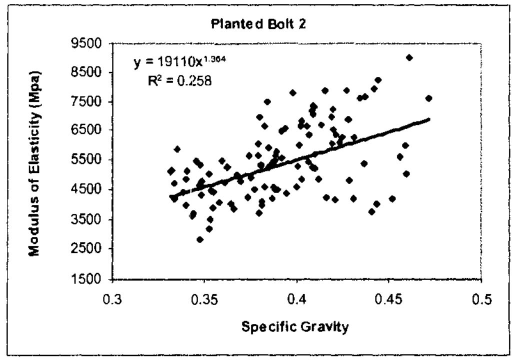


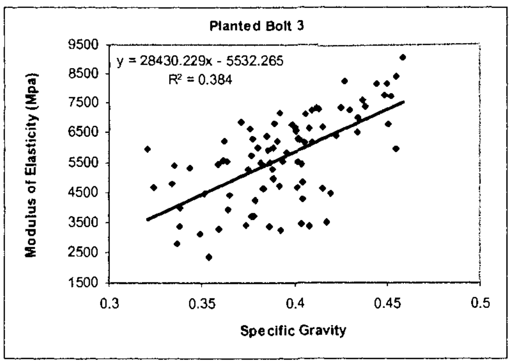
Planted MOE Regressions: Linear and Curvilinear

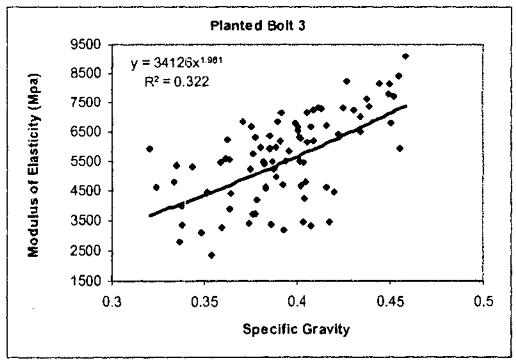


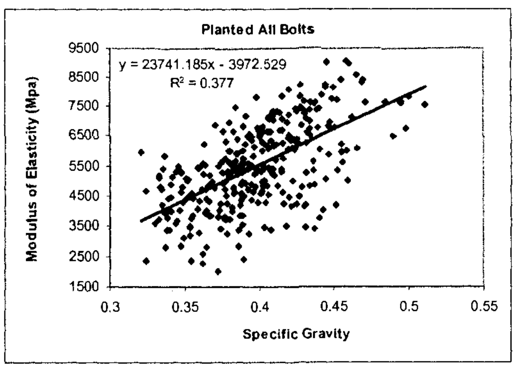


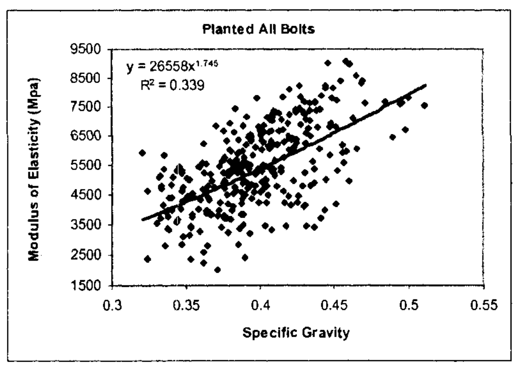












Natural MOE Regressions: Linear and Curvilinear