THERMAL MODIFICATION OF COLOUR IN RED ALDER WOOD

by

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Abstract

Red alder has become one of the most widely traded hardwood species in North America, and sliced red alder veneer is commonly applied as a decorative overlay on composite wood panels used by the furniture and cabinet industries. Red alder wood, however, acquires a mottled red-orange color following felling, which is undesirable when the wood is used for decorative purposes. The discolouration is caused by the enzymatic oxidation of oregonin, a diarylheptanoid xyloside that occurs naturally in red alder wood. Heating red alder wood remedies this problem to some extent, but there is still an unacceptable level of variability in the color of veneer sliced from heated veneer cants. Industry experience suggests that some of the variability in colour is caused by seasonal changes within red alder wood, the effect of log storage prior to heat treatments, and the type of wood used (inner/outer sapwood and position in the stem). This study attempted to clarify the causes of variability in colour of thermally modified red alder wood. First, the effect of various treatment temperatures (30, 50, 70 and 90°C) and treatment durations (8, 24, 36, 48 and 72 hours) on colour in red alder was examined. Secondly, the effects of season, storage and wood type on colour in thermally modified red alder wood were examined. In both experiments, heat was applied under isothermal conditions. Initial experimentation found that increasing treatment temperature resulted in wood that was darker and less red. Heating the wood at 70°C for at least 24 hours produced a uniform colour from pith to bark. Our findings suggest that the final colour of the wood depends on the strength of reactions that produce red-orange chromophoric groups in the wood, thermal darkening of the wood, and destruction of red-orange chomophoric groups. Subsequent experimentation revealed a highly significant interactive effect of season and storage on the colour of heat treated wood. Wood colour (following heat treatment) in samples harvested in spring and summer was dependent on the length of storage time prior to processing. When stored for up to two weeks, spring and summer samples became noticeably redder and darker, followed by an increase in lightness and decrease in redness when stored for 4 weeks. Fall and winter harvested samples were less affected by the length of storage and maintained colour within industry preferences. In both experiments, wood type (inner/outer sapwood) had a significant effect on the colour of heat treated wood and the inner sapwood was darker than the outer sapwood when heated at 70°C. The position of the sample along the stem also had a significant effect, but the colour change was small and indiscernible to the human eye. The findings from this study should provide the basis for further research required to develop differential heating and storage schedules in order to minimise seasonal variability in the colour of red alder. Also, alternative heating methods should be tested to reduce thermal gradients throughout the wood during heat treatments.

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1.0 General Introduction

In recent years, red alder (*Alnus rubra* Bong.) has become one of the most sought after hardwood species in the Pacific Northwest and British Columbia (AHEC 2003). Its favourable manufacturing characteristics, appearance and range of uses have created demand for red alder logs, lumber and secondary products throughout North America and the world (AHEC 2003). In 2002, red alder lumber was the most abundantly exported hardwood lumber into China, exceeding red oak, yellow poplar maple and white oak (AHEC 2003). Uses for red alder have diversified from low grade lumber used in pallets, to high quality lumber and veneer used in specialty, high value applications (Raettig *et al.* 1995). In fact, recent customer preference studies have actually placed red alder ahead of oak based on appearance (Nichols *et al.* 2002; Fell 2002).

A distinct characteristic of red alder is a red-orange staining occurring on the surface of freshly cut wood (Hibbs *et al.* 1994). Simpson (1991) suggests that the staining is the result of an oxidative reaction between the extractives found in alder and the atmosphere. More detailed studies have found that the stain results from the enzymatic polymerisation of oregonin, a diarylheptanoid xyloside found in alder (Karchesy and Laver 1974). Specifically, the formation of red-orange chromophores in alder from oregonin is thought to be catalyzed by peroxidase enzymes. Studies by Gonzalez-Hernandez *et al.* (1999) and Terazawa *et al.* (1984) found that this type of diarylheptanoid is most concentrated in spring and summer, decreasing into the fall and winter. Allen (1993) adds that the stain in freshly cut alder will spread over time. This study found that stain in logs cut in the spring and summer will spread into logs over a period of 4 months while stain in fall and winter cut logs will spread over a period of 6 months and to a lesser extent than in logs felled in spring and summer.

The highly variable nature of colour in red alder presents a problem for wood products manufacturers who are seeking to produce products with a consistent appearance. To overcome this problem in lumber manufacturing, sawn alder lumber is steamed at temperatures of 66 to 100°C for varying periods of time (Kozlik 1962, 1967, 1987; Kozlik and Boone 1987). Steaming produces a uniform tan colour on the surface of red alder lumber, but no studies have examined the thermal modification of colour in red alder cants used in the production of sliced veneer.

Industry reports suggest that it is much more difficult to achieve uniformity and favourable colour in veneer sliced sequentially from steamed cants (Kaufmann 2003). Common industrial hearsay suggests that several factors contribute to the difficulty of achieving desirable results during alder veneer production. These factors include the temperature and/or duration of a heat/steam treatment prior to slicing, the season of harvest, the length of log storage prior to processing, and the location in the log (inner/outer sapwood and vertical position in stem) (Kaufmann 2003). However, it seems reasonable to assume that difficulties in alder veneer production also arise from radial variation in wood colour due to thermal gradients within the cant during steaming, as well as within tree variation in the susceptibility of red alder to thermal discolouration. Variability in the colour of sliced veneer is highly undesirable because veneer sheets pressed onto wood panels need to be colour matched to meet the demands of customers requiring materials for red alder furniture and cabinets with uniform colour (Raettig *et al.* 1995).

This study aimed to clarify the causes of variability in the colour of thermally modified red alder wood. Following this introduction, Chapter 2 reviews relevant literature on red alder wood and focuses on its use for the manufacture of wood products, colour of the wood and thermal modification of colour. Initial experimentation (Chapter 3) examined the variation in colour of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions using four temperatures (30, 50, 70 and 90°C) and five heating times (8, 24, 36, 48 and 72 hours). The aim was to examine whether within-tree variation in the susceptibility of red alder wood to thermal darkening could explain variation in colour of veneer sliced from steamed red alder cants, and secondly to determine the optimal thermal treatment (temperature and time) that can impart the favoured tan colour to red alder wood.

Previous studies have found that the chemical constituents in red alder wood that are responsible for its characteristic red-orange stain to vary seasonally. Industry reports indicate that the colour of thermally modified red alder wood also varies seasonally. Therefore, it seems reasonable to hypothesize that the two are linked. Chapter 4 examined the effect of season, storage time and wood type (inner and outer sapwood and location along the stem) on the colour of red alder wood following a 48 hour heat treatment at 70 °C under isothermal conditions. A better understanding of the extent and causes of variability in thermally modified red alder wood will help manufacturers of red alder veneer modify their processing techniques to produce more uniformly coloured veneer. Chapters 5 and 6 offer discussion and conclusions, respectively, which provide recommendations which will allow manufacturers to produce red alder veneer of a uniform and favourable colour.

2.0 Literature Review

2.1 Introduction

Red alder is the most abundant Pacific coastal hardwood species in Canada and the United States. The species is also known as Oregon alder, western alder and pacific coast alder. Red alder is a relatively short lived species capable of tolerating wet soil and fixing atmospheric nitrogen. Its rapid juvenile growth and acceptance of disturbed sites make red alder a common pioneer species (Hibbs *et al.* 1994). Historically, red alder was known as a weed species requiring removal by herbicide or fire to create space for more commercially valuable species (Hibbs *et al.* 1994). Over the past three decades, however, red alder has become the most valuable commercial hardwood species in the Pacific Northwest with many commercial applications, including furniture, cabinets, pallets, paper, and veneer (Raettig *et al.* 1995).

2.2 Tree Information

Red alder (genus *Alnus*) is a member of the family *Betulaceae.* Other North American genera included in this family are the birches (*Betula*) and hazelnuts (*Corylus*). The most noticeable similarity between these genera is the presence of male catkins (aggregates of staminate flowers) (Brayshaw 1976).

Red alder has a normal life-span of 60 to 70 years with a maximum age of 100 years (Worthington *et al.* 1962). On desirable sites, red alder trees can be 30 to 40m tall and 55 to

75cm in diameter at breast height (dbh). Typically, these larger dimensions occur in trees older than 50 years (Worthington *et al.* 1960).

The native range of red alder extends from southern California (lat. 34° N) to south-eastern Alaska (60° N). It is generally found within 200km of the ocean at elevations of less than 750m. In Alaska, red alder is generally found at sea level, however, scattered pockets of trees are found at nearly 1100m in the southern regions (Hibbs *et al.* 1994). Red alder is seldom found east of the coastal mountain ranges, although some isolated populations have been found in northern Idaho (Johnson 1968) (Figure 1).

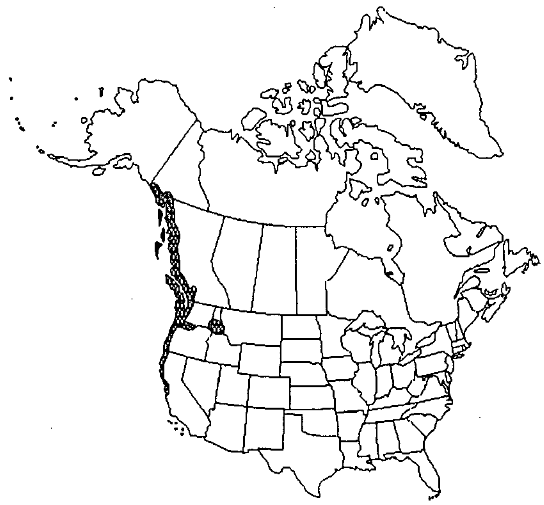

Figure 1. Red alder distirbution map
(Source: Little 1971)

Climates found in the native range of red alder vary from humid to superhumid with annual precipitation ranging from 400 to 5600 mm per year. Most of this precipitation occurs as rain in the winter months. Temperature ranges from -30°C in Alaska and Idaho to 46°C in California (Hibbs *et al.* 1994).

Red alder exists on soils ranging from well-drained sands to poorly drained organics. In British Columbia, it occurs on Brunisol, Gleysol, Organic, Podzol and Regosol soil types. In Washington and Oregon, red alder typically grows on Inceptisol and Entisol soil types (Hibbs *et al.* 1994). The most productive alder stands are found on the alluvial soils of river or stream flood plains, however, good stands are also found on upland sites on residual or colluvial soils (Hibbs *et al.* 1994).

2.3 Wood Characteristics

2.3.1 Anatomical Characteristics

Schweingruber (1990) describes alder as a wood with indistinct heartwood, orange in colour when freshly cut. Its porosity tends to range from diffuse- to semi-ring-porous with fibres developing in radial rows. Parenchyma cells are diffuse, and aggregate rays are generally present. These rays are uniseriate and tend to be homogeneous and up to 25 cells high. Aggregate rays are very broad rays which appear lighter in colour on cross- sectional samples, as opposed to normal rays which rarely exceed one cell in width and are thus inconspicuous. Aggregate rays form dark longitudinal lines one to two inches long on tangential surfaces. Red alder also has a triangular pith with frequent pith flecks.

The majority of red alder wood consists of early wood (Parker 1978), however, Leney *et al.* (1978) notes there is little change in wood structure from earlywood to latewood. This transition is marked by a denser band that makes the growth ring noticeable and produces a subdued grain figure on the tangential surface of a processed board. Leney *et al.* (1978) describes the pores or vessels of alder as small and evenly distributed among the fibres. This even distribution gives the wood a uniform grain with a smooth texture. Gartner *et al.* (1997) found that the wood of red alder was quite uniform within individual trees with the exception of fibre length and vessel diameter which increased radially in the first several growth rings.

2.3.2 Physical Properties

According to Leney *et al.* (1978), red alder's overall index of workability and colour uniformity ranks highly when compared to other North American hardwoods. Its finishing characteristics are similar to yellow birch (*Betula alleghaniensis* Britt.), black cherry (*Prunus serotina* Ehrh.), and sugar maple (*Acer saccharum* Marsh.). The machining properties of red alder are second to only yellow birch, black cherry, and black walnut (*Juglans nigra* L.), and only black walnut equals the sanding and polishing characteristics of red alder (Hibbs *et al.* 1994). Briggs *et al.* (1978) rank the gluing properties and specific gravity of red alder behind only cottonwood (*Populus trichocarpa* Torr. & Gray) and yellow poplar (*Liriodendron tulipifera* L.). Red alder is ranked first for its turning characteristics while its shaping properties are rated below average.

According to testing done by the U.S. Forest Products Laboratory, red alder has superior gluing, machining, sanding and finishing characteristics (WHA 2004). Its resistance to splitting, joint strength, and dimensional stability is also among the highest. The U.S. Forest Products Laboratory rated the hardness, bending strength and compression strength of red alder as below average. Only poplar (*Populus sp.*) rated lower than red alder in these three categories. The species that were used for comparison included bigleaf maple (*Acer macrophyllum* Pursh), red oak (*Quercus rubra* L.), pacific madrone (*Arbutus menziesii*

Pursh), tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.), white oak (*Quercus alba* L.), golden chestnut (*Castanea dentata* Marsh.), poplar, ash (*Fraxinus sp.*), sycamore (*Platanus occidentalis* L.), and black walnut. (WHA 2004).

Red alder's specific gravity (0.41) and density (28.7) ranked ahead of every tested species, with the exception of poplar. Low specific gravity and density have several advantages; however, they are largely responsible for red alder's lower hardness, bending strength and compression strength ratings (WHA 2004).

2.4 Resource Availability, Extraction and Utilization

2.4.1 Resource Availability

Washington and Oregon dominate red alder supply and have standing volumes of 120 and 88 million m^3, respectively. The growing stock is substantially lower in British Columbia and California, however, rapid growth and recent planting efforts have created a significant red alder resource base in British Columbia with the growing stock approaching 9 million m^3 (COFI 2000; Raettig *et al.* 1995) (Figure 2).

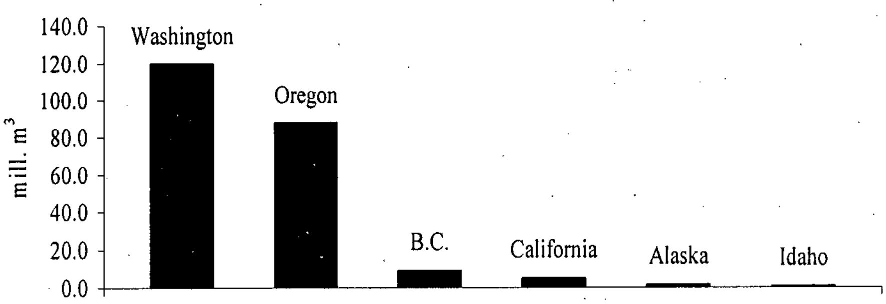

Figure 2. Red alder growing stock (mill. m^3)
(Sources: COFI 2000 & Raettig *et al.* 1995)

According to the United States Department of Agriculture (USDA), the majority of Alaska's red alder stands are found in the Tongass National Forest in south-eastern Alaska (the pan-handle). The growing stock of red alder in this region is estimated to be nearly 1.2 million m^3 (van Hees 2001). The growing stock of red alder is not included in Idaho's forest inventories, but it is estimated to be quite limited (Troyer 2004).

Red alder is the dominant hardwood species in Washington and Oregon, representing 69% and 53% of the total hardwood supply, respectively. In British Columbia and California, alder's representation falls to 2% and 1%, respectively, however, the abundance of aspen throughout the interior of British Columbia creates a distorted view of the provincial hardwood supply. Red alder, while representing only 2% of the province's total hardwood supply, represents 40% of the province's coastal hardwood supply (COFI 2000 ; Raettig *et al.* 1995).

2.4.2 Annual Harvest

British Columbia

In 2002, red alder represented nearly 15% (344,000 m^3) of the total hardwood harvest and over 80% (341,000 m^3) of the coastal hardwood harvest in British Columbia. Province-wide, red alder harvest levels are surpassed only by trembling aspen (*Populus tremuloides* Michx.), an abundant interior species commonly used for the manufacture of oriented strand board (OSB). Aspen is rarely found in coastal forests which makes red alder the province's dominant coastal hardwood. The harvest of red alder grew by nearly 100,000m^3 between 1998 and 2002 (Harvest Billing System 2004).

Washington and Oregon

Annual harvest data for Washington and Oregon hardwoods is available from 1985 onwards. Historically, Washington and Oregon have led western North America in the harvest of red alder. In 1993, both states were harvesting nearly 400,000m^3 per year, with harvest levels in Washington growing to nearly 550,000m^3 in 1995. However, decades of intensive harvesting and recent changes to riparian harvest regulations have limited the volume of available mature alder in both states. As red alder is a common riparian species and 51% of red alder volume is located on Federal lands, much of the growing stock in Washington and Oregon is now protected. In addition, spraying practices used by timber companies throughout the 1980's to reduce alder in softwood stands has created a lack of mature alder of harvestable size (Larson and Nguyen 2003; Oregon Dept of Forestry 2004).

2.4.3 Milling Facilities

British Columbia

There are 14 milling facilities processing red alder in British Columbia, including 7 lumber/pallet mills, 6 veneer plants and 1 specialty shop (Madison's 2002). Each of the 6 veneer plants uses a method of heating red alder prior to slicing. Weyerhaeuser's Northwest Hardwoods is the leading producer of alder lumber and pallets with annual production exceeding 45 million board feet (MMBF) or 110,000m^3, a substantial portion of the province's overall red alder harvest (343,891m^3 in 2002) (Weyerhaeuser 2004).

Washington and Oregon

During the mid-1980's, 25 red alder mills operated in Washington and Oregon. Since then, mill consolidation and closures have allowed a small group of producers to dominate the red alder market, thus dictating the price and availability of alder lumber and creating further reductions in the number of alder mills in the Pacific Northwest. In 2000, 10 companies accounted for over 95% of hardwood lumber production (Eastin & Braden 2000). Weyerhaeuser's Northwest Hardwoods is the leading alder lumber producer in the Pacific Northwest and has 8 milling facilities located in Washington, Oregon, and British Columbia (Weyerhaeuser 2004).

Weyerhaeuser's dominance of the Pacific Northwest's red alder industry has led to several lawsuits filed by independent red alder producers. Following a $78 million judgment in favour of a small-scale competitor in April 2003, Weyerhaeuser settled with a group of independent producers for a sum of $34.5 million. Both suits accused Weyerhaeuser of using monopoly power to influence log prices in order to inhibit an independent producer's ability to compete (SAF 2004).

According to an Oregon log buyer's database developed by Oregon State University researchers, more than thirty independent and consolidated mills process red alder logs. Many of these firms, however, are small and have limited market share (Hansen 2003).

2.5 Red Alder Products

2.5.1 International Trade

Japanese hardwood consumption has declined nearly 65% since 1995, and China has become an increasingly important trading partner with North America (most predominantly, the United States). For example, exports of wood products to China have grown from less than

US$10 million in 1995 to nearly US$1.2 billion in 2002. In 2002, red alder lumber was the most abundantly exported hardwood lumber into China accounting for approximately US$20 million in exports. Other commonly exported hardwood lumber species included red oak, yellow poplar, maple and white oak (AHEC 2003). Red alder is found primarily in western coastal regions and, hence, alder producers have a distinct advantage over eastern hardwood producers due to their proximity to the expanding Chinese market. Between 2000 and 2002, exports of red alder to China have grown by nearly 8,500m^3. Again, this expansion is timely and beneficial to producers, as exports to several other alder markets such as Japan, Taiwan and Korea have declined (Strategis 2004; AHEC 2003).

2.5.2 Applications

In recent years, uses for red alder have diversified from low grade lumber used in pallets to high quality veneer and lumber used in specialty applications such as mouldings, vertical pilasters (columns), and guitar bodies.

Historically, issues with drying, colour, and strength hindered the use of red alder in applications other than low grade pallet stock. While this was a thriving industry, research suggested that alder, if properly processed, would be much more valuable than low grade stock (Raettig *et al.* 1995). Red alder has since become a widely used high grade lumber and veneer species in the furniture industry. Its colour creates a "classic" look that is popular in dining rooms, living rooms and kitchens, most notably, in kitchen cabinet applications (Figure 3). Consumer preference studies have actually placed alder ahead of oak based on appearance (Nichols *et al.* 2002; Fell 2002).

Figure 3. Applications for red alder lumber and veneer

Alder has also become a very popular wood for electric guitar bodies (Pekerti 2002). Fender, a leading guitar manufacturer, now manufactures most of its guitars from alder (Figure 4). Historically, guitar bodies for Fender's signature guitar series, Stratocaster, were made entirely of ash. Red alder has now completely displaced ash in this market. A combination of light weight, excellent strength, and ease of machining and finishing makes alder guitars appealing to a broad range of manufacturers and consumers. Alder veneer is also used for acoustic guitar tops and backs, as well as veneered headstock.

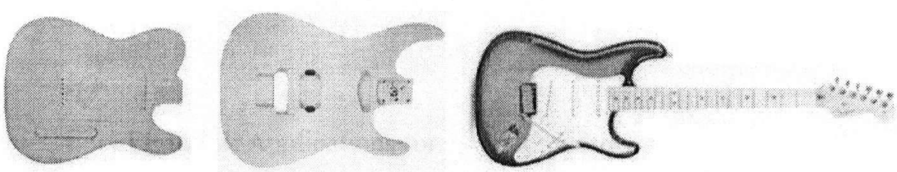

Figure 4. Red alder used to manufacture guitars

2.5.3 Consumer Preference

A study by Nichols *et al.* (2002) aimed to determine consumer preferences for hardwood cabinet doors (alder with three levels of staining, maple, red oak, cherry (*Prunus sp.*) and hickory (*Carya sp.*)). Each consumer respondent participated in one of three labelling scenarios: species name known, species name unknown, and species name known with logos. When consumers based their choice entirely on visual appearance (Scenario 2), red alder compared favourably to other hardwoods. The popularity of red alder relative to other species, however, was reduced when consumers were exposed to the species name, "red alder." Only one exception to this finding was noted: middle-aged, high-income consumers viewed the name red alder as desirable. Therefore, consumers preference is generally negatively affected by the name "red alder" and this should be considered when marketing alder products. When exposed to three levels of staining (none, light and heavy), consumers preferred the heavier stain on red alder cabinets.

A similar study by Fell (2002) attempted to evaluate consumer acceptance of less utilized Canadian wood species used in value-added applications. Consumer respondents were exposed to six "lesser used" hardwood species and two "industry standard" species which were included as 'benchmarks' in the study. The six species included white birch (*Betula pendula* Roth), red alder, broadleaf maple, trembling aspen, red oak and sugar maple (*Acer saccharum* Marsh.). Alder's look was appealing to consumers, making it a favourite for dining room and living room applications where a "classic" look was desirable. Red alder was also chosen quite frequently for kitchen cabinet applications and ranked ahead of red oak for flooring. Overall, red alder was rated higher than industry-favoured species. Broadleaf maple was the top-rated species in the study, while trembling aspen was consistently chosen as the least attractive species.

2.6 Colour

2.6.1 Colour Measurement

The importance of wood colour in decorative products has led to the development of colour measurement systems suitable for the wood products industry. The following are examples of colour models that can be used to quantify colour. Colour models are used to classify colours and to qualify them according to such attributes as hue, saturation, chroma, lightness, or brightness.

Examples of colour models include:

- The RGB (CMY) Colour Model
- The Munsell Colour System
- The HSB/HLS Colour Model
- The CIE Colour Models
    - CIEXYZ
    - CIELUV
    - CIELAB (1976 CIE L*a*b* Space)

CIELAB is one of two systems approved by CIE in 1976 that shows uniform colour spacing values (Adobe 2003). The CIELAB system places these values within a 3-dimensional model with the axes: L*, a* and b* where **L*** is Lightness (0 = black; 100 = white), **a*** is greenness/redness (-60 = green; 60 = red), and **b*** is blueness/yellowness (-60 = blue; 60 = yellow) (Minolta 1998) (Figure 5).

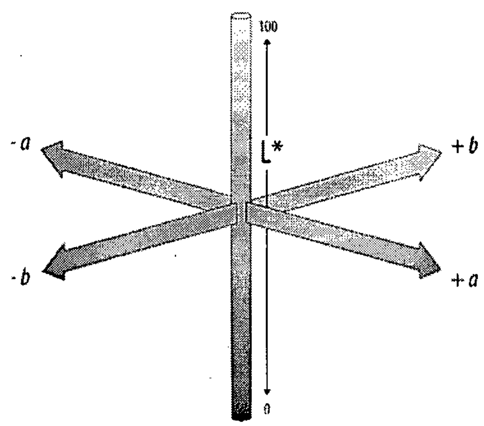

Figure 5. CIE LAB: 3-dimensional colour model (Adobe 2003)

According to Phelps *et al.* (1994), a difference of approximately three colour units is required to be noticed by the human eye. However, this finding is purely observational and is put forward as common knowledge only.

2.6.2 Red Alder Discolouration

Simpson (1991) described the red-orange discolouration that occurs in freshly cut red alder logs or boards as an oxidative reaction between the extractives found in alder and the atmosphere. This discolouration tends to be confined to the outer 1.5mm of the wood and can generally be eliminated by planing. Simpson (1991) also noted that at temperatures above 60°C, a brown discolouration becomes quite noticeable throughout the sapwood. According to White and Dietenberger (2001), darkening of wood during heat treatment is caused by the thermal degradation of hemicelluloses and lignin. Such degradation can begin at temperatures as low as 65°C, depending on the wood pH and moisture content, heating medium, exposure period and species (White and Dietenberger 2001).

A study by Karchesy and Laver (1974) suggested that the red-orange staining in freshly cut red alder wood was caused by the formation of orange chromophores. Their results indicate that oregonin, a diarylheptanoid xyloside found in red alder, reacted with peroxidase enzymes to form the red-orange chromophores. In a more recent study by Gonzalez-Hernandez *et al.* (1999), oregonin was found to vary seasonally in red alder. Concentrations decreased from spring to fall, with levels in the fall being approximately 50% of those in the spring.

Allen (1993) studied the development of stain within alder logs harvested in each of the four seasons. The red-orange discolouration was strong in the spring and summer months, but less evident in the fall and winter. The stain spread over time up to 4 months in the spring and summer, while a less noticeable spread of staining was seen after 6 months in the fall and winter harvested logs (most likely due to the gradual increase in temperature over time). For all seasons, logs stored under cool, moist conditions developed less stain. The study did not mention the colour or strength of the stain over time, but rather the depth (cm) into the log from the cut ends.

A study of phenolic compounds in the living tissues of Japanese alder species (*Alnus hirsuta* Turcz. and *Alnus japonica* Steud.) found that hirsutoside, a diarylheptanoid (identical to oregonin), was the precursor for the red-orange staining of wood in these species. Hirsutoside decreased in the cork cambium, inner bark, and xylem as winter neared (Terazawa *et al.* 1984). Similarly, Gonzalez-Hernandez *et al.* (1999) found that oregonin (responsible for the formation of red-orange chromophores in red alder) varied seasonally. Concentrations of oregonin decreased from spring to fall, with levels in the fall approximately 50% of the levels in the spring.

2.6.3 Discolouration of Red Alder Lumber

Kozlik (1962) aimed to find an optimum drying schedule for red alder that would reduce discolouration of sawn and kiln dried lumber. Lengths of 2.44 metres (8-feet) and dimensions of 2.54 centimetres (1-inch) by 7.62 to 35.56 centimetres (3 to 14 inches) were used. It was deemed that a favourable schedule would achieve desired board quality, colour uniformity, and moisture content while minimising drying time. The study found that pre-steaming at 88°C to 93°C for 11 to 12 hours prior to drying resulted in lumber with the best colour uniformity.

A subsequent study by Kozlik (1967) focused only on the establishment of desirable colour in red alder without mentioning board quality and moisture content. Lengths of 8-feet and dimensions of 1-inch were also used. The study found that steaming at 100°C for at least 4 hours before air or kiln drying eliminated sticker stain and prevented mottling. This treatment produced a uniform colour ranging from white in the sapwood to ivory in the heartwood. Several temperatures and steaming times were tested but none of the combinations were able to achieve both colour uniformity and an absence of sticker stain.

Kozlik and Boone (1987) attempted to optimise drying schedules for red alder lumber, 6, 7 or 8 feet long and 1 inch thick. As in previous research (Kozlik 1962), board quality, colour uniformity, and moisture content were examined. Desirable colour was achieved by steaming the wood at 99°C for 6 hours. Kozlik (1987) found that, to improve colour uniformity, freshly sawn red alder should be pre-steamed for at least 12 hours at 66°C to 77°C. Air dried lumber at 18 to 30% moisture content required at least 24 hours of pre-steaming under the same conditions. Lumber at 16 to 18% moisture content required 30 hours.

The observations mentioned above pertain to red alder lumber without mention of veneer discolouration. Information on discolouration in red alder veneer due to heating, storage, and season is apparently absent from the literature.

2.7 Basic Colour Change

2.7.1 Enzymes

Karchesy and Laver (1974) suggested that the red-orange staining in freshly cut red alder wood was caused by the formation of orange chromophores. Their results indicate that oregonin, a diarylheptanoid xyloside found in red alder, reacted with peroxidase enzymes to form the red-orange chromophores. In a more recent study by Gonzalez-Hernandez *et al.* (1999), oregonin was found to vary seasonally in red alder. Concentrations decreased from spring to fall, with levels in the fall being approximately 50% of those in the spring.

Hon and Shiraishi (1990) describe an enzymatic reaction occurring in several wood species upon exposure of green wood to oxygen. This reaction often results in a mottled discolouration of the exposed surface. Moisture, humidity, and temperature are thought to have a significant effect on the colour of the wood. The surrounding humidity must be approximately 100% for a successful reaction to occur and the rate of discolouration increases steadily above 20°C. Abe *et al.* (1994), however, found that the colour changes in freshly cut sugi (*Cryptomeria japonica* D. Don.) were caused by the reaction of certain extractives and atmospheric oxygen under weakly alkaline conditions. They concluded that enzymes were not responsible for the colour change.

2.7.2 Heat

As wood is dried at high temperatures, it tends to change colour. The extent of this colour change depends on the wood species, drying temperatures and drying times. Kollmann (1951) and Millett (1952) found that temperatures above 50°C were required to produce a red colour change in maple (*Acer sp.*) and beech (*Fagus sp.*) when the wood was heated at a relative humidity of 65%. Under similar conditions, sugar pine (*Pinus lambertiana* Dougl.), oak, and spruce (*Picea sp.*) required temperatures of 65°C, 80°C, and 90°C, respectively, to change to a similar brown colour. Discolouration of todomatsu (*Abies sachalinensis* Schmidt) also increased with an increase in temperature and drying time.

A study by Sundqvist (2002) examined the response of Scots pine (*Pinus sylvestris L.*), Norway spruce (*Picea abies* L.) and birch (*Betula* sp.) to heat treatments. Temperatures of 65°C, 80°C, and 95°C were used to heat wood for 0, 1, 3, and 6 days. The study showed that heating time was more important than temperature in effecting colour change in birch, while time and temperature were of similar importance for Scots pine and Norway spruce. Accelerated darkening for all species was noted when the heating temperature exceeded 80°C.

Thomassen (1986) found that a brown-red discolouration formed in the core of European beech boards during convection drying at ~40°C. Discolouration occurred when the wood reached the fibre saturation point (25-35% moisture content). Similarly, Yeo and Smith (2004) found that internal darkening of hard maple developed at or above 43°C when the wood moisture content was at or above the fibre saturation point. Stenudd (2004) also found similar results in silver birch (*Betula pendula* Roth).

Brauner and Conway (1964) described the effect of various steaming treatments on the colour of black walnut. They found colour change to be dependent on both temperature and heating time. As expected, the rate of colour change increased as the heating temperature increased. This was most noticeable between 100 and 110°C. Significant increases were not noticed above 110°C. They also found rapid changes in colour in the first 4 to 6 hours with only slight changes thereafter. A subsequent study by Charrier *et al.* (2002) found that immersing walnut logs in water at temperatures of 80°C to 90°C for up to 51 hours promoted the darkening and reddening of veneer. The darkening reaction, however, was more prominent in heartwood than in sapwood.

2.7.3 Kiln Stain

Kapp *et al.* (2003) reviewed the effects of kiln drying schedules and species on the degree of kiln brown and yellow stain. Maillard reactions, a common form of discolouration prevalent in the food industry, were thought to be responsible for kiln staining of wood. Maillard reactions are interactions between sugars and amino acids generating colours varying from light yellow, yellow, orange, brown to dark brown. Kapp *et al.*'s study found varying reactions in individual pine species. However, a transition from yellow to brown stain was noticed above 80°C.

Kiln brown stain in radiata pine (*Pinus radiata D. Don*) develops as a chocolate brown discolouration in the sapwood. According to McDonald *et al.* (2000), the intensity of this stain is dependent on kiln temperature and it is also thought to be caused by Maillard reactions. Previous work reviewed by McDonald *et al.* (2000) suggested that these reactions are dependent on chemical structure of extractives, wood pH, and drying temperature.

2.8 Assessment of Colour

2.8.1 Felled Trees

Mononen *et al.* (2002) examined colour differences in silver birch wood using the CIE L*a*b* colour space system. After felling, stems were sawn to remove a 4m butt log. Sample boards were cut from the outer and inner sapwood of each log and a small piece of wood was cut from each board. The colour of cross-sectional surfaces was measured. Rappold and Smith (2004) also used the CIE L*a*b* colour space to determine colour differences in maple. Two hard maple trees (dbh 35.6 to 71.1 cm) were selected, felled and flat-sawn using a small commercial band saw mill. The boards were specifically selected to be free of knots, discoloured sapwood, and stains. All of the sample boards consisted of 100% sapwood. After processing and drying, each sample board was hand-planed and its colour measured at four locations on the board using a spectrophotometer. Measurements were taken from clear areas on both tangential surfaces for a total of eight readings for each board.

2.8.2 Standing Trees

Variation in wood colour, both within and between shining gum (*Eucalyptus nitens* Maiden) samples, was studied by Raymond and Bradley (2002). To measure variation between trees, a 12 mm diameter core was removed using a motor-driven corer at 0.9 m above ground for each tree. Each core was air dried and reduced to woodmeal (1 mm mesh) in a Wiley Mill and colour assessed using a Minolta Chroma Meter. To measure variation within trees, 25 mm discs were cut at 10% height intervals along the tree.

All samples were frozen and colour was measured while in the frozen state. Colour measurements were taken at pre-determined locations on the disc.

2.9 Effects of Season and Storage on Wood Colour

2.9.1 Season

As mentioned previously, Gonzalez-Hernandez *et al.* (1999) found that oregonin (responsible for the formation of red-orange chromophores in red alder) varied seasonally in red alder trees. Concentrations of oregonin decreased from spring to fall, with the levels in the fall being approximately 50% of the levels in the spring. Allen (1994) found that the red-orange discolouration in red alder logs was strong in the spring and summer, but less evident in the fall and winter. For all seasons, logs stored under cool, moist conditions developed less stain. The study did not mention the colour or strength of the stain over time, but rather the depth of staining into the log from the cut ends.

A study of phenolic compounds in the living tissues of Japanese alder (*Alnus hirsuta* Turcz. and *Alnus japonica* Steud.) found that hirsutoside (which was identical in structure to oregonin) was the precursor for the red-orange staining forming on the surface of freshly cut wood. Hirsutoside decreased in the cork cambium, inner bark, and xylem as winter neared (Terazawa *et al.* 1984).

Mononen *et al.* (2002) found that silver birch samples felled in autumn and winter displayed high lightness ($L^* > 83.23$), low redness ($a^* < 3.69$), and average yellowness ($b^* = 19.63 – 26.90$). Samples felled in spring and summer had lower lightness, higher redness, and higher yellow values. The outer sapwood was generally lighter, less red, and less yellow than the inner sapwood. A similar study that examined the effects of season on the colour of maple lumber found that there was no visual or measured colour change across each harvest season (Rappold and Smith 2004).

2.9.2 Storage

Allen (1993) found that the stain within cut red alder logs spread over time up to 4 months in the spring and summer, while a less noticeable spread in staining was seen after 6 months in the fall and winter logs (most likely due to the gradual increase in temperature over time).

Samples of silver birch exposed outdoors for five weeks showed a significant decrease in lightness ($L^* = 67.51 - 72.21$) and an increase in redness ($a^*>7.34$) and yellowness ($b^*>27.93$) for autumn and winter-felled samples (Mononen *et al.* 2002). Storage had an insignificant effect on the colour of samples felled in the spring. Samples felled in summer decreased in lightness and increased in redness and yellowness during storage. Following ten weeks of storage, autumn-felled samples became lighter with decreasing redness and yellowness. The opposite occurred in winter-felled samples, with lightness decreasing and redness and yellowness increasing. Spring and summer-felled samples showed a decrease in lightness, increase in redness and moderate decrease in yellowness. A similar study conducted on maple found that there was no visually perceptible colour difference between maple logs stored for 0, 4, and 8 weeks (Rappold and Smith 2004).

2.10 Conclusions

Colour is an important feature of wood used in decorative applications such as furniture stock, and veneer. Without adequate control of colouration in processed wood, the marketing, production, and sale of hardwood products in a competitive wood products industry is problematic. The literature outlines a variety of colour changes and responses of wood to various treatments, but fails to provide significant insights into the problem of colour control faced by producers of red alder products. The difficulty of achieving a uniform tan colour in red alder warrants new research that will answer some very important questions about the processing of this economically valuable species. To achieve favourable colouration, the effects of factors such as temperature, treatment duration, wood type, season, storage period and position in tree, on the colour of thermally modified red alder need to be quantified. It is anticipated that the results of this study, along with previous findings in the literature (described above), will lead to the development of better thermal treatments to control the colour of red alder wood.

3.0 Effects of temperature, heating time and wood type on the colour of red alder wood[1]

3.1 Introduction

Red alder has become one of the most economically important hardwood species in North America (AHEC 2003). Sliced red alder veneer is commonly used as a decorative overlay on composite wood panels (particleboard and medium density fibreboard), which are then used in the manufacture of cabinets and furniture (Hibbs *et al.* 1994). Red alder wood, however, acquires a mottled red-orange colour after felling, which is undesirable when the wood is used for cabinets and furniture (Kozlik 1987; Kaufmann 2003; Simpson 1991). To overcome this problem, sawn alder lumber is steamed at temperatures of 66 to 100°C for varying periods of time (Kozlik 1962, 1967, 1987; Kozlik and Boone 1987). Steaming produces a uniform tan colour on the surface of red alder lumber, but no studies have examined the thermal modification of colour in red alder veneer cants. Industry reports, however, suggest that it is much more difficult to achieve colour uniformity in veneer sliced sequentially from steamed cants (Kaufmann 2003). Radial variation in wood colour in the cants, possibly caused by thermal gradients within veneer cants during steaming, could explain such variability. Alternatively, within tree variation in the susceptibility of red alder to thermal discolouration could be responsible for the variation in colour of sliced veneer. Variability in the colour of sliced veneer is highly undesirable because veneer sheets pressed onto composite wood panels need to be colour matched to meet the demands of consumers for red alder furniture and cabinets with uniform colour (Raettig *et al.* 1995).

[1] This study has been accepted in Wood and Fiber Science and appears in the July 2005 issue.

This study examined the variation in colour of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions using four temperatures (30, 50, 70 and 90°C) and five heating times (8, 24, 36, 48 and 72 hours). The aim was to examine whether within-tree variation in the susceptibility of red alder wood to thermal darkening can explain variation in colour of veneer sliced from steamed red alder cants, and secondly to determine the optimal thermal treatment (temperature and time) that can impart the favoured tan colour to red alder wood.

3.2 Methods and Materials

3.21 Sample preparation

Four red alder trees growing in the Malcolm Knapp Research Forest in Maple Ridge, British Columbia, were selected based on similarities in their height (18 – 25 m), diameter (25 – 32 cm at breast height), age (26 – 31 years), and growing conditions (non-riparian). Trees growing in riparian zones (adjacent to streams) were avoided as harvest restrictions in British Columbia limit the removal of any species in or adjacent to such areas. A single tree was sampled each week over a period of 4 weeks in August 2003 (4 trees in total). Thus, each tree and sampling period acted as a separate replication.

Trees were marked at breast-height (1.3 m above ground level), felled, and inspected for the presence of abnormalities such as rot or scarring. Four cross-sectional discs were cut from each tree: two immediately above and two immediately below breast-height (Figure 5). Each disc was 15 cm thick (longitudinally) and was free from internal rot or scarring. The four discs were randomly assigned a letter (A, B, C or D) and immediately transported to the laboratory for further processing.

Five quarter-sawn slats were cut from each of the four discs using a band-saw. Slats were 1 cm wide (tangentially) and cut from bark to pith (Figure 5). The moisture content of separate pith to bark samples, expressed as a percentage of their oven dry weight (obtained by oven drying samples overnight at 105 °C), was found to vary from 95 to 127%. The location of each slat was randomly selected on the outer circumference of the disc prior to sawing. A 1 x 1 cm pith-to-bark sample was then cut from the middle (7 cm from top and bottom) of each slat resulting in five 1 x 1 cm samples from within each disc. Each sample was sealed in an 8 x 23 cm sheet of aluminium foil to reduce the rate of drying of samples during heating, labelled with the appropriate disc letter (A – D), and randomly assigned a treatment number (1-5) (Figure 5).

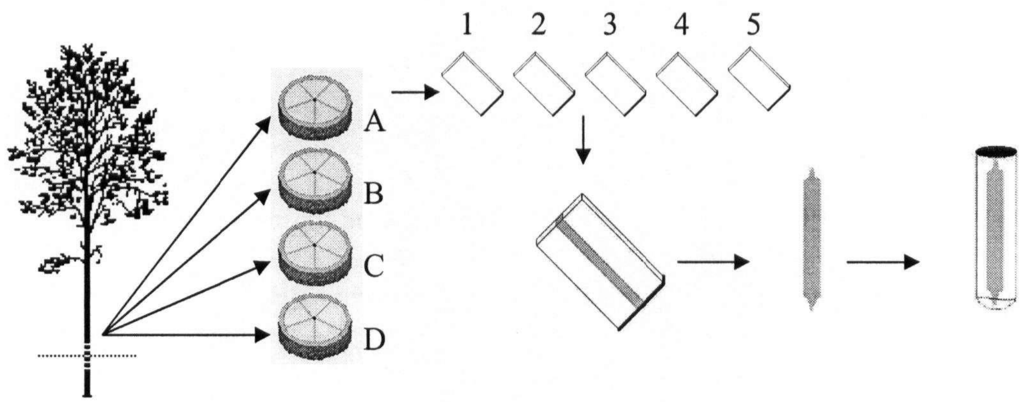

Figure 6. Sampling of red alder trees and preparation of wood samples

3.22 Thermal treatments and colour measurement

Samples obtained from the same discs were allocated to the same treatment temperature. Thus, samples from discs A, B, C and D were subjected to thermal modification at temperatures of 30, 50, 70 and 90°C, respectively. The 5 samples from within each disc were randomly allocated to the different heating times, 8, 24, 36, 48 and 72 hours.

Samples were placed in 25 x 200 mm test-tubes which were submerged in pre-heated glycerol baths set at 30, 50, 70 or 90°C. Each test-tube was covered, but not completely sealed, to avoid pressure build-up. Samples were removed from the tubes after heating and allowed to cool at room temperature for 30 minutes. They were then unwrapped from the aluminium foil and cross-cut every fifth growth ring starting at the pith and finishing in the outer sapwood. Thus, five sub-samples were produced from each pith-to-bark sample, each containing five growth rings with the earlywood exposed longitudinally. Exposed earlywood faces were allowed to dry for 24 hours at room temperature and their colour was then measured using a spectrophotometer (Minolta CM-2600d). Earlywood was chosen for colour measurements as it forms the majority of the wood in red alder (Parker *et al.* 1978). A total of 400 colour measurements were made. Colour is expressed using the CIE L*a*b* space system, which consists of three parameters; **L*** is lightness (0 = black; 100 = white), **a*** is greenness/redness (-60 = green; 60 = red), and **b*** is blueness/yellowness (-60 = blue; 60 = yellow) (Minolta 1998). Yellowness and blueness were insignificant characteristics of colour change in thermally modified red alder, and hence b* measurements are not presented or discussed in this thesis.

Separate pith to bark samples were weighed, wrapped in foil, and heated, as above, at 20 (room temperature), 30, 50, 70 and 90 °C. The samples were removed from the test tubes periodically (after 8, 24, 36, 48 and 72 hours) and reweighed. After 72 hours the samples were oven-dried at 105 °C for 7 hours and their moisture contents calculated.

In order to compare the colour of samples subjected to the different heat treatments with that of commercially produced veneer, the colour of several red alder veneer sheets with the desired tan colour was measured. The colour of these veneers provided reference maxima and minima for L* and a* values obtained from the measurement of the colour of red alder tree samples (above), and are displayed as dashed lines on graphs depicting results of this study in Figures 6-9. While these maxima and minima provide a general range of favourable colour measurements, they were not mathematically derived, nor do they represent a colour standard for the red alder veneer industry as a whole.

3.23 Experimental design and statistical analysis

This experiment used factorial principles to determine the effects of three fixed factors (treatment temperature, heating time, and ring location) on two response variables (L* (lightness) and a* (redness)). Random effects arise due to between- and within-tree variation in wood properties, and elapsed time between replicate measures. Analysis of variance was used to examine fixed and random effects on the response variables. Statistical computation was performed using Genstat 5, using a p-value of 0.05 (5%) (Lawes Agricultural Trust 1994). Before the final analysis, diagnostic checks were performed to determine whether data conformed to the underlying assumptions of analysis of variance, i.e., normality with constant variance. Significant results ($p<0.05$) are presented graphically and least significant difference (LSD) bars are used to compare differences between means.

3.3 Results

There were significant effects of temperature, heating time and ring location on L* (lightness) and a* (redness) (Table 1). There were also significant two-way interactions of temperature and heating time on a* and temperature and ring location on L* and a* (Table 1).

Table 1. Significant effects of, and interactions between, treatment temperature, heating time, and ring location on L* and a* colour parameters

Response Variables	Fixed Factors						
	Temperature (T)	Heating time (H)	Ring Location (R)	T x H	T x R	H x R	T x H x R
L* - lightness	***	***	***	NS	***	NS	NS
a* - redness	***	***	***	***	***	NS	NS

*** = $p < 0.001$; NS = not significant ($p > 0.05$)

The overall effect of increasing temperature during the thermal modification of red alder wood was to make samples slightly less red (a* decreased) and darken them (L* decreased) (Figures 7 and 8, respectively). Differences in the lightness and redness of samples heated at 70 and 90°C were small and generally statistically insignificant. The effect of temperature on the colour of the wood, however, depended on the location of the sample within the tree, as indicated by the significant temperature x ring location interaction in Table 1. Wood samples cut adjacent to the bark developed a more pronounced red-orange colour when heated at 30°C than samples cut close to the pith. This observation is reflected by the relatively high a* values and lower L* values for the relevant samples (3 to 5) in Figures 7 and 8. In contrast, the effect of ring location on the colour of samples heated at 50, 70 and 90°C was smaller. Within-tree differences in the colour of thermally modified samples were least pronounced for those heated at 70°C, and the colour of these samples all fell within the preferred colour limits for red alder veneer.

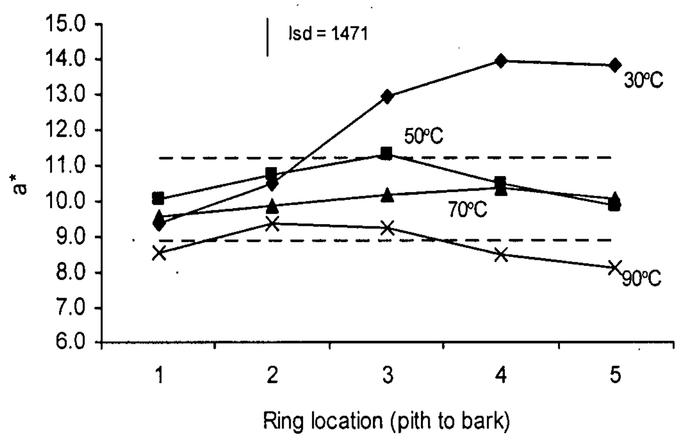

Figure 7. Effects of temperature and ring location on a* (redness) of heated red alder wood

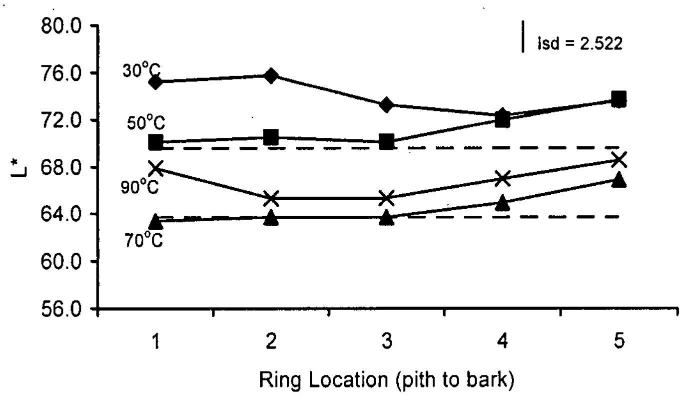

Figure 8. Effects of temperature and ring location of L* (lightness) of heated red alder wood

If results in Figures 7 and 8 are compared, it can be seen that there were marked differences in the pith to bark variation in redness and lightness of red alder wood following thermal modification at different temperatures. Differences in the redness of wood close to the pith (samples 1 and 2) were small irrespective of heating temperature, including samples heated at 30°C. As mentioned above, wood close to the bark was redder and darker when heated at 30°C, but differences in the redness of samples heated at 50, 70 and 90°C were small, irrespective of their location in the tree stem. In contrast, there were significant differences in the lightness of wood heated at higher temperatures (70 and 90°C) compared to those heated at lower temperatures (30 and 50°C), particularly for wood close to the pith. Samples heated at 70°C were darker than those heated at 90°C, but the differences were not statistically significant.

Figure 9 shows the effect of heating time on the L* value for thermally modified samples. Results in this figure are averaged across temperature and ring number as there were no significant interactions of heating time with temperature or ring location (Table 1). Wood samples became darker as the length of time that they were exposed to heat increased. Thus, the L* decreased from 73.90 for samples heated for 8 hours to 67.18 for samples heated for 72 hours. Heating times of 24 to 72 hours produced values for L* that fell within industry preferences.

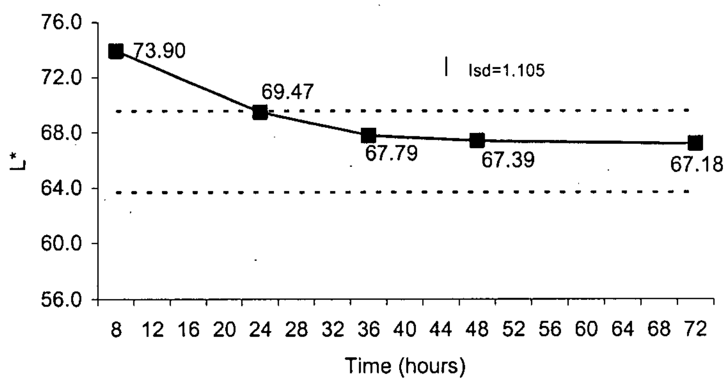

Figure 9. Effects of heating time on L* (lightness) of red alder wood

The effect of heating time on the redness of samples depended on temperature as indicated by the significant temperature x heating time interaction in Table 1. This occurred because there was a pronounced increase in the redness of samples heated at 30°C over the first 36 h, followed by a pronounced decrease over the following 36 hours, whereas there was little change over time in the redness of samples heated at higher temperatures (with the exception of samples heated at 50°C from 8 to 24 hours) (Figure 10).

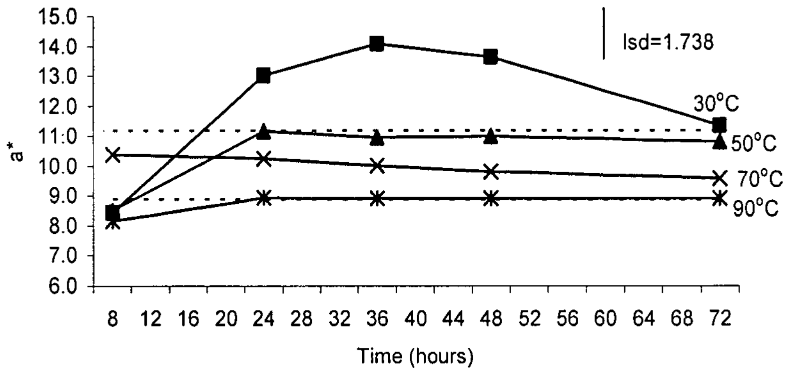

Figure 10. Effects of temperature and heating time on a* (redness) red alder

The redness of samples heated at 70°C remained consistent irrespective of heating time and fell within industry preferences. Heating times of 24 to 72 hours seemed to produce the colour that industry prefers. Measurement of the moisture content of separate pith to bark samples heated at different temperatures showed a decrease in their moisture content over time. Decreases in moisture content were pronounced at the higher (70 and 90 °C) temperatures (Table 2).

Table 2. - Moisture content of pith to bark samples heated at different temperatures

Temperature	Heating time (hours)					
°C	0	8	24	36	48	72
20	98.5	96.1	94.4	92.1	88.1	83.1
30	102.3	99.8	97.9	95.4	92.4	88.4
50	126.8	119.2	103.5	96.3	84.7	69.3
70	105.7	84.2	60.8	50.7	31.1	15.1
90	95.0	61.7	16.2	6.7	1.8	1.2

3.4 Discussion

From first principles, it can be assumed that the colour of thermally modified red alder wood results from the production and/or destruction of chromophoric groups. It is well known that red alder wood changes from a cream to a red-orange colour on exposure to air (Simpson 1991). This colour change occurs at ambient temperatures and is probably caused by the reaction between the diarylheptaniod xyloside, oregonin, and peroxidase enzymes (Karchesy and Laver 1974). The production of new chromophores as a result of these reactions may explain our finding that wood close to the bark, where concentrations of oregonin are likely to be high (Terazawa *et al.* 1984), was much redder than wood close to the pith when wood samples were heated at 30°C. It is also well established that hemicelluloses are degraded by heat, causing thermally modified wood to be darker than unmodified wood (White and Dietenberger 2001). Thermal degradation of wood may explain why red alder wood heated at higher temperatures (70 or 90°C) was darker than wood heated at 30 or 50°C, as well as the positive correlation between heating time and darkening of wood. Wood heated at 70°C, however, was darker than wood heated at 90°C, and wood close to the bark and heated at 30°C was as dark as wood heated at 50°C. The latter observation suggests that the red colour (a*), which was pronounced in the outer wood heated at 30°C, contributed to the darkness (decreased L*) of thermally modified red alder wood. Accordingly, samples heated at 90°C were lighter than those heated at 70°C, possibly because of their lower redness. This suggestion is supported by results showing that wood heated at 70°C was redder than wood heated at 90°C, and the association between decreased redness and reduced darkening in wood samples heated at 70 and 90°C (compare Figures 7 and 8). This negative correlation between redness of samples and heating temperature could result from inhibition of the reactions that produce the red-orange colour in red alder wood and/or the destruction of the complexes responsible for the colour. We consider the latter more likely since samples subjected to prolonged (72h) heating at 30°C were less red than samples heated for shorter periods of time at the same temperature. This suggests that the red-orange complexes produced in red alder are thermolabile and, hence, are degraded by prolonged exposure to heat and higher temperatures.

Clearly, the thermal modification of colour in red alder involves a complex suite of reactions. Our findings suggest that the final colour of the wood depends on the strength of reactions that produce red-orange chromophoric groups in the wood, thermal darkening of the wood, and destruction of red-orange chromophoric groups. Therefore, the key to controlling colour in veneer cants during steaming may lie in balancing these competing reactions through careful control of heating temperatures and times, and wood moisture content. Colour control is complicated by within-tree and, possibly, seasonal variation in the strength of the reactions that generate the red-orange chromophores in wood and thermal and moisture gradients within veneer cants during steaming. The effects of season, storage time and wood type on the colour of thermally modified red alder wood are examined in Chapter 4. A more complete understanding of the sources of variation in the colour of thermally modified red alder wood would assist efforts to obtain better colour uniformity in veneer sliced sequentially from heated veneer cants. Nevertheless, our findings on small samples indicate that heating red alder wood at 70°C for 24 to 36 hours can produce the preferred tan colour for this species. Higher temperatures in the outer layers of veneer cants may compensate for the tendency of outer wood to become redder by destroying red-orange chromophores and this may produce more uniformly coloured veneer. Large thermal gradients from the outer to the inner wood, however, are likely to produce the pronounced differences in the colour of veneer sheets that industry currently observes. A technology capable of more evenly heating veneer cants, possibly involving a combination of steaming and radio-frequency heating, might reduce the extent of such gradients and colour variation in red alder veneer. Direct thermal modification of veneer might achieve a similar effect, although higher temperatures would be needed to accelerate colour changes.

3.5 Conclusions

1. There is variation in the colour of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions, but differences are only pronounced when wood is heated at 30°C. Wood close to the bark tends to be redder than wood close to the pith when heated at low temperatures, but such a difference is absent in wood heated at higher temperatures (50-90°C).
2. Heating small pith-to-bark red alder wood samples at 70°C for 36 hours produced wood that had an even tan colour from pith to bark and fell within the current industry colour preferences.
3. It is hypothesised that the colour of thermally modified red alder wood depends on the strength of reactions that produce red-orange chromophores in the wood, thermal darkening of the wood, and destruction of red-orange chromophores. The key to controlling colour in veneer cants during steaming lies in balancing these competing reactions through careful control of heating temperatures and times.
4. A better understanding of reactions that generate the red-orange chromophores in thermally modified red alder wood and the magnitude of thermal gradients within veneer cants during steaming would assist efforts to obtain better colour uniformity in veneer sliced sequentially from heated veneer cants.

4.0 Effects of season, storage time and wood type on the colour of thermally modified red alder wood

4.1 Introduction

In Chapter 3, it was shown that freshly harvested red alder wood became red-orange when heated at low temperatures, but the intensity of the orange colour decreased if heating was prolonged or carried out at higher temperatures (Thompson *et al.* 2005). The colour of red alder wood after heat treatment appeared to depend on the strength of the reactions that produced the red-orange colour, thermal darkening of the wood, and destruction of red-orange chromophores. Heating schedules for red alder logs are not normally varied and, therefore, seasonal variation in the colour of red alder veneer sliced from heat treated cants probably occurs as a result of factors that influence the development of red-orange chromophores in the parent wood. These could include the length of time that red alder logs are stored for prior to heating because there was a positive correlation between heating time (up to 36 hours) at 30°C and the red colour of thermally modified wood (Figure 10). The colour of heated wood may also change seasonally due to variation in ambient temperature and the concentrations of oregonin and peroxidase enzymes in red alder wood which react to produce red-orange chromophores.

A study by Gonzalez-Hernandez *et al.* (1999), found that oregonin varied seasonally in red alder. Concentrations decreased from spring to fall, with levels in the fall being approximately 50% of the spring levels. Similarly, a study on Japanese alder (*Alnus hirsuta* Turcz. and *Alnus japonica* Steud.) found that hirsutoside, identical to oregonin, decreased in the cork cambium, inner bark, and xylem as winter neared (Terazawa *et al.* 1984). Allen (1993) studied the development of stain within alder logs harvested in each of the four seasons. The red-orange discolouration was strong in the spring and summer months, but less evident in the fall and winter. A recent study found that silver birch (*Betula pendula* Roth) wood harvested in spring and summer was redder and darker than wood harvested in autumn and winter (Mononen et al. 2002). Furthermore, the red colour of spring and summer felled wood was enhanced by prolonged storage (Mononen et al. 2002).

Based on these observations and our earlier findings in Chapter 3, it is hypothesized that heat treated red alder wood will be darker and redder when the wood is obtained from logs harvested during spring and summer, and stored for longer periods of time, than when the wood is obtained from trees harvested during the autumn and winter and stored for shorter periods of time. The aim of this research was to test this hypothesis by examining the effect of season, storage time, and wood type (inner and outer sapwood and location along the stem) on the colour of red alder wood following 48 hour heat treatment at 70 °C under isothermal conditions. A better understanding of the extent and causes of variability in thermally modified red alder wood would help manufacturers of red alder veneer modify their processing techniques to produce more uniformly coloured veneer.

4.2 Methods and Materials

4.21 Sample Preparation

Two groups of 16 trees were selected based on similarities in height (18-25 m), diameter (25-32 cm at breast height), age (26 -31 years), and growing conditions (non-riparian). The groups of trees were located over 2 km apart on opposite sides of Malcolm Knapp Research Forest in Haney, British Columbia. Four trees from each group were felled every three months in the autumn (November/December), winter (February/March), spring (May/June) and summer (July/August). The two groups of trees acted as two separate, higher-level replicates.

Trees were felled 30 cm above ground level and a log measuring 3.05 m (10 feet) was cut from each tree. Each log was randomly assigned a number corresponding to its storage time prior to processing (0, 1, 2 or 4 weeks). The log in each group marked '0' was immediately sampled in the field. The remaining logs were transported to the University of British Columbia where they were placed on 15 x 15 cm lumber spacers to ensure they were not resting directly on the ground. Each log was exposed to the weather without any cover or protection. The ambient temperatures during the different storage periods are summarised below (Table 3).

Table 3. Ambient air temperature - University of British Columbia (Biomet 2005)

	November / December 2003	February / March 2004	May / June 2004	July / August 2004
Average Ambient Temperature (°C)	5.23°C	7.12°C	13.35°C	19.69°C

After storage of logs, four 15 cm discs were removed at distances of 71 cm apart to ensure that discs were evenly spaced along the log (Figure 11). The discs were labelled according to their location within the stem (A = 45 cm, B = 131 cm, C = 217 cm, and D = 303 cm above ground level) and a slat was cut from each disc using a band-saw. These slats were 1 cm wide and cut from bark-to-pith. The location of the slat was randomly selected on the outer edge of the disc prior to sawing. A 1 x 1 cm bark-to-pith sample was then cut from the middle (7 cm from top and bottom) of each slat (Figure 10). Each sample was wrapped in 8 x 23 cm sheets of aluminium foil and labelled with the appropriate disc and sample group numbers (e.g. C2).

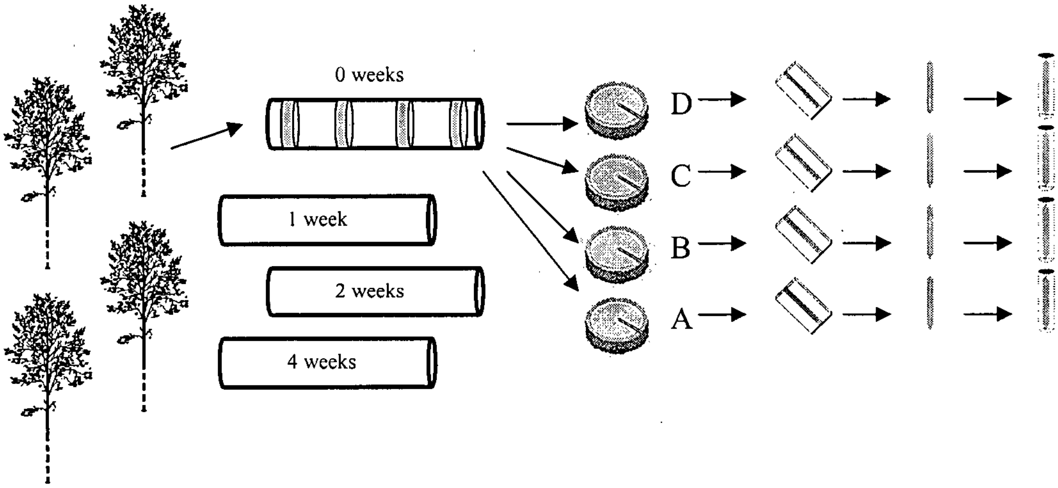

Figure 11. Sampling of red alder trees and preparation of samples

4.22 Thermal treatments and colour measurement

Samples were placed in 25 x 200 mm test-tubes which were submerged in pre-heated glycerol baths set at 70°C as previously prescribed (Chapter 3). Samples were heated for 48 hours and then removed from the aluminium foil. Samples were cross-cut within earlywood at positions located 3 rings from the pith and 5 rings from the bark, thus allowing colour measurements to be made on inner and outer sapwood. The exposed longitudinal surfaces were allowed to dry for 24 hours at room temperature and the colour of the thermally modified wood was measured using a Minolta CM-2600d spectrophotometer, as described previously (Chapter 3). The L* and a* parameters of several slices of veneer with desirable colour characteristics were also quantified. These measurements provide maximum and minimum acceptable limits for L* and a* values and are displayed as dashed lines on graphs displaying the colour of red alder wood samples following heat treatment (Figures 12 – 17).

4.23 Experimental design and statistical analysis

This experiment used factorial principles to determine the effects of four fixed factors (season, storage time, bole position, and wood type) on two response variables (L* - lightness and a* - redness). Random effects arise due to between- and within-tree variation in wood properties, and elapsed time between replicate measures. Analysis of variance was used to examine fixed and random effects on the response variables. Statistical computation was performed using Genstat 5 at a p-value of 0.05 (5%) (Lawes Agricultural Trust 1994). Before the final analysis, diagnostic checks were performed to determine whether data conformed to the underlying assumptions of analysis of variance, i.e., normality with constant variance. Significant results ($p<0.05$) are presented graphically and least significant difference (LSD) bars are used to compare differences between means. In addition, we present a table (Table 4) summarising the significance of the fixed factors and their interactions on the colour of thermally modified red alder wood.

4.3 Results

Table 4 summarises the statistically significant effects of experimental factors (season, storage time, and wood types) on the colour of thermally modified red alder wood. There were significant effects of season and wood type on L* (lightness) and storage, bole position, and wood type on a* (redness) (Table 4). There were also highly significant interactions of season and storage time on both L* and a*, and significant interactions of storage and bole position on L* and a* (Table 4).

Table 4. Significant effects of, and interactions between, season, storage time, bole position and wood type on L* and a* colour parameters

Response Variables	Fixed Factors					
	Season (S)	Storage (ST)	Bole Position (BP)	Wood Type (W)	Interaction S x ST	Interaction ST x BP
L* - lightness	***	NS	NS	***	***	**
a* - redness	NS	*	*	***	***	NS

*** = p < 0.001; ** = p < 0.01; * = p< 0.05 NS = not significant (p > 0.05)

There was little variation in the lightness (L*) of wood harvested in different seasons and heated at 70°C immediately after felling, but significant differences in the colour of thermally modified wood samples occurred following storage of parent logs for 1, 2, and 4 weeks. In particular, wood harvested in spring and summer and stored for 1 and 2 weeks became significantly darker after heat treatment (Figure 12). This effect was pronounced in wood samples obtained from logs harvested in spring and stored outdoors for two weeks (Figure 12). Further storage of logs for 4 weeks, however, resulted in a lightening of the colour of thermally modified samples obtained from logs harvested in spring and particularly summer (Figure 12). The lightness of thermally modified wood obtained from logs harvested in autumn and winter decreased slightly as storage time increased, but differences in lightness were small.

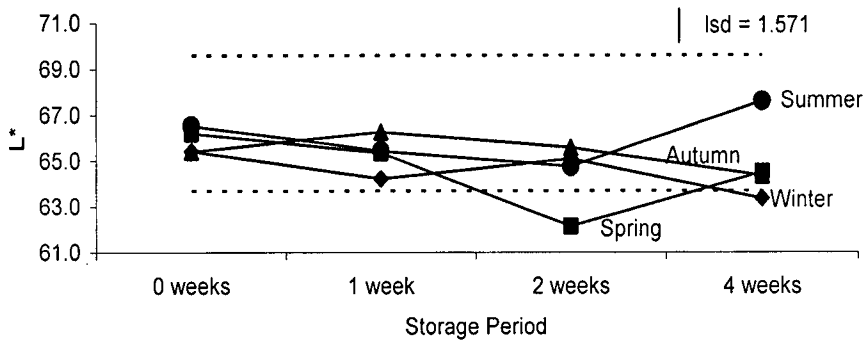

Figure 12. Effects of season and storage time on the L* (lightness) of heated red alder wood

Wood harvested in different seasons and heated at 70°C immediately after felling also showed significant differences in redness (a*) (Figure 13), in contrast to the results for lightness (Figure 12). The redness of thermally modified wood obtained from logs harvested in the different seasons and heated immediately after felling decreased as follows: winter > autumn >summer > spring. In spring, in particular, and also in summer there was a positive correlation between storage time of logs up to two weeks and redness of thermally modified wood (Figure 13). After 4 weeks storage, however, the redness of heated samples from logs harvested in summer, autumn, and spring decreased significantly. In contrast, the colour of thermally modified wood obtained from trees harvested in winter decreased with storage up to 2 weeks and then increased slightly thereafter (Figure 13).

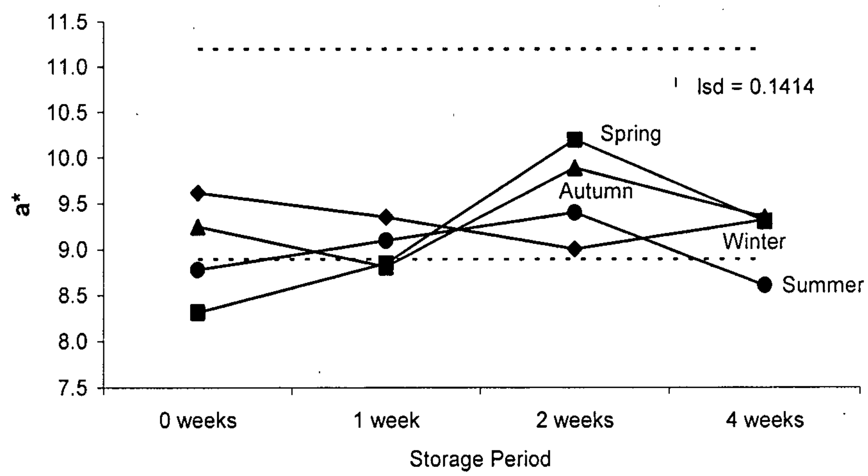

Figure 13. Effects of season and storage time on the a* (redness) of heated red alder wood

The effect of storage of logs on the lightness of thermally modified wood depended on the location of the wood along the bole. The lightness of heated samples obtained from positions A and C (45 and 217 cm above ground level) was negatively correlated with storage time of logs (Figure 14). Samples obtained from positions B and D (131 and 303 cm above ground level) showed a similar trend up to two weeks storage, but samples obtained from logs stored for 4 weeks were lighter following heat treatment than those obtained from logs stored for two weeks.

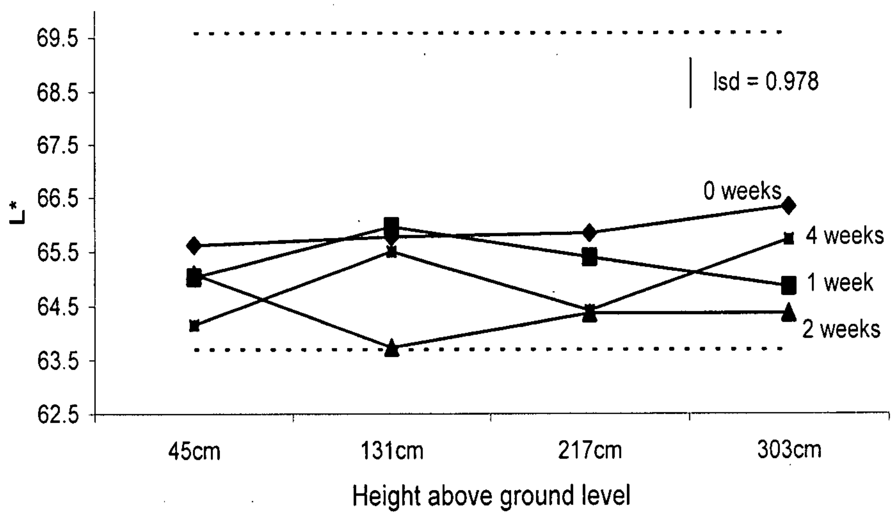

Figure 14. Effects of storage time and bole position on the L* (lightness) of heated red alder wood

There was no significant interaction of storage time and bole position on the redness of heated samples, as heated samples obtained from lower in the stem were redder than those obtained further up the stem, irrespective of how long the logs were stored prior to sampling (Figure 15).

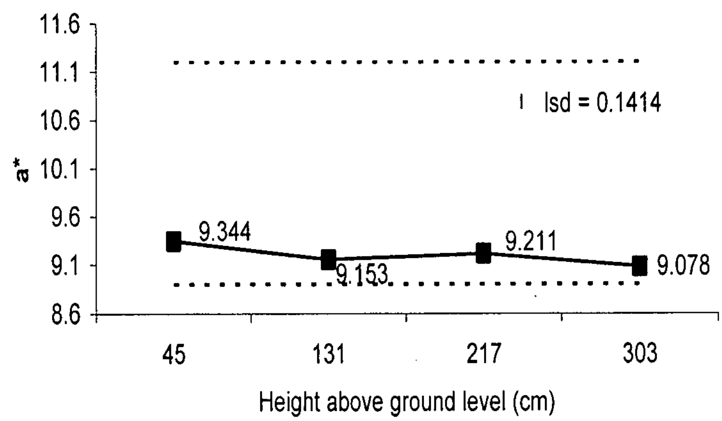

Figure 15. Effect of bole position on the a* (redness) of heated red alder wood

Wood obtained closer to the pith was significantly darker and redder following heat treatment than wood closer to the bark (Figures 16 and 17). There was no significant interaction of wood type with the other experimental factors (season, storage, and bole position) and, therefore, results in Figures 16 and 17 are averaged across these factors in accordance with the factorial design of the experiment.

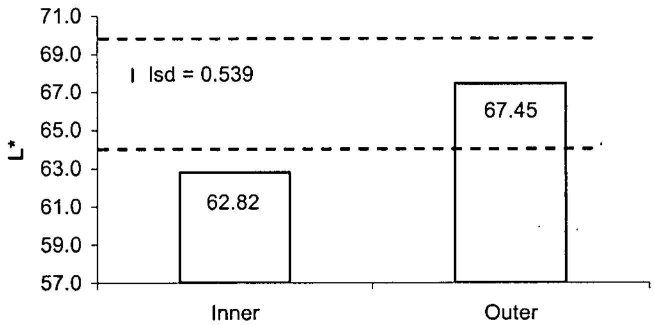

Figure 16. Effect of wood type on the L* (lightness) of heated red alder wood

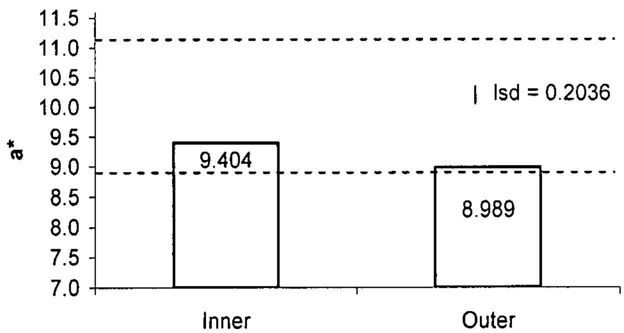

Figure 17. Effect of wood type on the a* (redness) of heated red alder wood

4.4 Discussion

Manufacturers of red alder veneer sliced from heated cants have remarked on seasonal variation in the colour of the veneer (Kaufmann 2003). Our results suggest that the basis for such variability lies in a complex interaction between the season in which trees are harvested and the length of time logs are stored prior to heat treatment. For example, wood harvested in spring and stored for two weeks prior to heat treatment was significantly darker and redder following heat treatment than similarly heated wood obtained from logs harvested in other seasons. If the storage time of wood harvested in spring was extended to four weeks, however, the wood became lighter and less red following heat treatment. More pronounced, but directionally similar, colour reversion was noted for heat treated wood obtained from logs harvested and stored in summer. In Chapter 3, it was hypothesised that the colour of thermally modified wood depended on the production and destruction of red-orange chromophores during heating, and the thermal darkening of the wood during heat treatment. Wood heated at 30°C was significantly darker than wood heated at higher temperatures and it was suggested that this was due to the development of red-orange chromophores that influenced the final colour of the heat treated wood. Wood samples were heated immediately after trees were felled, whereas, in this chapter, some logs were stored for 1, 2, and 4 weeks prior to sampling and heat treatment of wood. Storage of logs prior to heat treatment would allow the development of red-orange chromophores in wood particularly in spring when temperatures were moderately high (13.35°C, Table 1) and concentrations of oragonin in the wood are likely to be high. Karchesy and Laver (1974) found that oregonin was involved in the formation of red-orange chromophores in red alder and Gonzalez-Hernandez *et al.* (1999) showed that oregonin varied seasonally and was at a maximum in spring. Terazawa *et al.* (1984) also found that oregonin (hirsutoside) was at a maximum in the spring and summer. These previous findings and the results in this chapter strongly suggest that reactions responsible for the red-orange discolouration of red-alder wood at ambient temperatures also influence the colour of the wood following thermal modification.

The generation of orange-red chromophores in wood during storage and their retention in the wood following heat treatment (thereby influencing the final colour of the heat treated wood) may explain why there was a positive correlation between storage time of logs up to two weeks and redness of thermally modified wood. In accordance with this suggestion, Hon and Shiraishi (1990) mention that the rate of enzymatic induced discolouration of several wood species is positively correlated with temperature and increases steadily above 20°C.

The colour reversion in heat treated samples obtained from logs stored for 4 weeks may be due to decreases in the concentrations of red-orange chromophores in wood following prolonged storage. Such decreases would be consistent with our previous observations in Chapter 3 that the red-orange colour of red alder wood heated at 30°C increased initially, but then decreased. The latter observation was explained as being due to destruction of red orange-chromophores and such an explanation would also explain why the colour reversion of heat treated wood was most pronounced in samples obtained from logs stored for 4 weeks in summer, when ambient temperatures were at their highest (19.69°C, Table 3) (Figure 13).

Differences in CIE Lab parameters of 3 units are discernable to the human eye according to Phelps *et al.* (1994) and variation in the colour of thermally modified red alder wood of this order of magnitude occurred in wood harvested in spring and stored for two weeks before thermal modification. Furthermore, such wood was darker than the maximum level preferred in veneer sliced commercially from heated veneer cants. Some manufacturers of red alder veneer from heat treated wood have observed that it is difficult to obtain veneer with acceptable colour in the spring when the 'sap is running' (Kaufmann 2003), and our findings are in accordance with their observations. It may be possible to reduce the darkness of thermally modified veneer cut from heated cants harvested in spring by processing wood immediately after harvesting, since there was a positive correlation between the darkness of heat treated wood and storage time (up to two weeks). Alternatively, storage could be extended because thermally modified veneer cut from logs stored for four weeks was lighter than similarly modified veneer cut from logs stored for 1 and 2 weeks. However, thermally modified veneer cut from logs stored from 4 weeks lacked sufficient redness and, in practice, it might be difficult to control colour by adjusting storage time of logs prior to heat treatment because of seasonal variation in temperature. Without further research to develop season/storage specific heating schedules, manufacturers may have greater success in processing fall and winter felled logs if they want to obtain more uniformity of colour in heat treated veneer.

In Chapter 3, small, but statistically insignificant differences in the colour of pith-to-bark red alder wood samples heated at 70°C were found, whereas results here clearly showed that wood nearer the bark was lighter and less red than wood near the pith following thermal modification at 70°C, irrespective of season in which the parent log was felled or the length of time it was stored prior to processing. Kozlik (1967) also found that red alder wood nearer the bark was lighter after heat treatment than wood nearer the pith. Similar findings were found for kiln dried silver birch in Mononen *et al.* (2002). Temperature gradients are likely to exist in veneer cants during steaming and higher temperatures in the outer wood and increased thermal browning are likely to compensate for the tendency of the outer wood to be lighter after heat treatment. In contrast, higher temperatures in the periphery of the veneer cant during heat treatment would tend to reduce the redness of outer wood further because of the negative correlation between temperature and redness of heat treated red alder wood (Chapter 3).

Wood samples obtained from lower in the stem tended to be redder than those higher up following thermal modification, but the differences were small and would be barely discernable to the human eye. Similarly, differences in lightness of thermally modified wood as a result of the interaction of bole position of samples and season were also small. Therefore, differences in colour of thermally modified wood due to sampling position along the tree stem are unlikely to translate into large colour variation along the length of veneer sheets.

In Chapter 3, it was found that the colour of thermally modified red alder wood depended on heating time and temperature and suggested that processing technology needed to be developed to evenly heat veneer cants in order to obtain uniformly coloured veneer from such cants. The results here suggest that even if veneer cants could be more evenly heated by reducing their size or employing different heating technology, significant seasonal variation in veneer colour would still persist as a result of the season x storage interactions noted here. In Chapter 3, it was found that increasing heating time and temperature could alter the colour of thermally modified red alder wood, and careful adjustment of these parameters could be used to reduce seasonal variation in colour of veneer sliced from heated cants. Further research involving thermal modification of large veneer cants would be needed to develop heating schedules to minimise seasonal variation in the colour of sliced red alder veneer.

4.5 Conclusions

1. Variation in the colour of red alder wood heated at 70°C may arise as a result of complex interaction between the season in which parent trees are harvested and the length of time that logs are stored prior to heat treatment. In particular, large variation in the colour of thermally modified red alder wood can develop in wood harvested in spring and stored for two weeks prior to heat treatment. The colour of heat treated wood from fall and winter felled logs are less affected by storage time and matches industry colour preferences.
2. Wood cut from nearer the bark was lighter and less red than wood near the pith following thermal modification at 70°C, irrespective of season in which the parent log was felled or the length of time that it was stored prior to processing.
3. The effects of season, log storage time, and wood type on the colour of thermally modified red alder wood, in addition to the known effects of temperature and heating time on wood colour, explain why it is very difficult in practice to obtain uniformly coloured veneer from heated red alder cants.
4. Careful control of heating temperature and time and development of differential heating schedules or storage times for wood harvested in different seasons could be used to minimise seasonal variation in the colour of veneer sliced from heated red alder cants.

5.0 General Discussion

Industrial manufacturers of red alder veneer find it difficult to achieve uniform colour in sequentially sliced veneer due to the complex suite of competing reactions and thermal gradients involved in the thermal modification of red alder wood. Added variability arises from the dependence of these reactions on treatment temperature and time, seasonal changes, effects of storage prior to processing, and wood type (inner/outer sapwood and position in the stem). Results from experiments described in this thesis (Chapters 3 and 4) have suggested changes to the processing of red alder that could lead to better colour uniformity in sliced alder veneer.

In Chapter 3, samples of red alder were exposed to different temperatures and heating times in order to better understand the effect of thermal treatments used in industry on the colour of veneer sliced from cants. Results showed that colour variation from pith to bark was minimised and the desired colour was imparted by heating red alder at 70°C for a period greater than 24 hours. It should also be noted that moisture contents of alder samples decreased as treatment temperature and heating time increased. The colour of heat treated wood depends on temperature and wood moisture content (Thomassen 1986; Yeo and Smith 2004). Therefore, the key to controlling wood colour in veneer cants during heat treatments may lie in carefully balancing treatment temperature / time and wood moisture content.

In Chapter 3, the 70°C / 36 hour heat treatment, which was successful in producing a uniform colour in red alder, was only applied to breast height wood samples taken from trees harvested in summer and processed immediately after felling. In Chapter 4, the optimised heating protocols developed in Chapter 3 were applied to wood harvested in different seasons (spring, summer, fall and winter), stored for different time periods (0, 1, 2, and 4 weeks), and consisting of inner/outer sapwood obtained from various position along the stem. Results in Chapter 4 showed that these three factors had a significant effect on the colour of heated red alder samples. In particular, season and storage had a significant interactive effect on both the lightness (L*) and redness (a*) of heated red alder samples. Heated samples taken from trees harvested in spring and summer, were redder and darker as storage time of the parent wood increased to 2 weeks. However, the effect reversed after 4 weeks of storage with redness decreasing and lightness increasing. Allen (1993) found that stain persisted within red alder logs for up to 6 months. Findings in Chapter 4 strongly suggested that reactions responsible for the red-orange discolouration of red alder wood at ambient temperatures also influenced the colour of the wood following thermal modification. The reversion in red colour of heated wood obtained from logs stored for 4 weeks may be associated with a decrease in the intensity of red-orange colour of wood during storage. Such decreases would be consistent with observations in Chapter 3 that the red-orange colour of red alder wood heated at 30°C increased initially, but then decreased with further heating. Accordingly, manufacturers of red alder veneer from raw logs should consider processing spring and summer felled logs immediately or once the intensity of the stain has decreased. Overall, the colour of heat treated wood from fall and winter harvested logs was less affected by storage and also produced wood samples that better matched industry colour preferences.

The effect of bole position on the colour of heat treated wood, although significant, was less important than the effects of season and storage, and for all wood types (positions in stem), the colour measurements for both L* and a* remained within the desirable colour limits. Also, differences in a* values at different stem heights, although statistically significant, were quite small and indiscernible to the human eye (Phelps *et al.* 1994).

The effects of wood type (inner and outer sapwood) on the colour of heat treated red alder was examined in both experimental chapters. However, it should be noted that the effect of wood type on the colour of heat-treated wood in Chapter 3 was only based on data for wood sampled in one month (August). In contrast, results in Chapter 4 were based on data for wood samples collected in each season. In both experiments, the inner sapwood was significantly darker than the outer sapwood following heat treatment at 70°C for 48 hours. In Chapter 4, it was that the found the inner sapwood was redder following heat treatment (agreeing with lightness measurements); however, the same trend was not observed in Chapter 3.

In Chapter 3, it was found that the colour of thermally modified red alder wood was influenced by the temperature and length of time that samples were heated. It was suggested that technology needed to be developed or utilized to evenly heat veneer cants in order to achieve colour uniformity from pith to bark or throughout the entire cant. The results from Chapter 4 suggest, however, that even if veneer cants could be evenly heated by reducing their size or using different heating technology, the effects of harvesting season and storage would still create variation between and possibly within slices of veneer. Based on the results from Chapters 3 and 4, it is suggested that further research is required to develop treatment schedules to minimise variation in the colour of heat treated red alder caused by season and storage.

6.0 Overall Conclusions

1. The colour of thermally modified red alder wood depends on the strength of reactions that produce red-orange chromophores in the wood, thermally darken the wood, and destroy the red-orange chromophores. Therefore, the key to controlling colour in veneer cants during thermal treatments lies, in part, in balancing these competing reactions through careful control of heating temperatures and durations.
2. Variation in the colour of red alder wood following heating appears to be due to a complex interaction between the season in which parent trees are harvested and the length of time logs are stored prior to heat treatment. In particular, large variation in colour of thermally modified red alder wood can develop in wood harvested in spring (when concentrations of oregonin are high) and stored for two weeks prior to heat treatment. Overall, fall and winter felled logs were less affected by storage and produced samples within industry colour preferences.
3. There was evidence to suggest that red-orange chromophores responsible for the staining of red alder wood at ambient temperatures influences the colour of the wood following thermal modification.
4. Wood cut from the outer sapwood and heated was lighter and less red than similarly heated wood cut from the inner sapwood.
5. Heating small pith-to-bark red alder wood samples at 70°C for 36 hours produced wood that had an even tan colour from pith to bark and matched the current industry colour preference. However, the effects of season, log storage time, and wood type are an obstacle to consistently achieving a desired uniform colour.

6. Differential heating schedules or storage times, and careful control of heating temperatures and time, for wood harvested in different seasons could be used to minimise seasonal variation in the colour of veneer sliced from heated red alder cants.

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Appendix 1 - Publication

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Thermal Modification of Colour in Red Alder Veneer.
1, Effects of Temperature, Heating Time and Wood Type

THERMAL MODIFICATION OF COLOR IN RED ALDER VENEER. 1, EFFECTS OF TEMPERATURE, HEATING TIME AND WOOD TYPE

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ABSTRACT

Red alder has become one of the most widely traded hardwood species in North America, and sliced red alder veneer is commonly applied as a decorative overlay on composite wood panels used by the furniture and cabinet industries. Red alder wood, however, acquires a mottled orange color following felling, which is undesirable when the wood is used for decorative purposes. Heating red alder wood remedies this problem to some extent, but there is still an unacceptable level of variability in the color of veneer sliced from heated veneer cants. This study examined the variation in color of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions. The aim was to examine whether within-tree variation in the susceptibility of red alder wood to thermal darkening can explain variation in color of veneer sliced from steamed red alder cants, and to determine the optimal thermal treatment (temperature and time) that can impart the tan color to red alder wood that industry is seeking. Results indicated that there was within-tree variation in the color of red alder samples following thermal treatment, but differences were pronounced only when wood was heated at a low temperature. Wood close to the bark tended to be redder than wood close to the pith when heated at 30°C, but such a difference was absent in wood heated at higher temperatures (50–90°C). Heating red alder wood, *in vitro*, at 70°C for 36 h produced wood that was evenly colored from pith to bark and matched the current industry color preference. It is suggested that the color of thermally modified red alder wood depends on the strength of reactions that produce orange/red chromophores in the wood, thermal darkening of the wood, and destruction of orange/red chromophores.

Keywords: Red alder, veneer, color, thermal modification.

INTRODUCTION

Red alder (*Alnus rubra* Bong.) has become one of the most economically important hardwood species in North America (AHEC 2003). Sliced red alder veneer is commonly used as a decorative overlay on composite wood panels (particleboard and medium density fiberboard), which are then used in the manufacture of cabinets and furniture (Hibbs et al. 1994). Red alder wood, however, acquires a mottled orange color after felling, which is undesirable when the wood is used for cabinets and furniture (Kozlik 1987; Kaufmann 2003; Simpson 1991). To over-

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come this problem, sawn alder lumber is steamed at temperatures of 66° to 100°C for varying periods of time (Kozlik 1962, 1967, 1987; Kozlik and Boone 1987). Steaming produces a uniform tan color on the surface of red alder lumber, but no studies have examined the thermal modification of color in red alder veneer cants. Industry reports, however, suggest that it is much more difficult to achieve color uniformity in veneer sliced sequentially from steamed cants (Kaufmann 2003). Radial variation in wood color in the cants, possibly caused by thermal gradients within veneer cants during steaming, could explain such variability. Alternatively, within-tree variation in the susceptibility of red alder to thermal discoloration could be responsible for the variation in color of sliced veneer. Variability in the color of sliced veneer is highly undesirable because veneer sheets pressed onto composite wood panels need to be color matched to meet the demands of consumers for red alder furniture and cabinets with uniform color (Raettig et al. 1995).

This study examined the variation in color of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions using four temperatures (30°, 50°, 70°, and 90°C) and five heating times (8, 24, 36, 48, and 72 h). The aim was to examine whether within-tree variation in the susceptibility of red alder wood to thermal darkening can explain variation in color of veneer sliced from steamed red alder cants, and secondly to determine the optimal thermal treatment (temperature and time) that can impart the favored tan color to red alder wood.

LITERATURE REVIEW

The majority of research on the discoloration of wood at ambient temperatures and thermal modification of wood color has been undertaken in order to eliminate the discoloration of wood that can occur during the kiln-drying of lumber. Few studies have focused directly on the thermal modification of wood color in veneer cants, despite the widespread presteaming of such cants prior to veneer slicing. The results of several studies that have examined color changes in wood at ambient and elevated temperatures, however, are relevant to the thermal modification of color in veneer cants.

Changes in the color of wood can occur at ambient temperatures as a result of enzyme-mediated (Maillard) reactions between sugars, phenolic compounds, and amino acids. These reactions, which are similar to the ones causing the browning of freshly cut fruit, occur in living parenchyma cells where they create amorphous globules of colored material (Yeo and Smith 2004). Simpson (1991) described a red to orange discoloration that occurs in freshly cut red alder wood and suggested that it was due to an oxidative reaction between extractives and the atmosphere. Abe et al. (1994) also suggested that the reaction between extractives and atmospheric oxygen under weakly alkaline conditions was responsible for color changes in freshly cut sugi (*Cryptomeria japonica* (L.f.) Don) wood. They concluded, however, that enzymes were not responsible for the color changes. Enzymatic reactions, however, were thought to be responsible for the mottled discoloration of several species upon exposure of green wood to oxygen (Hon and Shiraishi 1991).

The discoloration of wood during kiln-drying has also been linked to Maillard reactions, although heat applied during drying may cause colored compounds to darken and migrate towards the surface of boards as free water is removed during drying. Kapp et al. (2003) suggested that Maillard reactions were responsible for kiln brown and yellow stain of South African grown pine species (*Pinus elliottii* Engelm, *P. patula* Schlecht and Chamisso, and *P. taeda* L.) during kiln-drying. They noted a distinct transition from yellow to brown stain as the drying temperature exceeded 80°C. McDonald et al. (2000) also suggested that Maillard reactions were responsible for the chocolate brown discoloration of radiata pine (*Pinus radiata* D. Don) sapwood during drying. The degree of discoloration was thought to be dependent on the chemical composition of extractives, wood pH, and drying temperature.

Heat can directly alter the color of wood by causing hydrolysis and oxidation of wood components. According to White and Dietenberger (2001), darkening of wood due to heat is caused by thermal degradation of hemicelluloses and lignin, and can commence at temperatures as low as 65°C, depending on wood pH, moisture content, heating medium, exposure period, and species. Hence, hydrolysis of hemicelluloses can occur at temperatures within the range employed to kiln-dry timber, and several studies have examined the discoloration of hardwoods during drying. Kollmann et al. (1951) found that temperatures and relative humidities in excess of 50°C and 65% RH were required to produce a red color change in maple (*Acer sp.*) and beech (*Fagus sp.*). Millett (1952) found that drying temperatures of 65°, 80°, and 90°C produced a brown color in sugar pine (*Pinus lambertiana* Dougl.), oak (*Quercus sp.*), and spruce (*Picea sp.*), respectively, when the relative humidity during drying was 65%. Sundqvist (2002) exposed white birch (*Betula pubescens* Ehrh.), Scots pine (*Pinus sylvestris* L.), and Norway spruce (*Picea abies* L.) to temperatures of 65°, 80°, and 95°C for 0, 1, 3, and 6 days. Each species showed pronounced darkening when the temperature exceeded 80°C. The duration of heat treatment was more important than temperature in changing the color of birch, whereas both factors were of similar importance in altering the color of pine and spruce. Thomassen (1986) cited by Stenudd (2004) found a brown-red discoloration of the core of European beech (*Fagus sylvatica* L.) boards during convection drying at ~40°C. Discoloration occurred when the wood reached fiber saturation point (25 to 35% moisture content). Stenudd (2004) reached the same conclusion when examining the discoloration of silver birch (*Betula pendula* Roth.) during kiln-drying. Recently, Yeo and Smith (2004) found that internal darkening of hard maple (*Acer saccharum* Marsh.) developed at or above 43°C when wood moisture content was at and above fiber saturation point.

Discoloration of wood during kiln-drying is generally regarded as a defect; however, heating of wood is sometimes deliberately employed to change wood color. Brauner and Conway (1964) found that color change in black walnut (*Juglans nigra* L.) was most noticeable when the wood was steamed at between 100 and 110°C for 4 to 6 h. Charrier et al. (2002) immersed walnut logs in water at temperatures of 80° to 90°C for up to 51 h and then measured color changes in sapwood and heartwood using a spectrophotometer. They found that the thermal treatments promoted the darkening and reddening of the wood, but the darkening was more prominent in heartwood than in sapwood. Kozlik (1962) found that presteaming red alder lumber at 88° to 93°C for 11 to 12 h resulted in wood with the best color uniformity. Kozlik (1967) tested several combinations of temperatures and heating times during the drying of red alder, but none of them were able to achieve both color uniformity and absence of sticker stain. A subsequent study, however, found that steaming red alder lumber at 100°C for at least 4 h (before air- or kiln-drying) eliminated sticker stain and prevented mottling (Kozlik 1987). Kozlik and Boone (1987) found that steaming red alder lumber at 99°C for 6 h during kiln-drying produced boards with the desired quality, color uniformity, and moisture content. However, to improve color uniformity, Kozlik (1987) recommended that red alder lumber should be presteamed for at least 12 h at 66°C to 77°C, with the duration of steaming increasing as initial moisture content decreased. It should be noted that observations by Kozlik and Boone (1987) are relevant only to surface discoloration of red alder lumber, and they did not examine subsurface color changes in logs or cants, which are of greater importance for wood used for the production of sliced veneer.

MATERIALS AND METHODS

Sample preparation

Four red alder trees growing in the Malcolm Knapp Research Forest in Maple Ridge, British Columbia, were selected based on similarities in their height (18–25 m), diameter (25–32 cm at breast height); age (26–31 years), and growing conditions (non-riparian). Trees growing in riparian zones (adjacent to streams) were avoided, as harvest restrictions in British Columbia limit the removal of any species in or adjacent to such areas. A single tree was sampled each week over a period of 4 weeks in August 2003 (4 trees in total). Thus each tree and sampling period acted as a separate replication.

Trees were marked at breast-height (1.3 m above ground level), felled, and inspected for the presence of abnormalities such as rot or scarring. Four cross-sectional discs were cut from each tree: two immediately above and two immediately below breast-height (Fig. 1). Each disc was 15 cm thick (longitudinally) and was free from internal rot or scarring. The four discs were randomly assigned a letter (A, B, C, or D) and immediately transported to the laboratory for further processing.

Five quarter-sawn slats were cut from each of the four discs using a bandsaw. Slats were 1 cm wide (tangentially) and cut from bark to pith (Fig. 1). The moisture content of separate pith-to-bark samples, expressed as a percentage of their oven-dry weight (obtained by oven-drying samples overnight at 105°C), was found to vary from 95 to 127%. The location of each slat was randomly selected on the outer circumference of the disc prior to sawing. A 1- × 1-cm pith-to-bark sample was then cut from the middle (7 cm from top and bottom) of each slat resulting in five 1- × 1-cm samples from within each disc. Each sample was sealed in an 8- × 23-cm sheet of aluminum foil to reduce the rate of drying of samples during heating, labeled with the appropriate disc letter (A–D) and randomly assigned a treatment number (1–5) (Fig. 1).

Thermal treatments and color measurement

Samples obtained from the same discs were allocated to the same treatment temperature. Thus, samples from discs A, B, C, and D were subjected to thermal modification at temperatures of 30°, 50°, 70°, and 90°C, respectively. The 5 samples from within each disc were randomly allocated to the different heating times, 8, 24, 36, 48, and 72 h.

Samples were placed in 25- × 200-mm test-tubes that were submerged in preheated glycerol baths set at 30°, 50°, 70° or 90°C. Each test tube was covered, but not completely sealed, to avoid pressure build-up. Samples were removed from the tubes after heating and allowed to cool at room temperature for 30 min. They were then unwrapped from the aluminum foil and cross-cut every fifth growth ring starting at the pith and finishing in the outer sapwood. Thus, five sub-samples were produced from each pith-to-bark sample, each containing five growth rings with the earlywood exposed longitudinally. Exposed earlywood faces were allowed to dry for 24 h at room temperature and their color was then measured using a spectrophotometer (Minolta CM-2600d). Earlywood was chosen for color measurements as it forms the majority of the wood in red alder (Parker et al. 1978). A total of 400 color measurements were made. Color is ex-

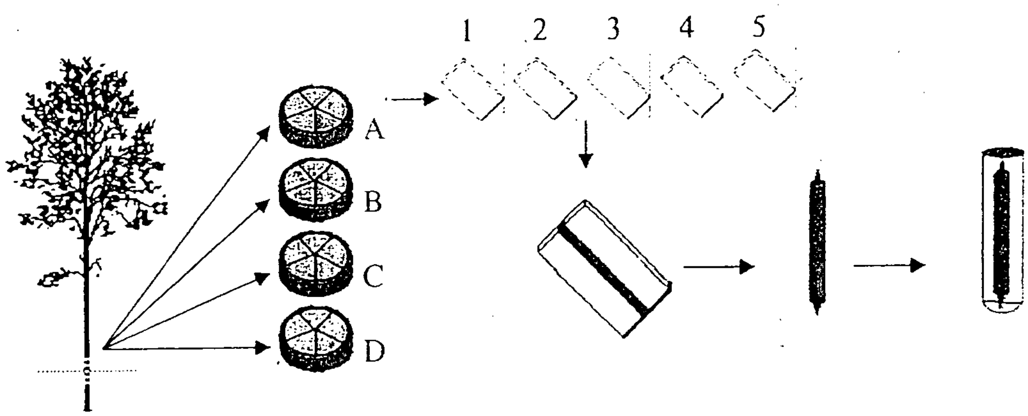

FIG. 1. Sampling of red alder trees and preparation of wood samples.

pressed using the CIE L*a*b* space system, which consists of three parameters: **L*** is lightness (0 = black; 100 = white), **a*** is greenness/redness (−60 = green; 60 = red), and **b*** is blueness/yellowness (−60 = blue; 60 = yellow) (Minolta 1998). According to Phelps et al. (1994), a difference of approximately three color units can be detected by the human eye. Yellowness and blueness were insignificant characteristics of color change in thermally modified red alder, and hence b* measurements are not presented or discussed in this paper.

Separate pith-to-bark samples were weighed, wrapped in foil, and heated, as above, at 20° (room temperature), 30°, 50°, 70°, and 90°C. The samples were removed from the test tubes periodically (after 8, 24, 36, 48, and 72 h) and reweighed. After 72 h, the samples were oven-dried at 105°C for 7 h and their moisture contents calculated.

In order to compare the color of samples subjected to the different heat treatments with that of commercially produced veneer, the color of several red alder veneer sheets with the desired tan color was measured. The color of these veneers provided reference maxima and minima for L* and a* values obtained from the measurement of the color of samples from red alder trees (above), and are displayed as dashed lines on graphs depicting results of this study in Figs.
F2 2–5. While these maxima and minima provide a general range of favorable color measurements, they were not mathematically derived, nor do they represent a color standard for the red alder veneer industry as a whole.

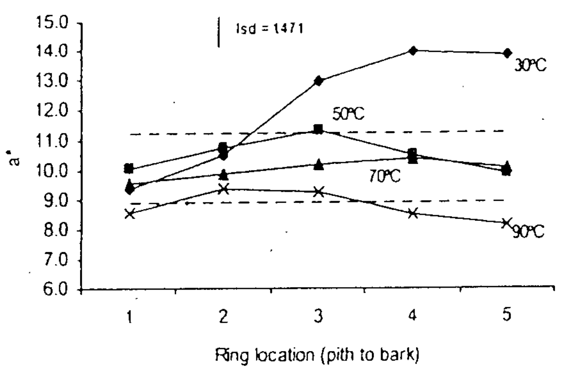

FIG. 2. Effects of temperature and ring location on a* (redness) of heated red alder wood.

Experimental design and statistical analysis

This experiment used factorial principles to determine the effects of three fixed factors (treatment temperature, heating time, and ring location) on two response variables (L* (lightness) and a* (redness)). Random effects arise because of between- and within-tree variation in wood properties, and elapsed time between replicate measures. Analysis of variance was used to examine fixed and random effects on the response variables. Statistical computation was performed using Genstat 5, using a p-value of 0.05 (5%) (Lawes Agricultural Trust 1994). Before the final analysis, diagnostic checks were performed to determine whether data conformed to the underlying assumptions of analysis of variance, i.e., normality with constant variance. Significant results ($p < 0.05$) are presented graphically and least significant difference (LSD) bars are used to compare differences between means.

RESULTS

There were significant effects of temperature, heating time, and ring location on L* (lightness) and a* (redness) (Table 1). There were also significant two-way interactions of temperature and heating time on a* and temperature and ring location on L* and a* (Table 1). T1

The overall effect of increasing temperature during the thermal modification of red alder wood was to make samples slightly less red (a* decreased) and darken them (L* decreased) (Figs. 2 and 3, respectively). Differences in the lightness and redness of samples heated at 70° and 90°C were small and generally statistically insignificant. The effect of temperature on the color of the wood, however, depended on the location of the sample within the tree, as indicated by the significant temperature × ring location interaction in Table 1. Wood samples cut adjacent to the bark developed a more pronounced orange/red color when heated at 30°C

TABLE 1. *Significant effects of, and interactions between, treatment temperature, heating time, and ring location on L* and a* color parameters.*

	Fixed Factors						
Response variables	Temperature (T)	Heating time (H)	Ring Location (R)	T × H	T × R	H × R	T × H × R
L*-lightness	***	***	***	NS	***	NS	NS
a*-redness	***	***	***	***	***	NS	NS

*** = $p < 0.001$; NS = not significant ($p > 0.05$)

than samples cut close to the pith. This observation is reflected by the relatively high a* values and lower L* values for the relevant samples (3 to 5) in Figs. 2 and 3. In contrast, the effect of ring location on the color of samples heated at 50°, 70° and 90°C was smaller. Within-tree differences in the color of thermally modified samples were least pronounced for those heated at 70°C, and the color of these samples all fell within the preferred color limits for red alder veneer.

If results in Figs. 2 and 3 are compared, it can be seen that there were marked differences in the pith-to-bark variation in redness and lightness of red alder wood following thermal modification at different temperatures. Differences in the redness of wood close to the pith (samples 1 and 2) were small irrespective of heating temperature, including samples heated at 30°C. As mentioned above, wood close to the bark was redder and darker when heated at 30°C, but differences in the redness of samples heated at 50°, 70° and 90°C were small, irrespective of their location in the tree stem. In contrast, there were significant differences in the lightness of wood heated at higher temperatures (70° and 90°C) compared to those heated at lower temperatures (30° and 50°C), particularly for wood close to the pith. Samples heated at 70°C were darker than those heated at 90°C, but the differences were not statistically significant.

Figure 4 shows the effect of heating time on the L* value for thermally modified samples. Results in this figure are averaged across temperature and ring number as there were no significant interactions of heating time with temperature or ring location (Table 1). Wood samples became darker as the length of time that they were exposed to heat increased. Thus, the L* decreased from 73.90 for samples heated for 8 h to 67.18 for samples heated for 72 h. Heating times of 24 to 72 h produced values for L* that fell within industry preferences.

The effect of heating time on the redness of samples depended on temperature as indicated by the significant temperature × heating time interaction in Table 1. This occurred because there was a pronounced increase in the redness of samples heated at 30°C over the first 36 h followed by a pronounced decrease over the following 36 h, whereas there was little change over time in the redness of samples heated at higher temperatures (with the exception of

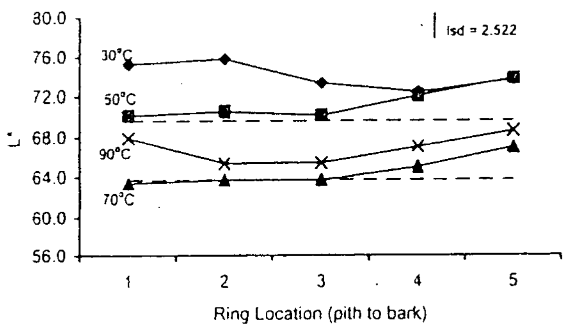

FIG. 3. Effects of temperature and ring location on L* (lightness) of heated red alder wood.

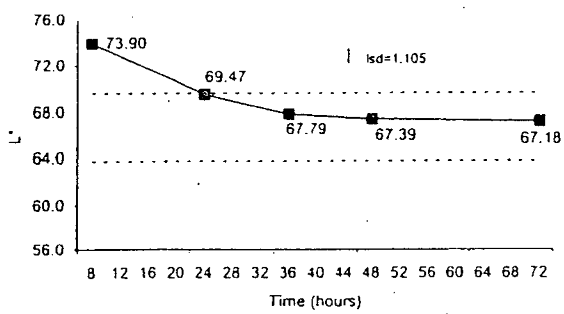

FIG. 4. Effects of heating time on L* (lightness) of red alder wood.

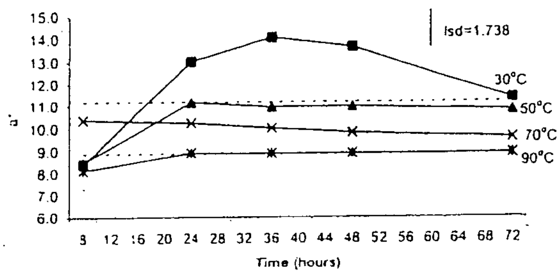

FIG. 5. Effects of temperature and heating time on a* (redness) red alder wood.

samples heated at 50°C from 8 to 24 h) (Fig. 5). The redness of samples heated at 70°C remained consistent irrespective of heating time and fell within industry preferences. Heating times of 24 to 72 h seemed to produce the color that industry prefers. Measurement of the moisture content of separate pith-to-bark samples heated at different temperatures showed a decrease in their moisture content over time. Decreases in moisture content were pronounced at the higher (70° and 90°C) temperatures (Table 2).

DISCUSSION

From first principles, it can be assumed that the color of thermally modified red alder wood results from the production and/or destruction of chromophoric groups. It is well known that red alder wood changes from a cream to a red/orange color on exposure to air (Simpson 1991). This color change occurs at ambient temperatures, and is probably caused by Maillard reactions between sugars and amino acids/proteins in wood (Kapp et al. 2003; McDonald et al. 2000). The production of new chromophores as a result of these reactions may explain our finding that wood close to the bark, where concentrations of sugars are likely to be high, was much redder than wood close to the pith when wood samples were heated at 30°C. It is also well established that hemicelluloses are degraded by heat, causing thermally modified wood to be darker than unmodified wood (White and Dietenberger 2001). Thermal degradation of wood may explain why red alder wood heated at higher temperatures (70° or 90°C) was darker than wood heated at 30° or 50°C, and the positive correlation between heating time and darkening of wood. Wood heated at 70°C, however, was darker than wood heated at 90°C, and wood close to the bark and heated at 30°C was as dark as wood heated at 50°C. The latter observation suggests that the red color (a*), which was pronounced in the outer wood heated at 30°C, contributed to the darkness (decreased L*) of thermally modified red alder wood. Accordingly, samples heated at 90°C were lighter than those heated at 70°C, possibly because of their lower redness. This suggestion is supported by results showing that wood heated at 70°C was redder than wood heated at 90°C, and the association between decreased redness and reduced darkening in wood samples heated at 70° and 90°C (compare Figs. 2 and 3). This negative correlation between redness of samples and heating temperature could result from inhibition of the (Maillard) reactions that produce the orange/red color in red alder wood and/or the destruction of the complexes responsible for the color. We consider the latter more likely since samples subjected to prolonged (72 h) heating at 30°C were less red than samples heated for shorter periods of time at the same temperature. This suggests that the orange/red complexes produced in red alder are thermolabile, and hence

TABLE 2. *Moisture content of pith to bark samples heated at different temperatures.*

Temperature °C	Heating time (hours)					
	0	8	24	36	48	72
20	98.5	96.1	94.4	92.1	88.1	83.1
30	102.3	99.8	97.9	95.4	92.4	88.4
50	126.8	119.2	103.5	96.3	84.7	69.3
70	105.7	84.2	60.8	50.7	31.1	15.1
90	95.0	61.7	16.2	6.7	1.8	1.2

are degraded by prolonged exposure to heat and higher temperatures.

Clearly, the thermal modification of color in red alder involves a complex suite of reactions. Our findings suggest that the final color of the wood depends on the strength of reactions that produce orange/red chromophoric groups in the wood, thermal darkening of the wood, and destruction of orange/red chromophoric groups. Therefore, the key to controlling color in veneer cants during steaming may lie in balancing these competing reactions through careful control of heating temperatures and times, and wood moisture content. Color control is complicated by within-tree and, possibly, seasonal variation in the strength of the reactions that generate the orange/red chromophores in wood and thermal and moisture gradients within veneer cants during steaming. A more complete understanding of these sources of variation through research on the thermal modification of larger samples would assist efforts to obtain better color uniformity in veneer sliced sequentially from heated veneer cants. Nevertheless, our findings on small samples indicate that heating red alder wood at 70°C for 24 to 36 h can produce the preferred tan color for this species. Higher temperatures in the outer layers of veneer cants may compensate for the tendency of outer wood to become redder by destroying red/orange chromophores and this may produce more uniformly colored veneer. Large thermal gradients from the outer to the inner wood, however, are likely to produce the pronounced differences in the color of veneer sheets that industry currently observes. A technology capable of more evenly heating veneer cants, possibly involving a combination of steaming and radio-frequency heating, might reduce the extent of such gradients and color variation in red alder veneer. Direct thermal modification of veneer might achieve a similar effect, although higher temperatures would be needed to accelerate color changes.

CONCLUSIONS

1. There is variation in the color of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions, but differences are pronounced only when wood is heated at 30°C. Wood close to the bark tends to be redder than wood close to the pith when heated at low temperatures, but such a difference is absent in wood heated at higher temperatures (50°–90°C).
2. Heating small pith-to-bark red alder wood samples at 70°C for 36 h produced wood that had an even tan color from pith to bark and fell within the current industry color preferences.
3. It is hypothesized that the color of thermally modified red alder wood depends on the strength of reactions that produce orange/red chromophores in the wood, thermal darkening of the wood, and destruction of orange/red chromophores. The key to controlling color in veneer cants during steaming lies in balancing these competing reactions through careful control of heating temperatures and times.
4. A better understanding of reactions that generate the orange/red chromophores in red alder wood and the magnitude of thermal gradients within veneer cants during steaming would assist efforts to obtain better color uniformity in veneer sliced sequentially from heated veneer cants.

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Appendix 2 – Referee Comments

Review of paper "Thermal Modification of Color in Red Alder Veneer. Effects of Temperature, Heating Time and Wood Type"

There is relatively little information available on changes in the color of wood during steaming; and even less for red alder. The effect of thermal modification of color in veneer is worth publishing. I suggest that this paper be published with moderate revision. My comments and questions are numbered and refer to the same numbers shown in the margin of the manuscript.

1. It is difficult for this objective to be accomplished given that small blocks were used. This objective should be rephrased.
2. Include Thomassen in the reference section.
3. Include month of tree sampling and initial moisture content of the samples before thermal treatments. The effect of the sampling period was not mentioned in the discussion.
4. How efficient was the sealing in avoiding drying of samples during treatment?
5. Initial moisture content needs to be included given that this parameter affects the optimal duration of steaming (see Kozlik 1987, cited in Literature review section).
6. There is some disagreement with this decision in respect with the objectives of the work. The authors were looking for uniformity of color and at the same time admit that variation in color exists between latewood and earlywood.
7. What was the moisture content of samples after treatment? Did it differ among the different temperatures? This is related to item 4, it is completely ignored in the discussion. Optimal thermal treatments depend on the moisture content control.
8. No clear evidence is given to affirm that the optimal treatment obtained for small blocks can be extrapolated to treat veneer cants. This treatment needs to be validated on veneer cants before any recommendations are given.
9. No chemical evidence is given to affirm this conclusion. This conclusion must be written as a hypothesis (as in the abstract).

I hope the above comments and suggestions will be useful to improve the paper. I enjoyed reading this well done manuscript. The marked manuscript with minor corrections and suggested changes is enclosed. Thank you for giving me the opportunity to review this paper for Wood and Fiber Science.

Appendix 3 – Statistical Analysis Data (Chapter 3)

Effects of treatment temperature, treatment time and wood type
on L* and a* colour parameters

```
GenStat Release 4.21  (PC/Windows XP)           15 September 2003 16:28:48
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                ________________________________________

                GenStat Fifth Edition (Service Pack 1)
                GenStat Procedure Library Release PL12.1
                ________________________________________

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   2  "Data taken from File: \
  -3  C:/Documents and Settings/phil.evans/Desktop/Measurements.xls"
   4  DELETE [Redefine=yes] _stitle_: TEXT _stitle_
   5  READ [print=*;SETNVALUES=yes] _stitle_
   9  PRINT [IPrint=*] _stitle_; Just=Left

 Data imported from Excel file: C:\Documents and Settings\phil.evans\Desktop\Mea
surements.xls
  on: 15-Sep-2003 16:29:10

  taken from sheet "Sheet1", cells A1:J401


  10  DELETE [redefine=yes] Tree,Section,Strip,Sample,Temp,Time,Ring,L,a,b
  11  FACTOR [modify=yes;nvalues=400;levels=4] Tree
  12  READ Tree; frepresentation=ordinal

    Identifier     Values   Missing    Levels
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  24  FACTOR [modify=yes;nvalues=400;levels=4] Section
  25  READ Section; frepresentation=ordinal

    Identifier     Values   Missing    Levels
       Section        400         0         4

  37  FACTOR [modify=yes;nvalues=400;levels=5] Strip
  38  READ Strip; frepresentation=ordinal

    Identifier     Values   Missing    Levels
         Strip        400         0         5

  50  FACTOR [modify=yes;nvalues=400;levels=5] Sample
  51  READ Sample; frepresentation=ordinal

    Identifier     Values   Missing    Levels
        Sample        400         0         5

  63  FACTOR [modify=yes;nvalues=400;levels=!(30,50,70,90)] Temp
  64  READ Temp; frepresentation=ordinal

    Identifier     Values   Missing    Levels
          Temp        400         0         4

  76  FACTOR [modify=yes;nvalues=400;levels=!(8,24,36,48,72)] Time
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    Identifier     Values   Missing    Levels
          Time        400         0         5

  89  FACTOR [modify=yes;nvalues=400;levels=5] Ring
```

```
 90  READ Ring; frepresentation=ordinal

   Identifier    Values   Missing    Levels
         Ring       400         0         5

 102  VARIATE [nvalues=400] L
 103  READ L

   Identifier   Minimum       Mean   Maximum     Values    Missing
            L     57.21      69.15     85.77        400          0

 136  VARIATE [nvalues=400] a
 137  READ a

   Identifier   Minimum       Mean   Maximum     Values    Missing
            a     1.890      10.34     18.18        400          0

 167  VARIATE [nvalues=400] b
 168  READ b

   Identifier   Minimum       Mean   Maximum     Values    Missing
            b     16.18      25.63     36.32        400          0

 201  RESTRICT Tree,Section,Strip,Sample,Temp,Time,Ring,L,a,b
 202

 203  "Split-Split-Plot Design."
 204  BLOCK Tree/Section/Strip/Sample
 205  TREATMENTS Temp*Time*Ring
 206  COVARIATE "No Covariate"
 207  ANOVA [PRINT=aovtable,information,means; FACT=32; FPROB=yes; PSE=diff,lsd;
LSDLEVEL=5]\
 208    L
```

208...

***** Analysis of variance *****

Variate: L

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tree stratum	3	79.692	26.564	0.55	
Tree.Section stratum					
Temp	3	5537.886	1845.962	38.53	<.001
Residual	9	431.180	47.909	3.96	
Tree.Section.Strip stratum					
Time	4	2521.320	630.330	52.13	<.001
Temp.Time	12	266.695	22.225	1.84	0.068
Residual	48	580.348	12.091	1.89	
Tree.Section.Strip.Sample stratum					
Ring	4	288.642	72.161	11.27	<.001
Temp.Ring	12	411.137	34.261	5.35	<.001
Time.Ring	16	70.579	4.411	0.69	0.804
Temp.Time.Ring	48	174.241	3.630	0.57	0.990
Residual	240	1537.050	6.404		
Total	399	11898.770			

```
* MESSAGE: the following units have large residuals.

Tree 2     Section 2              2.19   s.e. 1.04

Tree 1     Section 1    Strip 1               -5.16   s.e. 1.20
Tree 2     Section 2    Strip 1                2.87   s.e. 1.20
Tree 3     Section 1    Strip 1                3.04   s.e. 1.20

Tree 1     Section 1    Strip 1    Sample 4            -5.66   s.e. 1.96
Tree 2     Section 1    Strip 3    Sample 1            -6.33   s.e. 1.96
Tree 2     Section 1    Strip 3    Sample 3             6.78   s.e. 1.96
Tree 3     Section 1    Strip 3    Sample 2            -5.63   s.e. 1.96
Tree 4     Section 1    Strip 1    Sample 1            -6.36   s.e. 1.96
Tree 4     Section 2    Strip 5    Sample 5             5.80   s.e. 1.96


***** Tables of means *****

Variate: L

Grand mean  69.15

     Temp    30.00    50.00    70.00    90.00
             74.02    71.28    64.50    66.80

     Time     8.00    24.00    36.00    48.00    72.00
             73.90    69.47    67.79    67.39    67.18

     Ring        1        2        3        4        5
             69.14    68.80    68.08    69.04    70.68

     Temp     Time     8.00    24.00    36.00    48.00    72.00
    30.00             78.60    73.78    71.71    71.65    74.35
    50.00             77.36    71.97    69.64    69.59    67.84
    70.00             68.80    65.06    63.82    63.07    61.75
    90.00             70.86    67.09    66.00    65.25    64.79

     Temp     Ring        1        2        3        4        5
    30.00             75.23    75.72    73.23    72.30    73.59
    50.00             70.12    70.50    70.10    71.98    73.70
    70.00             63.35    63.70    63.69    64.90    66.87
    90.00             67.88    65.28    65.31    66.96    68.55

     Time     Ring        1        2        3        4        5
     8.00             73.68    74.49    72.90    73.53    74.92
    24.00             69.67    69.53    67.44    69.59    71.15
    36.00             67.92    67.31    67.23    67.20    69.30
    48.00             67.50    66.41    66.34    67.31    69.39
    72.00             66.93    66.27    66.52    67.55    68.64

     Temp     Time     Ring        1        2        3        4        5
    30.00     8.00             79.82    81.22    77.83    76.97    77.16
             24.00             75.59    77.54    70.30    71.14    74.32
             36.00             71.87    73.43    71.91    69.44    71.89
             48.00             74.35    71.61    70.41    70.45    71.41
             72.00             74.53    74.81    75.71    73.52    73.17
    50.00     8.00             75.09    76.81    76.19    78.99    79.72
             24.00             71.11    71.21    70.34    73.18    74.01
             36.00             68.60    68.74    68.85    70.23    71.78
             48.00             68.86    68.69    68.38    69.90    72.13
             72.00             66.93    67.07    66.75    67.59    70.86
    70.00     8.00             68.67    69.01    67.83    67.95    70.52
```

	24.00	64.20	63.98	64.37	65.97	66.80
	36.00	62.25	63.27	63.52	63.61	66.43
	48.00	60.97	62.14	62.64	63.36	66.23
	72.00	60.64	60.07	60.08	63.58	64.38
90.00	8.00	71.14	70.91	69.74	70.22	72.26
	24.00	67.79	65.39	64.74	68.05	69.46
	36.00	68.98	63.78	64.62	65.52	67.09
	48.00	65.84	63.21	63.91	65.51	67.79
	72.00	65.64	63.11	63.54	65.52	66.15

*** Standard errors of differences of means ***

Table	Temp	Time	Ring	Temp Time
rep.	100	80	80	20
s.e.d.	0.979	0.550	0.400	1.388
d.f.	9	48	240	30.51
Except when comparing means with the same level(s) of				
Temp				1.100
d.f.				48

Table	Temp Ring	Time Ring	Temp Time Ring
rep.	20	16	4
s.e.d.	1.213	0.971	2.118
d.f.	20.97	246	135.27
Except when comparing means with the same level(s) of			
Temp	0.800		1.942
d.f.	240		246
Time		0.895	
d.f.		240	
Temp.Time			1.789
d.f.			240
Temp.Ring			1.942
d.f.			246

*** Least significant differences of means (5% level) ***

Table	Temp	Time	Ring	Temp Time
rep.	100	80	80	20
l.s.d.	2.214	1.105	0.788	2.832
d.f.	9	48	240	30.51
Except when comparing means with the same level(s) of				
Temp				2.211
d.f.				48

Table	Temp Ring	Time Ring	Temp Time Ring
rep.	20	16	4
l.s.d.	2.522	1.912	4.189
d.f.	20.97	246	135.27
Except when comparing means with the same level(s) of			
Temp	1.576		3.825
d.f.	240		246
Time		1.763	
d.f.		240	
Temp.Time			3.525
d.f.			240

	DTL.out_L
Temp.Ring	3.825
d.f.	246

209 DAPLOT fitted,normal,halfnormal,histogram

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GenStat Release 4.21  (PC/Windows XP)            17 September 2003 14:08:47
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                  GenStat Fifth Edition (Service Pack 1)
                  GenStat Procedure Library Release PL12.1
                  ________________________________________

   1  %CD 'C:/Documents and Settings/phil.evans/Desktop'

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  -3  C:/Documents and Settings/phil.evans/Desktop/Measurements.xls"
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surements.xls
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  10  DELETE [redefine=yes] Tree,Section,Strip,Sample,Temp,Time,Ring,L,a,b
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  12  READ Tree; frepresentation=ordinal

    Identifier     Values    Missing     Levels
          Tree        400          0          4

  24  FACTOR [modify=yes;nvalues=400;levels=4] Section
  25  READ Section; frepresentation=ordinal

    Identifier     Values    Missing     Levels
       Section        400          0          4

  37  FACTOR [modify=yes;nvalues=400;levels=5] Strip
  38  READ Strip; frepresentation=ordinal

    Identifier     Values    Missing     Levels
         Strip        400          0          5

  50  FACTOR [modify=yes;nvalues=400;levels=5] Sample
  51  READ Sample; frepresentation=ordinal

    Identifier     Values    Missing     Levels
        Sample        400          0          5

  63  FACTOR [modify=yes;nvalues=400;levels=!(30,50,70,90)] Temp
  64  READ Temp; frepresentation=ordinal

    Identifier     Values    Missing     Levels
          Temp        400          0          4

  76  FACTOR [modify=yes;nvalues=400;levels=!(8,24,36,48,72)] Time
  77  READ Time; frepresentation=ordinal

    Identifier     Values    Missing     Levels
          Time        400          0          5

  89  FACTOR [modify=yes;nvalues=400;levels=5] Ring
```

```
 90  READ Ring; frepresentation=ordinal

   Identifier     Values   Missing    Levels
         Ring        400         0         5

 102  VARIATE [nvalues=400] L
 103  READ L

   Identifier    Minimum       Mean    Maximum     Values    Missing
            L      57.21      69.15      85.77        400          0

 136  VARIATE [nvalues=400] a
 137  READ a

   Identifier    Minimum       Mean    Maximum     Values    Missing
            a      1.890      10.34      18.18        400          0

 167  VARIATE [nvalues=400] b
 168  READ b

   Identifier    Minimum       Mean    Maximum     Values    Missing
            b      16.18      25.63      36.32        400          0

 201  RESTRICT Tree,Section,Strip,Sample,Temp,Time,Ring,L,a,b
 202

 203  "Split-Split-Plot Design."
 204  BLOCK Tree/Section/Strip/Sample
 205  TREATMENTS Temp*Time*Ring
 206  COVARIATE "No Covariate"
 207  ANOVA [PRINT=aovtable,information,means; FACT=32; FPROB=yes; PSE=diff,lsd;
LSDLEVEL=5]\
 208    a
0

208.................................................................................

***** Analysis of variance *****

Variate: a
```

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Tree stratum	3	104.022	34.674	2.52	
Tree.Section stratum					
Temp	3	572.377	190.792	13.88	0.001
Residual	9	123.751	13.750	2.35	
Tree.Section.Strip stratum					
Time	4	250.087	62.522	10.71	<.001
Temp.Time	12	291.449	24.287	4.16	<.001
Residual	48	280.335	5.840	1.90	
Tree.Section.Strip.Sample stratum					
Ring	4	123.525	30.881	10.03	<.001
Temp.Ring	12	272.800	22.733	7.39	<.001
Time.Ring	16	40.046	2.503	0.81	0.670
Temp.Time.Ring	48	79.280	1.652	0.54	0.994
Residual	240	738.767	3.078		
Total	399	2876.439			

```
* MESSAGE: the following units have large residuals.

Tree 2     Section 2          -1.242   s.e. 0.556

Tree 1     Section 1     Strip 1          2.859    s.e. 0.837
Tree 2     Section 2     Strip 1         -2.593    s.e. 0.837
Tree 3     Section 1     Strip 1         -2.743    s.e. 0.837
Tree 3     Section 1     Strip 2          2.187    s.e. 0.837
Tree 4     Section 1     Strip 3          1.972    s.e. 0.837

Tree 1     Section 1     Strip 1     Sample 1          -3.968    s.e. 1.359
Tree 1     Section 1     Strip 2     Sample 1          -4.166    s.e. 1.359
Tree 1     Section 1     Strip 4     Sample 1          -4.572    s.e. 1.359
Tree 2     Section 1     Strip 3     Sample 1           4.877    s.e. 1.359
Tree 2     Section 1     Strip 3     Sample 3          -5.260    s.e. 1.359
Tree 3     Section 1     Strip 3     Sample 2           5.487    s.e. 1.359
Tree 3     Section 1     Strip 3     Sample 5          -4.640    s.e. 1.359
Tree 3     Section 1     Strip 4     Sample 4          -4.491    s.e. 1.359


***** Tables of means *****

Variate: a

Grand mean  10.345

     Temp    30.00    50.00    70.00    90.00
            12.107   10.489   10.014    8.768

     Time     8.00    24.00    36.00    48.00    72.00
             8.871   10.846   10.995   10.843   10.170

     Ring        1        2        3        4        5
             9.384   10.129   10.917   10.825   10.469

     Temp     Time      8.00    24.00    36.00    48.00    72.00
    30.00              8.427   13.025   14.077   13.648   11.359
    50.00              8.504   11.170   10.961   10.994   10.819
    70.00             10.393   10.252   10.021    9.817    9.591
    90.00              8.159    8.937    8.920    8.913    8.910

     Temp     Ring         1        2        3        4        5
    30.00              9.355   10.511   12.935   13.923   13.811
    50.00             10.044   10.737   11.310   10.493    9.863
    70.00              9.561    9.899   10.170   10.365   10.078
    90.00              8.574    9.369    9.253    8.517    8.124

     Time     Ring         1        2        3        4        5
     8.00              7.889    8.141    9.706    9.464    9.152
    24.00              9.804   10.253   12.098   11.407   10.668
    36.00             10.192   10.972   11.339   11.606   10.864
    48.00              9.628   11.028   11.498   11.110   10.952
    72.00              9.404   10.253    9.945   10.536   10.711

     Temp     Time     Ring          1        2        3        4        5
    30.00     8.00               5.292    5.682    9.560   10.952   10.647
             24.00               9.895   10.047   15.570   15.757   13.855
             36.00              12.280   12.580   14.657   15.712   15.157
             48.00               9.992   13.337   15.152   14.420   15.340
             72.00               9.317   10.910    9.737   12.775   14.057
    50.00     8.00               8.747    8.370    9.815    7.727    7.858
             24.00              10.745   11.200   12.400   11.032   10.475
```

```
           36.00            10.257   11.898   11.470   11.452    9.725
           48.00             9.990   11.250   11.895   11.012   10.820
           72.00            10.477   10.968   10.970   11.243   10.435
   70.00    8.00             9.723   10.092   10.683   10.833   10.633
           24.00             9.530   10.198   10.545   10.622   10.363
           36.00             9.827    9.778    9.883   10.417   10.198
           48.00             9.598    9.863    9.860   10.288    9.477
           72.00             9.125    9.565    9.880    9.663    9.720
   90.00    8.00             7.795    8.420    8.765    8.345    7.470
           24.00             9.047    9.567    9.878    8.215    7.977
           36.00             8.405    9.632    9.347    8.842    8.375
           48.00             8.930    9.660    9.085    8.720    8.170
           72.00             8.695    9.567    9.192    8.465    8.630
```

```
*** Standard errors of differences of means ***

Table                     Temp        Time        Ring        Temp
                                                              Time
rep.                       100          80          80          20
s.e.d.                  0.5244      0.3821      0.2774      0.8615
d.f.                         9          48         240       42.54
Except when comparing means with the same level(s) of
 Temp                                                       0.7642
 d.f.                                                           48

Table                     Temp        Time        Temp
                          Ring        Ring        Time
                                                  Ring
rep.                        20          16           4
s.e.d.                  0.7220      0.6737      1.4048
d.f.                     31.39      245.50      202.14
Except when comparing means with the same level(s) of
 Temp                   0.5548                  1.3473
 d.f.                      240                  245.50

 Time                               0.6203
 d.f.                                  240
 Temp.Time                                      1.2406
 d.f.                                              240
 Temp.Ring                                      1.3473
 d.f.                                           245.50

*** Least significant differences of means (5% level) ***

Table                     Temp        Time        Ring        Temp
                                                              Time
rep.                       100          80          80          20
l.s.d.                  1.1863      0.7683      0.5465      1.7380
d.f.                         9          48         240       42.54
Except when comparing means with the same level(s) of
 Temp                                                       1.5366
 d.f.                                                           48

Table                     Temp        Time        Temp
                          Ring        Ring        Time
                                                  Ring
rep.                        20          16           4
l.s.d.                  1.4717      1.3269      2.7700
d.f.                     31.39      245.50      202.14
Except when comparing means with the same level(s) of
 Temp                   1.0929                  2.6538
 d.f.                      240                  245.50
```

Time	1.2219	
d.f.	240	
Temp.Time		2.4439
d.f.		240
Temp.Ring		2.6538
d.f.		245.50

```
209  DAPLOT fitted,normal,halfnormal,histogram
```

Appendix 4 – Statistical Analysis Data (Chapter 4)

Effects of season, storage and wood type on L* and a* colour parameters

```
GenStat Release 4.21  (PC/Windows XP)                 17 June 2004 06:47:02
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                 ________________________________________

                 GenStat Fifth Edition (Service Pack 1)
                 GenStat Procedure Library Release PL12.1
                 ________________________________________


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Settings/phevans/Desktop/seasons.xls\
  -3  "
   4  DELETE [Redefine=yes] _stitle_: TEXT _stitle_
   5  READ [print=*;SETNVALUES=yes] _stitle_
   9  PRINT [IPrint=*] _stitle_; Just=Left

 Data imported from Excel file: C:\Documents and Settings\phevans\Desktop\season
s.xls
  on: 17-Jun-2004 6:47:29

  taken from sheet "Data", cells A1:K193


  10  DELETE [redefine=yes]
Block,Tree,Posit,Type,Season,Storage,Height,SWHW,L,a,b
  11  FACTOR [modify=yes;nvalues=192;levels=2] Block
  12  READ Block; frepresentation=ordinal

    Identifier     Values   Missing    Levels
         Block        192         0         2

  19  FACTOR [modify=yes;nvalues=192;levels=4] Tree
  20  READ Tree; frepresentation=ordinal

    Identifier     Values   Missing    Levels
          Tree        192         0         4

  27  FACTOR [modify=yes;nvalues=192;levels=4] Posit
  28  READ Posit; frepresentation=ordinal

    Identifier     Values   Missing    Levels
         Posit        192         0         4

  35  FACTOR [modify=yes;nvalues=192;levels=2] Type
  36  READ Type; frepresentation=ordinal

    Identifier     Values   Missing    Levels
          Type        192         0         2

  43  FACTOR [modify=yes;nvalues=192;levels=3;labels=!t('Feb','May','Nov')]
Season
  44  READ Season; frepresentation=ordinal

    Identifier     Values   Missing    Levels
        Season        192         0         3

  51  FACTOR [modify=yes;nvalues=192;levels=4;labels=!t('0 weeks','1 week',\
  52  '2 weeks','4 weeks')] Storage
  53  READ Storage; frepresentation=ordinal

    Identifier     Values   Missing    Levels
       Storage        192         0         4
```

```
 60  FACTOR [modify=yes;nvalues=192;levels=!(45,131,217,303)] Height
 61  READ Height; frepresentation=ordinal

   Identifier     Values   Missing     Levels
       Height        192         0          4

 68  FACTOR [modify=yes;nvalues=192;levels=2;labels=!t('HW','SW')] SWHW
 69  READ SWHW; frepresentation=ordinal

   Identifier     Values   Missing     Levels
         SWHW        192         0          2

 76  VARIATE [nvalues=192] L
 77  READ L

   Identifier    Minimum       Mean    Maximum     Values    Missing
            L      56.91      64.82      72.78        192          0

 93  VARIATE [nvalues=192] a
 94  READ a

   Identifier    Minimum       Mean    Maximum     Values    Missing
            a      6.210      9.272      11.80        192          0

108  VARIATE [nvalues=192] b
109  READ b

   Identifier    Minimum       Mean    Maximum     Values    Missing
            b      19.00      24.96      32.80        192          0

125  RESTRICT Block,Tree,Posit,Type,Season,Storage,Height,SWHW,L,a,b
126

127  "Split-Split-Plot Design."
128  BLOCK Block/Tree/Posit/Type
129  TREATMENTS Season*Storage*Height*SWHW
130  COVARIATE "No Covariate"
131  ANOVA [PRINT=aovtable,information,means; FACT=32; FPROB=yes; PSE=diff,lsd;
LSDLEVEL=5]\
132   L
```

132..

***** Analysis of variance *****

Variate: L

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	1	19.958	19.958	2.99	
Block.Tree stratum					
Storage	3	86.780	28.927	4.33	0.130
Residual	3	20.025	6.675	3.60	
Block.Tree.Posit stratum					
Height	3	8.102	2.701	1.46	0.276
Storage.Height	9	37.885	4.209	2.27	0.093
Residual	12	22.272	1.856	0.30	
Block.Tree.Posit.Type stratum					
SWHW	1	1050.552	1050.552	168.54	<.001
Storage.SWHW	3	3.202	1.067	0.17	0.914
Height.SWHW	3	2.931	0.977	0.16	0.924
Storage.Height.SWHW	9	23.204	2.578	0.41	0.909
Residual	16	99.731	6.233	1.12	
Block.Tree.Posit.Type.*Units* stratum					
Season	2	31.645	15.823	2.85	0.065
Season.Storage	6	130.821	21.804	3.93	0.002
Season.Height	6	9.974	1.662	0.30	0.935
Season.SWHW	2	26.680	13.340	2.40	0.099
Season.Storage.Height	18	85.726	4.763	0.86	0.628
Season.Storage.SWHW	6	37.041	6.174	1.11	0.365
Season.Height.SWHW	6	17.844	2.974	0.54	0.779
Season.Storage.Height.SWHW	18	57.134	3.174	0.57	0.907
Residual	64	355.239	5.551		
Total	191	2126.749			

* MESSAGE: the following units have large residuals.

Block 1	Tree 2	Posit 3		0.78	s.e. 0.34
Block 2	Tree 2	Posit 3		-0.78	s.e. 0.34

Block 1	Tree 1	Posit 1	Type 1	1.47	s.e. 0.72
Block 1	Tree 1	Posit 1	Type 2	-1.47	s.e. 0.72
Block 2	Tree 1	Posit 1	Type 1	-1.47	s.e. 0.72
Block 2	Tree 1	Posit 1	Type 2	1.47	s.e. 0.72

***** Tables of means *****

Variate: L

Grand mean 64.82

Season	Feb	May	Nov
	64.52	64.54	65.39

Storage	0 weeks	1 week	2 weeks	4 weeks
	65.67	65.27	64.27	64.07

Height	45.00	131.00	217.00	303.00
	64.69	64.72	64.69	65.18

SWHW	HW	SW
	62.48	67.16

Season	Storage	0 weeks	1 week	2 weeks	4 weeks
Feb		65.42	64.22	65.08	63.36
May		66.20	65.34	62.14	64.50
Nov		65.40	66.25	65.58	64.34

Season	Height	45.00	131.00	217.00	303.00
Feb		64.17	64.76	64.31	64.85
May		64.75	64.47	64.18	64.78
Nov		65.16	64.93	65.58	65.90

Storage	Height	45.00	131.00	217.00	303.00
0 weeks		65.33	65.60	65.64	66.12
1 week		65.25	65.54	65.00	65.30
2 weeks		65.16	63.49	64.12	64.29
4 weeks		63.04	64.24	64.00	64.99

Season	SWHW	HW	SW
Feb		62.09	66.96
May		62.70	66.39
Nov		62.65	68.14

Storage	SWHW	HW	SW
0 weeks		63.12	68.23
1 week		63.02	67.52
2 weeks		61.95	66.59
4 weeks		61.84	66.30

Height	SWHW	HW	SW
45.00		62.52	66.87
131.00		62.43	67.00
217.00		62.18	67.20
303.00		62.79	67.56

Season	Storage	Height	45.00	131.00	217.00	303.00
Feb	0 weeks		65.18	65.34	65.37	65.80
	1 week		64.85	64.75	63.49	63.82
	2 weeks		65.79	64.63	64.98	64.91
	4 weeks		60.86	64.32	63.40	64.86
May	0 weeks		67.22	65.43	66.06	66.09
	1 week		64.17	66.16	65.55	65.46
	2 weeks		64.06	62.12	60.57	61.81
	4 weeks		63.54	64.16	64.56	65.73
Nov	0 weeks		63.59	66.02	65.50	66.47
	1 week		66.72	65.72	65.97	66.61
	2 weeks		65.62	63.73	66.82	66.15
	4 weeks		64.72	64.23	64.03	64.39

Season	Storage	SWHW	HW	SW
Feb	0 weeks		62.60	68.24
	1 week		61.82	66.63
	2 weeks		62.58	67.58
	4 weeks		61.35	65.37
May	0 weeks		64.15	68.25
	1 week		63.07	67.61
	2 weeks		60.14	64.14
	4 weeks		63.44	65.55
Nov	0 weeks		62.60	68.20
	1 week		64.17	68.33
	2 weeks		63.12	68.04

	4 weeks		60.71	67.97

Season	Height	SWHW	HW	SW
Feb	45.00		62.32	66.02
	131.00		62.17	67.35
	217.00		61.48	67.14
	303.00		62.38	67.32
May	45.00		63.23	66.27
	131.00		62.99	65.95
	217.00		61.91	66.46
	303.00		62.68	66.87
Nov	45.00		62.01	68.32
	131.00		62.14	67.72
	217.00		63.16	68.00
	303.00		63.30	68.51

Storage	Height	SWHW	HW	SW
0 weeks	45.00		63.27	67.39
	131.00		62.64	68.56
	217.00		62.90	68.39
	303.00		63.66	68.58
1 week	45.00		62.77	67.72
	131.00		63.59	67.50
	217.00		62.18	67.83
	303.00		63.54	67.05
2 weeks	45.00		62.86	67.46
	131.00		61.26	65.73
	217.00		61.64	66.60
	303.00		62.03	66.55
4 weeks	45.00		61.18	64.91
	131.00		62.24	66.23
	217.00		62.02	65.98
	303.00		61.91	68.07

Season	Storage	Height	SWHW	HW	SW
Feb	0 weeks	45.00		63.14	67.22
		131.00		61.95	68.74
		217.00		61.54	69.21
		303.00		63.80	67.81
	1 week	45.00		63.01	66.68
		131.00		62.47	67.03
		217.00		60.27	66.71
		303.00		61.54	66.10
	2 weeks	45.00		64.00	67.59
		131.00		60.89	68.38
		217.00		62.19	67.77
		303.00		63.23	66.59
	4 weeks	45.00		59.13	62.59
		131.00		63.39	65.25
		217.00		61.92	64.88
		303.00		60.96	68.76
May	0 weeks	45.00		66.47	67.98
		131.00		63.16	67.70
		217.00		63.39	68.71
		303.00		63.59	68.60
	1 week	45.00		61.77	66.57
		131.00		65.03	67.30
		217.00		61.74	69.37
		303.00		63.75	67.18
	2 weeks	45.00		61.56	66.58
		131.00		61.07	63.17
		217.00		58.44	62.70
		303.00		59.50	64.13
	4 weeks	45.00		63.12	63.97
		131.00		62.69	65.63
		217.00		64.06	65.05

		303.00	63.90	67.56
Nov	0 weeks	45.00	60.21	66.98
		131.00	62.81	69.24
		217.00	63.76	67.25
		303.00	63.60	69.33
	1 week	45.00	63.54	69.90
		131.00	63.28	68.17
		217.00	64.54	67.40
		303.00	65.34	67.87
	2 weeks	45.00	63.03	68.22
		131.00	61.81	65.64
		217.00	64.28	69.35
		303.00	63.38	68.93
	4 weeks	45.00	61.28	68.17
		131.00	60.64	67.82
		217.00	60.06	68.01
		303.00	60.88	67.90

*** Standard errors of differences of means ***

Table	Season	Storage	Height	SWHW
rep.	64	48	48	96
d.f.	64	3	12	16
s.e.d.	0.416	0.527	0.278	0.360

Table	Season Storage	Season Height	Storage Height	Season SWHW
rep.	16	16	12	32
s.e.d.	0.861	0.735	0.714	0.601
d.f.	18.83	75.88	8.60	69.01
Except when comparing means with the same level(s) of				
Storage	0.833		0.556	
d.f.	64		12	
Height		0.833		
d.f.		64		
SWHW				0.589
d.f.				64

Table	Storage SWHW	Height SWHW	Season Storage Height	Season Storage SWHW
rep.	24	24	4	8
s.e.d.	0.733	0.581	1.536	1.210
d.f.	'9.64	24.10	66.51	49.34
Except when comparing means with the same level(s) of				
Storage	0.721		1.470	1.202
d.f.	16		75.88	69.01
Height		0.721		
d.f.		16		
Season.Storage			1.470	1.202
d.f.			75.88	69.01
Storage.Height			1.666	
d.f.			64	
Storage.SWHW				1.178
d.f.				64

Table	Season Height SWHW	Storage Height SWHW	Season Storage Height SWHW
rep.	8	6	2
s.e.d.	1.123	1.245	2.291
d.f.	88.08	24.55	88.41
Except when comparing means with the same level(s) of			
Storage		1.161	2.247

```
 d.f.                              24.10        88.08
 Height               1.202
 d.f.                 69.01
 Season.Storage                                 2.247
 d.f.                                           88.08
 Season.Height        1.202
 d.f.                 69.01
 Storage.Height                     1.441       2.404
 d.f.                                  16       69.01
 Storage.SWHW                       1.161       2.247
 d.f.                               24.10       88.08
 Height.SWHW          1.178
 d.f.                    64
 Season.Storage.Height                          2.404

 d.f.                                           69.01
 Season.Storage.SWHW                            2.247
 d.f.                                           88.08
 Storage.Height.SWHW                            2.356
 d.f.                                              64

*** Least significant differences of means (5% level) ***

Table                    Season      Storage       Height         SWHW
rep.                         64           48           48           96
d.f.                         64            3           12           16
l.s.d.                    0.832        1.678        0.606        0.764

Table                    Season       Season      Storage       Season
                        Storage       Height       Height         SWHW
rep.                         16           16           12           32
l.s.d.                    1.802        1.463        1.627        1.199
d.f.                      18.83        75.88         8.60        69.01
Except when comparing means with the same level(s) of
 Storage                  1.664                     1.212
 d.f.                        64                        12
 Height                                1.664
 d.f.                                     64
 SWHW                                                            1.177
 d.f.                                                               64

Table                   Storage       Height       Season       Season
                           SWHW         SWHW      Storage      Storage
                                                   Height         SWHW
rep.                         24           24            4            8
l.s.d.                    1.642        1.198        3.067        2.430
d.f.                       9.64        24.10        66.51        49.34
Except when comparing means with the same level(s) of
 Storage                  1.528                     2.927        2.398
 d.f.                        16                     75.88        69.01
 Height                                1.528
 d.f.                                     16
 Season.Storage                                     2.927        2.398
 d.f.                                               75.88        69.01
 Storage.Height                                     3.328
 d.f.                                                  64
 Storage.SWHW                                                    2.353
 d.f.                                                               64

Table                    Season      Storage       Season
                         Height       Height      Storage
                           SWHW         SWHW       Height
                                                     SWHW
rep.                          8            6            2
l.s.d.                    2.233        2.566        4.553
d.f.                      88.08        24.55        88.41
```

Except when comparing means with the same level(s) of

Storage		2.396	4.465
d.f.		24.10	88.08
Height	2.398		
d.f.	69.01		
Season.Storage			4.465
d.f.			88.08
Season.Height	2.398		
d.f.	69.01		
Storage.Height		3.056	4.795
d.f.		16	69.01
Storage.SWHW		2.396	4.465
d.f.		24.10	88.08
Height.SWHW	2.353		
d.f.	64		
Season.Storage.Height			4.795
d.f.			69.01
Season.Storage.SWHW			4.465
d.f.			88.08
Storage.Height.SWHW			4.707
d.f.			64

```
 133   DAPLOT fitted,normal,halfnormal,histogram

 134   "Split-Split-Plot Design."
 135   BLOCK Block/Tree/Posit/Type
 136   TREATMENTS Season*Storage*Height*SWHW
 137   COVARIATE "No Covariate"
 138   ANOVA [PRINT=aovtable,information,means; FACT=32; FPROB=yes; PSE=diff,lsd;
LSDLEVEL=5]\
 139    a
```

139...

***** Analysis of variance *****

Variate: a

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	1	0.1271	0.1271	0.23	
Block.Tree stratum					
Storage	3	14.4076	4.8025	8.80	0.054
Residual	3	1.6379	0.5460	2.69	
Block.Tree.Posit stratum					
Height	3	3.4281	1.1427	5.63	0.012
Storage.Height	9	1.3307	0.1479	0.73	0.678
Residual	12	2.4378	0.2031	0.29	
Block.Tree.Posit.Type stratum					
SWHW	1	9.2138	9.2138	13.37	0.002
Storage.SWHW	3	0.7013	0.2338	0.34	0.797
Height.SWHW	3	0.4147	0.1382	0.20	0.894
Storage.Height.SWHW	9	6.1043	0.6783	0.98	0.488
Residual	16	11.0260	0.6891	0.87	
Block.Tree.Posit.Type.*Units* stratum					
Season	2	1.0658	0.5329	0.67	0.514
Season.Storage	6	28.4891	4.7482	5.99	<.001
Season.Height	6	0.5976	0.0996	0.13	0.993
Season.SWHW	2	2.5508	1.2754	1.61	0.208
Season.Storage.Height	18	9.3136	0.5174	0.65	0.843
Season.Storage.SWHW	6	2.0410	0.3402	0.43	0.857
Season.Height.SWHW	6	1.1131	0.1855	0.23	0.964
Season.Storage.Height.SWHW	18	8.7358	0.4853	0.61	0.877
Residual	64	50.7479	0.7929		
Total	191	155.4840			

***** Tables of means *****

Variate: a

Grand mean 9.272

Season	Feb	May	Nov
	9.324	9.166	9.325

Storage	0 weeks	1 week	2 weeks	4 weeks
	9.060	9.005	9.698	9.324

Height	45.00	131.00	217.00	303.00
	9.452	9.242	9.313	9.081

SWHW	HW	SW
	9.491	9.053

Season	Storage	0 weeks	1 week	2 weeks	4 weeks
Feb		9.616	9.350	9.006	9.323
May		8.314	8.851	10.199	9.302
Nov		9.249	8.815	9.888	9.348

Season	Height	45.00	131.00	217.00	303.00
Feb		9.562	9.239	9.359	9.136
May		9.273	9.109	9.304	8.979
Nov		9.520	9.378	9.275	9.128

Storage	Height	45.00	131.00	217.00	303.00
0 weeks		9.179	9.075	9.166	8.818
1 week		9.169	8.916	9.074	8.863
2 weeks		9.740	9.709	9.767	9.575
4 weeks		9.718	9.267	9.245	9.068

Season	SWHW	HW	SW
Feb		9.583	9.065
May		9.229	9.104
Nov		9.661	8.989

Storage	SWHW	HW	SW
0 weeks		9.174	8.945
1 week		9.265	8.745
2 weeks		9.949	9.446
4 weeks		9.575	9.074

Height	SWHW	HW	SW
45.00		9.634	9.270
131.00		9.413	9.070
217.00		9.547	9.079
303.00		9.369	8.793

Season	Storage	Height	45.00	131.00	217.00	303.00
Feb	0 weeks		9.928	9.610	9.635	9.292
	1 week		9.243	9.163	9.583	9.413
	2 weeks		9.255	8.780	9.093	8.898
	4 weeks		9.823	9.403	9.128	8.940
May	0 weeks		7.837	8.665	8.498	8.255
	1 week		9.205	8.595	8.903	8.703
	2 weeks		9.983	10.078	10.698	10.038
	4 weeks		10.068	9.098	9.120	8.923
Nov	0 weeks		9.773	8.950	9.365	8.908
	1 week		9.060	8.990	8.737	8.473
	2 weeks		9.983	10.270	9.510	9.790
	4 weeks		9.265	9.300	9.488	9.340

Season	Storage	SWHW	HW	SW
Feb	0 weeks		9.951	9.281
	1 week		9.596	9.104
	2 weeks		9.256	8.756
	4 weeks		9.526	9.120
May	0 weeks		8.262	8.365
	1 week		9.039	8.664
	2 weeks		10.318	10.080
	4 weeks		9.296	9.308
Nov	0 weeks		9.309	9.189
	1 week		9.161	8.469
	2 weeks		10.274	9.503
	4 weeks		9.901	8.795

Season	Height	SWHW	HW	SW
Feb	45.00		9.756	9.368
	131.00		9.579	8.899
	217.00		9.633	9.086
	303.00		9.362	8.909
May	45.00		9.356	9.190
	131.00		9.046	9.171
	217.00		9.443	9.166
	303.00		9.070	8.889

Nov	45.00		9.789	9.251
	131.00		9.615	9.140
	217.00		9.566	8.984
	303.00		9.675	8.580

Storage	Height	SWHW	HW	SW
0 weeks	45.00		9.407	8.952
	131.00		9.215	8.935
	217.00		9.312	9.020
	303.00		8.763	8.873
1 week	45.00		9.545	8.793
	131.00		8.912	8.920
	217.00		9.475	8.673
	303.00		9.130	8.595
2 weeks	45.00		9.805	9.675
	131.00		10.197	9.222
	217.00		10.003	9.530
	303.00		9.792	9.358
4 weeks	45.00		9.778	9.658
	131.00		9.330	9.203
	217.00		9.398	9.092
	303.00		9.792	8.343

Season	Storage	Height	SWHW	HW	SW
Feb	0 weeks	45.00		10.675	9.180
		131.00		10.435	8.785
		217.00		9.975	9.295
		303.00		8.720	9.865
	1 week	45.00		9.415	9.070
		131.00		9.180	9.145
		217.00		9.975	9.190
		303.00		9.815	9.010
	2 weeks	45.00		9.040	9.470
		131.00		9.495	8.065
		217.00		9.390	8.795
		303.00		9.100	8.695
	4 weeks	45.00		9.895	9.750
		131.00		9.205	9.600
		217.00		9.190	9.065
		303.00		9.815	8.065
May	0 weeks	45.00		7.680	7.995
		131.00		8.585	8.745
		217.00		8.630	8.365
		303.00		8.155	8.355
	1 week	45.00		9.420	8.990
		131.00		8.380	8.810
		217.00		9.435	8.370
		303.00		8.920	8.485
	2 weeks	45.00		10.310	9.655
		131.00		10.350	9.805
		217.00		10.640	10.755
		303.00		9.970	10.105
	4 weeks	45.00		10.015	10.120
		131.00		8.870	9.325
		217.00		9.065	9.175
		303.00		9.235	8.610
Nov	0 weeks	45.00		9.865	9.680
		131.00		8.625	9.275
		217.00		9.330	9.400
		303.00		9.415	8.400
	1 week	45.00		9.800	8.320
		131.00		9.175	8.805
		217.00		9.015	8.460
		303.00		8.655	8.290
	2 weeks	45.00		10.065	9.900
		131.00		10.745	9.795

	217.00	9.980	9.040
	303.00	10.305	9.275
4 weeks	45.00	9.425	9.105
	131.00	9.915	8.685
	217.00	9.940	9.035
	303.00	10.325	8.355

*** Standard errors of differences of means ***

Table	Season	Storage	Height	SWHW
rep.	64	48	48	96
d.f.	64	3	12	16
s.e.d.	0.1574	0.1508	0.0920	0.1198

Table	Season Storage	Season Height	Storage Height	Season SWHW
rep.	16	16	12	32
s.e.d.	0.2980	0.2730	0.2194	0.2177
d.f.	32.78	74.89	10.24	75.03
Except when comparing means with the same level(s) of				
Storage	0.3148		0.1840	
d.f.	64		12	
Height		0.3148		
d.f.		64		
SWHW				0.2226
d.f.				64

Table	Storage SWHW	Height SWHW	Season Storage Height	Season Storage SWHW
rep.	24	24	4	8
s.e.d.	0.2269	0.1928	0.5590	0.4285
d.f.	11.82	24.04	74.08	67.85
Except when comparing means with the same level(s) of				
Storage	0.2396		0.5460	0.4354
d.f.	16		74.89	75.03
Height		0.2396		
d.f.		16		
Season.Storage			0.5460	0.4354
d.f.			74.89	75.03
Storage.Height			0.6297	
d.f.			64	
Storage.SWHW				0.4452
d.f.				64

Table	Season Height SWHW	Storage Height SWHW	Season Storage Height SWHW
rep.	8	6	2
s.e.d.	0.4115	0.4037	0.8316
d.f.	86.79	25.29	88.30
Except when comparing means with the same level(s) of			
Storage		0.3856	0.8230
d.f.		24.04	86.79
Height	0.4354		
d.f.	75.03		
Season.Storage			0.8230
d.f.			86.79
Season.Height	0.4354		
d.f.	75.03		
Storage.Height		0.4793	0.8708
d.f.		16	75.03
Storage.SWHW		0.3856	0.8230
d.f.		24.04	86.79

```
 Height.SWHW         0.4452
 d.f.                    64
 Season.Storage.Height                            0.8708
 d.f.                                              75.03
 Season.Storage.SWHW                              0.8230
 d.f.                                              86.79
 Storage.Height.SWHW                              0.8905
 d.f.                                                 64

*** Least significant differences of means (5% level) ***

Table                  Season     Storage      Height        SWHW
rep.                       64          48          48          96
d.f.                       64           3          12          16

l.s.d.                 0.3145      0.4800      0.2005      0.2540

Table                  Season      Season     Storage      Season
                      Storage      Height      Height        SWHW
rep.                       16          16          12          32
l.s.d.                 0.6065      0.5439      0.4873      0.4337
d.f.                    32.78       74.89       10.24       75.03
Except when comparing means with the same level(s) of
 Storage               0.6289                  0.4009
 d.f.                      64                      12
 Height                            0.6289
 d.f.                                  64
 SWHW                                                      0.4447
 d.f.                                                          64

Table                 Storage      Height      Season      Season
                         SWHW        SWHW     Storage     Storage
                                               Height        SWHW
rep.                       24          24           4           8
l.s.d.                 0.4951      0.3979      1.1138      0.8551
d.f.                    11.82       24.04       74.08       67.85
Except when comparing means with the same level(s) of
 Storage               0.5080                  1.0878      0.8674
 d.f.                      16                   74.89       75.03
 Height                            0.5080
 d.f.                                  16
 Season.Storage                                1.0878      0.8674
 d.f.                                           74.89       75.03
 Storage.Height                                1.2579
 d.f.                                              64
 Storage.SWHW                                              0.8895
 d.f.                                                          64

Table                  Season     Storage      Season
                       Height      Height     Storage
                         SWHW        SWHW      Height
                                                 SWHW
rep.                        8           6           2
l.s.d.                 0.8179      0.8310      1.6526
d.f.                    86.79       25.29       88.30
Except when comparing means with the same level(s) of
 Storage                           0.7958      1.6359
 d.f.                               24.04       86.79
 Height                0.8674
 d.f.                   75.03
 Season.Storage                                1.6359
 d.f.                                           86.79
 Season.Height         0.8674
 d.f.                   75.03
 Storage.Height                    1.0160      1.7348
 d.f.                                  16       75.03
```

Storage.SWHW		0.7958	1.6359
d.f.		24.04	86.79
Height.SWHW	0.8895		
d.f.	64		
Season.Storage.Height			1.7348
d.f.			75.03
Season.Storage.SWHW			1.6359
d.f.			86.79
Storage.Height.SWHW			1.7789
d.f.			64

```
140  DAPLOT fitted,normal,halfnormal,histogram
```

Appendix 5 – Description of ANOVA

A two-way Analysis of Variance (ANOVA) was used to determine the significance of fixed factors on two response variables as shown below:

	Fixed Factors						
Response Variables	Temperature (T)	Heating time (H)	Ring Location (R)	T x H	T x R	H x R	T x H x R
L* - lightness	***	***	***	NS	***	NS	NS
a* - redness	***	***	***	***	***	NS	NS

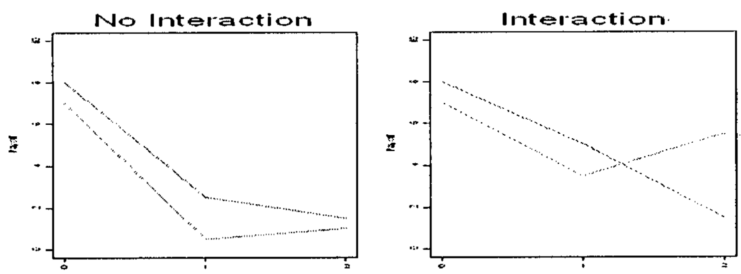
*** = p < 0.001; NS = not significant (p > 0.05)

The ANOVA was used to compare the means of individual factors or interactions between factors and determine if the difference in means is significant using an F-test. An F-test is expressed in terms of the F-ratio:

F = (variation in the group means)/(expected variation in the group means)

If no effects occurred (the null hypothesis Ho is correct), one would expect F to be close to 1. However, a high F value indicates that one of the fixed factors (or interactions between fixed factors) affected the response variable(s) significantly (reject Ho).

Interaction effects are a result of the interaction between two fixed factors. In the example below, Class 1 scores better than Class 2 when students study alone. However, Class 2 outscores Class 1 when studying in groups. Therefore, the effect of class number is dependant on the type of studying. This relationship can be noticed graphically. If data lines cross, the effect of a factor on a variable is influence by another fixed factor.



(StataCorp 2005)