Moisture content in radiata pine wood: Implications for wood quality and water-stress response

by

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Abstract

This thesis studied the influence of moisture content on the dynamic estimation of stiffness in wood of *Pinus radiata* D. Don. This is an important non-destructive measure for estimation of stiffness in standing trees, logs and lumber. Moisture content affects both acoustic velocity and density in the fundamental equation of dynamic MOE (DMOE = V^2?, where V = acoustic velocity and ? = density). Investigation included measurements with boards in the laboratory considering moisture contents below and above FSP as well as temperatures below and above 0°C. This also included field measurements of trees in contrasting climate sites and over different seasons including a long drought. Methods for measuring green density and moisture content and the patterns of variation of these parameters were also investigated. A secondary component of this thesis explored the wood quality and some mechanisms of tree response to water stress in two contrasting sites in terms or rainfall and water deficits in a region of Australia.

The large increases in DMOE for frozen wood above the FSP (4.5 to 6 GPa) will limit the use of DMOE for grading logs in regions with freezing winters. Results from the experiment remeasuring young trees and the upper range of moisture content and temperatures above 0°C from the experiment with boards showed small to moderate variation in DMOE (0.1 to 1 GPa) which calls for further investigation on analytical procedures for adjustment of DMOE. Such procedures should consider that variations in acoustic velocity and density with changes in moisture content are not proportional and that there are counteracting effects between the two parameters. It remains to be investigated whether the typical variation (under normal climate conditions) in sapwood green density observed in our experiments has some implications for the use of DMOE. On the other hand, it is anticipated that the large differences along the stem and among stands in whole-section green density may bias DMOE measurements in logs for resource assessment. This also needs to be investigated. A comparison between acoustic velocity alone and DMOE for resource assessment under different scenarios is recommended.

The study in two contrasting climate sites (high-altitude vs. warm-dry) in the Hume region of Forests NSW, Australia, including young (10-11 years) and mature trees (34-36 years) of radiata pine showed distinctive short and long-term responses of trees to cope with the water-limiting environment. In response to long-term water deficits the warm-dry site developed heartwood and thus reduced sapwood earlier and at faster rates than the high-altitude site. The onset of heartwood formation seemed to be triggered by some site threshold for water use as broadly indicated by the sapwood area/ha. The latter was consistently lower for the warm-dry site across the different stands. The warm-dry site also showed increased short-term responses to water stress and these were interpreted as seasonal mechanisms of the trees to cope with the limiting environment. The trees compensated for the lower available moisture and higher transpiration rates by lowering their saturation and disrupting water conduction at some points (cavitation). The inverse trends of cavitation spots and cavitation bands with height in the stem suggested the trees have different strategies to sacrifice conducting xylem depending on the position on the stem. Finally, it is suggested that saturation tended to fall to critical 'safe' levels as a result of water stress and this varied depending on age, site, and position in the stem.

Significant decreases in DMOE and basic density were observed for the warm-dry site and were attributed to lower proportions of latewood due to lower rainfall for that site during the period of latewood formation. These showed no obvious association with any of the long-term water-stress traits (sapwood percentage and number of heartwood rings).

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TABLE OF CONTENTS

1. Introduction

2. A study on the simultaneous effects of moisture content and temperature on acoustic velocity and dynamic MOE of radiata pine sapwood boards

2.2 METHODS

2.3 RESULTS

2.4 DISCUSSION

3. Destructive methods to determine the green density and moisture condition in live trees

3.2 METHODS

3.3 RESULTS

4. Predicting the green density and moisture condition of live trees from increment cores

4.2 METHODS

4.3 RESULTS

5. Influence of age, site, thinning regime, season, and height on green density and moisture condition; and effect of sampling and moisture content method

5.2 METHODS

5.3 RESULTS

5.3.4 Influence of season

5.3.5 Variation along the stem

5.4 DISCUSSION

6. Influence of moisture content and temperature on acoustic velocity and dynamic MOE of standing trees

7. Wood quality and water-stress response on two contrasting sites of the Hume region of Forests NSW

8. Conclusions

CHAPTER 1

INTRODUCTION

1.1 Importance of acoustic methods for resource evaluation

The use of acoustic methods for dynamic estimation of stiffness in standing trees and logs has become a widespread practice in New Zealand and Australia. This is largely in part due to research conducted at the School of Forestry of the University of Canterbury, which has been actively involved in the development of methods and acoustic tools for wood characterization over the last decade. This includes the development of the TreeTap, a time-of-flight tool for acoustic measurement of standing trees and logs, and collaboration with Industrial Research Limited on the development of WoodSpec, a resonance based tool suitable for a range of wood specimens. Research in acoustic methods at Canterbury include Walker and Nakada (1999), Xu *et al.* (1999), Buchanan *et al.* (1999), Tsehaye *et al.* (2000), Albert *et al.* (2002), Lindström *et al.* (2002), Andrews *et al.* (2003), Grabianowski (2003), Hsu (2003), Chauhan (2004), Chauhan and Walker (2006), Grabianowski *et al.* (2006), Dickson *et al.* (2006), Lasserre *et al.* (2007), and Toulmin and Raymond (2007). Acoustic tools have also been used in recent investigations to assess silviculture treatments and/or genetics (Lasserre *et al.* 2004, 2005; Grabianowski *et al.* 2004), wind effects (Bascuñan 2004, Walker *et al.* 2006), and climate and site effects (Watt *et al.* 2006). Published applications in tree breeding include Lindström *et al.* (2002, 2004).

Acoustic tools offer advantages over traditional methods whether destructive or non-destructive for assessing the stiffness of wood. Acoustic tools can distinguish the large variability among trees, so they have proved to be highly useful for segregating logs and screening trees (Buchanan *et al.* 1999, Xu *et al.* 1999, Andrews *et al.* 2003, Chauhan *et al.* 2006). Andrews (2002) attributes the generalized acceptance of the forestry industry to acoustics tools to the better understanding of the fundamental principles of acoustics in wood and the improved electronic technology. Another factor for the increased use of acoustics for sorting of logs and measurements in standing trees has been the advent of robust, cheap, field based acoustic tools (Chauhan *et al.* 2006). Time-of-flight (TOF) tools commonly used in New Zealand include Fakopp, TreeTap, IML hammer, and Director ST300, but no single tool has been accepted as the industry standard (Harris and Andrews 1999, Cown 2004). In contrast, the Director HM200 –a resonance based tool– is the most used hand-held instrument for acoustic measurements in felled stems and logs (Parker and Searles 2004, Cown 2004).

Other technologies include in-line grading systems at sawmills for logs or lumber. Examples of these technologies for log grading are the Logman and Stickman, of Carter Holt Harvey (Parker and Searles 2004). Technologies for lumber include the A-Grader of Scion (Gaunt 2004) and the Surveyor LDS200 of Carter Holt Harvey (Parker and Searles 2004). These systems calculate dynamic MOE (modulus of elasticity) from resonance acoustic velocity and in-line measurements of green density.

1.2 Importance of moisture content to the dynamic assessment of stiffness in green wood

Sound velocity in long solid rods is defined by the equation

$$V = \sqrt{\frac{E}{r}}$$

where E = modulus of elasticity (Young's modulus) and ? is the density of the material. From this relationship, the fundamental equation for dynamic MOE (DMOE) is commonly defined as follows:

$$DMOE = V^2 r$$

For calculation of DMOE in green wood it is fundamental to consider the variation patterns of acoustic velocity with changes in moisture content above the fibre saturation point (FSP) and the variation patterns of green density. Above FSP, the inverse effect of moisture content on velocity is less obvious than that below FSP: some reports have shown strong linear decreases in velocity below the FSP followed by little changes thereafter (Sakai *et al.* 1990), whereas others have shown curvilinear trends above the FSP with decreasing rates as moisture content increases (Gerhards 1975, Sandoz 1993, Ilic 2001). Research on the influence of moisture content on acoustic velocity and DMOE above the FSP is still limited (Bucur 2006, X. Wang and Ross 2002).

Green wood is a composite material containing: 1) cell wall or wood substance, 2) bound water contained in the cell walls, 3) free water partially or completely filling the cell cavities or lumens, and 4) vapour/air or void space in the empty cell cavity spaces. In green wood, components (1) and (3) occupy the larger proportion of space; also, component (2) varies proportionally with (1), whereas (4) varies independently of (1) and (2) but is related to (3). The proportion of cell wall or wood substance can be roughly interpreted as the basic density of wood. This is of relevance as it is well known that basic density varies depending on tree age, position in the stem (both with height and radial position), and is influenced by site, silviculture and genetics. It is easy to visualise that, other things being equal, green density would vary in direct proportion with changes in basic density; however, that is rarely the case because the amount of air in green wood varies independently of basic density and in turn it affects the amount of free water. Another factor to consider is the different intrinsic densities of each of the components; according to Walker (2006 p. 74-76), the densities of wood substance, free water, and bound water are 1500 kg/m^3, 1000 kg/m^3, and 1018 kg/m^3, respectively.

A further parameter to consider is the proportions of sapwood/heartwood in the stem. In live trees, sapwood would be expected to be close to saturation with large water contents and therefore high green densities. In contrast, heartwood has a low saturation with moisture contents just above the FSP and large proportions of air, thus low green densities. In New Zealand, the respective heartwood-sapwood volumetric proportions change with age from 0-100% at age 10 to 30-70% at age 40 (Cown 1999). Cown *et al.* (1991) reported higher absolute heartwood contents and more rapid heartwood formation for sites in the North Island compared to sites in the South Island. Cown (1991) stated that the green densities of the sapwood and heartwood in the tree are virtually constant at 1100 kg/m^3 and 600 kg/m^3, respectively. In New Zealand, green density is normally not quantified for the assessment of dynamic MOE in trees or logs; instead a nominal value of 1000 kg/m^3 is assumed (Xu *et al.* 1999, Chauhan *et al.* 2006). These assumptions are probably related to the apparent (published) low variation in this parameter in New Zealand.

Finally, Gerhards (1975), Sobue (1993), S. Y. Wang and Chuang (2000), S. Y. Wang *et al.* (2002), and S. Y. Wang *et al.* (2003) have observed significant increases in DMOE above the FSP which contradict the general assumption that mechanical properties remain constant above the FSP (Gerhards 1982). Gerhards (1975), Ross and Pellerin (1991), and Sobue (1993) have noted the need for correcting the DMOE obtained in wood above the FSP. X. Wang and Ross (2002) stated that the fundamental wave equation was developed for idealized elastic materials and has been proved to be adequate for dry wood materials; however, the effectiveness of its application for accurately predicting stiffness at high moisture contents remains to be fully validated. Further, X. Wang and Ross (2002) concluded that research is still needed on methods for the adjustment of DMOE for wood above the FSP to accurately predict the stiffness of green wood using stress wave methods.

1.3. Radiata pine plantations in water-limiting environments

Radiata pine is the main softwood plantation species in Australia comprising about 49% of the total plantation area (Bureau of Rural Sciences 2005). Radiata pine plantations extend across New South Wales (NSW), Victoria, and the south east border of South Australia with Victoria (‘The Green Triangle’). Many of the locations are characterised by relatively low rainfall and water deficits that increase during the dry season (Boardman 1988, Boomsma and Hunter 1990, Nambiar 1995, Boardman and McGuire 1997). Radiata pine plantations in Australia are established in lower-rainfall environments than those of New Zealand: almost half the plantations in Australia receive less than 900 mm/year, and 90% receive less than 1200 mm/year, whereas for example in the North Island of New Zealand, the mean annual rainfall is 1450 mm (range 870 – 2300 mm) (Boomsma and Hunter 1990). Comparison of monthly volume increment vs. rainfall distribution between a site in the south east of South Australia and a generalized example from New Zealand showed the marked impact of soil moisture deficits on productivity in South Australia (Boardman 1988).

Nambiar (1995) shows that even within Australia there are considerable differences in climatic and environmental conditions for plantations of radiata pine which lead to large differences in productivity: annual rainfall ranges from 500 to 1800 mm and the mean annual increment (MAI) in volume at age 11-15 varies from ca. 15 to 30 m^3/ha/year. Nambiar highlighted the very high yield obtained in South Australia (annual rainfall 660-800 mm mostly in winter, evaporation 1300-1600 mm mostly in summer) compared to other wetter regions in Victoria and NSW. From our own perspective, there are two main aspects to highlight from all this information: 1) radiata pine has indeed a natural capability to provide commercial yields even in limiting environments, 2) it is perhaps more important to identify what mechanisms allow the species to achieve this. One example is given by Boardman and McGuire (1997) for South Australia where commercially viable stands have been grown in areas with mean annual rainfall superior to 580 mm; however during drought years (defined as first-decile rainfall) this amount is reduced by half. In periods of drought, the dense foliage of *P. radiata* has been measured to intercept up to 42% of annual rainfall in closed-canopy stands under 22 years old with only 170 mm reaching the ground. In contrast, also in South Australia, Nambiar (1995) within a similar rainfall zone and on what might appear to be ‘common’ soil type, a twofold difference in MAI occurs despite all stands receive the same advanced management practices. Neither evapotranspiration based on water use, nor models describing depletion and recharge of water in upper layers of soil have been sufficient to explain the very large difference in MAI within a common rainfall zone.

As indicated below, a secondary component of this thesis consisted of exploring some mechanisms of tree response to drought and water stress in two contrasting sites in a region in NSW with large seasonal variations in rainfall and water deficits.

1.4 Scope of this thesis

The aim of this thesis was primarily to study the influence of moisture content on the dynamic estimation of stiffness in wood. A significant part of the thesis dealt with developing methodologies for the accurate destructive and non-destructive evaluation of the green density and moisture content in live trees as well as investigating their patterns of variation. Both variables are relevant to the use of acoustics for resource characterization and may contribute significantly to the state of knowledge given the lack of published research on the subject. Secondly, this thesis uses saturation percentage, cavitation signs, sapwood percentage, number of heartwood rings, and presence of dry sapwood to assess the response of trees growing in contrasting sites to water stress. An attempt is made to find relationships between these variables and wood quality.

Chapter 2 addresses the simultaneous influence of moisture content and temperature on acoustic velocity and DMOE of sapwood boards including moistures below and above the FSP at temperatures below and above the freezing point. The relevance of this study is twofold: 1) there is a gap in the literature on the variation of acoustic velocity and DMOE in green wood over the whole range of practical temperatures, i.e. from well below the freezing point to high temperatures; 2) literature is scarce on the simultaneous effects of moisture content and temperature on acoustic speed and DMOE and the underlying mechanisms that explain their influence. Additionally, methodologies for adjusting DMOE values in the green wood are explored. Applications of this investigation include referencing acoustic speed measured over a range of moisture contents and temperatures to that measured at controlled or base conditions; acoustic grading and/or dynamic estimation of stiffness in standing trees, logs, or fresh beams. Special applications include logs that have partially dried or frozen, and trees measured at considerable different temperatures and moisture conditions due to season and/or climate.

Chapter 3 presents the development of destructive methodologies to correctly determine the green density and moisture condition in live trees. To date there is no established methodology for measuring green density or moisture content of standing trees, although common approaches include disks, bole sections, and whole logs. The main aims were to test the influence of sample thickness and cutting methods on the accuracy of the results; experiments included sapwood from young and mature trees, and heartwood from mature trees. The concept of components of green wood is introduced in this Chapter and is used in the interpretation of results and to understand fundamental differences between methods.

Chapter 4 presents the development of non-destructive methods for predicting the green density and moisture condition of live trees. Similar to the lack of standard destructive procedures for measuring green density and moisture content, non-destructive methods have not been developed for this purpose. Increment cores are the most common non-destructive method for wood quality properties; however, their use for green density and moisture content has not been carefully analysed. Experiments in this Chapter included material from different ages and seasons so sound inferences could be made. The objective of one of the experiments with young material was to make a closer examination of the possible causes of the lower values and discrepancy of increment cores with respect to destructive samples. This included 5 and 12 mm manual increment cores. Subsequently, procedures were developed to overcome the fundamental drawbacks of the revised method and the revised method was validated against destructive samples. The efficacy of 12 mm cores for predicting green density, saturation, sapwood content, and the number of heartwood rings was tested using material of mature trees both at breast-height and whole-tree levels. Comparison of predictions using one side versus the two sides of cambium-to-cambium cores was also undertaken.

Chapter 5 addresses the patterns of variation of green density and moisture condition of radiata pine as influenced by age, site, thinning regime, height, and season. This investigation was prompted by the lack of systematic information in the literature on these traits. Such knowledge is necessary for resource evaluation using dynamic estimation of stiffness for standing trees and logs. A series of paired stands of mature trees in contrasting sites and different thinning regimes and a stand of young trees were measured destructively according to procedures developed in Chapter 3. The study included assessments over two successive seasons. Another component of the study was to compare three different measures to assess the moisture condition in live trees: moisture content expressed as the percentage of the ovendry weight, water content expressed volumetric percentage, and saturation percentage. Finally, the bias introduced by sampling different trees (as in the case of destructive sampling) for determining season effects was analyzed.

Chapter 6 addresses the influence of moisture content and temperature on acoustic velocity and dynamic MOE of standing trees. A particular problem of relevance for resource characterisation is the estimation of dynamic stiffness in standing trees at significantly different temperatures and moisture conditions caused by seasonal differences, and/or climate. As highlighted in Chapter 2, there is currently a lack of research on the influence of moisture content and temperature on acoustic velocity and DMOE of green wood; in particular, there are no published reports for live trees. Procedures included four successive non-destructive remeasurements of young trees in two contrasting sites over a period of 17 months covering three climate seasons. An additional part of the study was to validate the methodologies for adjustment of DMOE used in Chapter 2 with boards.

Chapter 7 addresses two issues (wood quality and water stress) rarely analysed together in the literature, but that are of importance for those regions where severe dry seasons and extended droughts are found as in the case of the Hume region of Forests NSW, Australia (FNSW). This research was prompted by prominent signs of drought and of lower wood quality of trees from the warm-dry site used in the experiments of Chapters 4 – 6. These aspects were not discussed in those Chapters because they were outside their scope. Research on the wood quality of this resource, the response of the trees to water-stress, or even the relationships between the two aspects is still very limited. Thus the aims of this chapter were to compare the wood quality, water-stress response, and any relationship between these two aspects in two contrasting sites in terms of climate for both mature and young trees. The study considered three types of traits: 1) wood quality (DMOE and basic density); 2) long-term water-stress response (sapwood percentage, number of heartwood rings, and dry sapwood presence); and 3) short-term water-stress response (sapwood saturation percentage and cavitation signs). Diameter at breast height was also considered as an indicator or growth. This investigation uses material and data from experiments in Chapters 5 and 6. The results obtained provide an insight into the phenomena and suggest further research.

CHAPTER 2

A study on the simultaneous effects of moisture content and temperature on acoustic velocity and dynamic MOE of radiata pine sapwood boards

2.1 INTRODUCTION

The simultaneous effects of moisture content and temperature on acoustic velocity and dynamic MOE (DMOE) of wood have not been fully addressed. Reports in the literature include James (1961), Sellevold *et al.* (1975), Sandoz (1993), Kang and Booker (2002) and investigations undertaken in Europe (mostly unpublished) discussed by Kollman and Coté (1968) and Bucur (2006). In particular there is a lack of information on the variation of acoustic velocity and DMOE in the range of moisture above the fibre saturation point (FSP) for temperatures well below and above the freezing point (0°C). This deficiency includes investigations with static tests; for example the only report on the influence of low temperatures on parallel-to-grain MOE of green wood is that of Comben (1964); furthermore, there is no published information on the effect of high temperatures on the static MOE of green wood.

Interest in ultrasonic stress grading in wood highlighted the importance of referencing acoustic speed measured over a range of moisture contents and temperatures to that measured at controlled or base conditions (Sandoz 1993). Referencing acoustic measurements to a constant moisture content and temperature is important for acoustic grading of standing trees, logs, or fresh beams. Bucur (2006) noted that the scientific literature is scarce on the dynamic nondestructive characterization of wood material operating in hostile environmental conditions, at elevated or low temperatures. Other applications in resource characterization using acoustic methods include assessment of logs which have partially dried, frozen or the combination of the two situations. Another example is the estimation of dynamic stiffness in standing trees at considerable different temperatures and moisture conditions (e.g. due to season and/or climate).

A number of authors have observed the need for adjusting the DMOE calculated for wood above the FSP. For example, Gerhards (1975) concluded that the variation in DMOE above FSP was driven mainly by moisture content and that DMOE should be corrected for moisture contents beyond 50%. Ross and Pellerin (1991) reanalyzing the data of Gerhards concluded that the sharp increase in DMOE above the FSP was related to changes in density. According to the results of Gerhards (1975) and his own work, Sobue (1993) concluded that above the FSP, DMOE increases as a result of the increased density as moisture content increases. Information is still limited on making moisture corrections to DMOE to accurately predict MOE of wood at different moisture conditions, especially above the FSP (X. Wang and Ross 2002).

Sobue (1993) developed the theory of ‘mobility of free water’ to solve the dilemma of estimating the DMOE for wood above FSP. This explains on one hand, the effects of free water on acoustic propagation; and on the other hand, the correction of density for calculation of DMOE. The author defined the mobility of free water (k) as the ratio of the weight of free water, which vibrates in the same phase as wood substance, to the weight of total free water. This is discussed further in Section 2.3.2. A number of authors have validated the procedures of Sobue (1993) for correcting density above FSP and hence DMOE, including S. Y. Wang and Chuang (2000), S. Y. Wang *et al.* (2002), and S. Y. Wang *et al.* (2003).

The objectives of this study were:

1) Investigate the patterns of variation of acoustic velocity and DMOE as influenced by the simultaneous effects of moisture content and temperature considering moisture levels below and above FSP and temperatures below and above the freezing point.

2) Model the influences of moisture content and temperature on acoustic velocity and DMOE.
3) Explore the methods of Sobue (1993) for correction of DMOE above FSP.
4) Explain the mechanisms that drive the variation of acoustic velocity and DMOE as influenced by changes in moisture content and temperature.

2.2. METHODS

36 boards of radiata pine sapwood with nominal dimensions 80 mm x 55 mm x 1200 mm from freshly sawn logs from the Canterbury region were used in this study. Two 75 mm long blocks were cut from the ends of the boards for preliminary work, giving boards 1050 long mm for the actual experiment. The experiment considered four preliminary moisture levels: two below fibre saturation point (FSP) and two above FSP; and seven nominal temperatures: three below freezing (-2, -20, and -70°C) and four above freezing (4, 20, 40, and 60°C). The boards were weighed and acoustic velocity measured in the fresh state in order to sort them into two groups of 18 boards each according to graphical dispersion of velocity versus weight. The aim was to include in each group the full range of velocity and weight, the latter as a surrogate of density.

2.2.1 Moisture and temperature conditioning

The general procedure consisted of conditioning the two groups of boards to one of the four nominal moisture contents and then testing sequentially at every temperature level. These combinations of moisture and temperature were called sequences or stages. Boards of group 1 started from the fresh (green) condition and moved progressively to drier conditions, whereas boards of group 2 were first dried and then gradually saturated (Table 2-1).

Before the actual moisture conditioning, preliminary work was done to determine expected or target weights of the boards at the different nominal moisture contents. In first place, the blocks cut from the ends of the boards were green weight measured and ovendried at 103°C in order to estimate their initial moisture content using formula (1) below. Moisture contents of the two blocks per board were averaged. From the initial moisture contents of the blocks (MC_{blocks}) and the fresh weights (GW_B) of the boards, formula (1) was solved to estimate an approximate ovendry weight for the boards ($EODW_B$) with formula (2) below.

$$MC_{ODW}(\%) = \frac{GW - ODW}{ODW} \times 100 \tag{1}$$

$$EODW_B = \frac{GW_B}{\left[\frac{MC_{blocks}}{100} + 1\right]} \tag{2}$$

Using the expected ovendry weights of the boards ($EODW_B$) and solving formula (1) for GW it was possible to estimate the expected weights of the boards (EW_B) at the different nominal moisture contents ($MC_{nominal}$) as follows:

$$EW_B = EODW_B \times \left[\frac{MC_{nominal}}{100} + 1\right] \tag{3}$$

Measurements for group 1 started from the fresh condition, in which the boards were assumed to be close to saturation. Conditioning for partial saturation and near FSP was done by kiln using a mild schedule 63/57°C (dry bulb/wet bulb). The reason for this was to avoid distortion and drying damage to the boards. It also allowed conditioning at the same time for the nominal temperature of 60°C. Thereafter, the boards were conditioned to well below FSP using a schedule of 65/55°C. The heaviest boards were used to monitor weight changes daily, yet it was difficult to reach target weights for every board. This was due on one hand, to the variation in air flow in the kiln; and on the other hand, to the natural variation of drying rates between boards caused by differences in permeability.

For group 2 the moisture conditioning process started by drying the boards to well below FSP. A very mild schedule was used, namely 25/20°C for days 1-2, 30/25°C for days 3-5, 30/20°C for days 6-7, and finally 24 hours in a controlled environment room at 20°C, RH 65%. In the next moisture stage the boards were taken to near FSP using the kiln to induce moisture uptake. A schedule of 61/59°C was applied for some hours until the approximate target weights of selected boards were reached. Conditioning for partial and full saturation was done according to the full-cell method using a preservation cylinder (Figure 2-1). This included initial vacuum followed by water flooding and pressure, and final vacuum. The process was repeated until the approximate target weights of some boards were met. Thereafter, the remaining water on the surface of the boards was left to drain for some time.

The boards were thoroughly wrapped with cling-wrap film at every stage of moisture to prevent moisture changes. The boards remained wrapped through the process of conditioning and measurements at the different temperature levels. At the end of every moisture round, the wrapping was removed and the boards reweighed.

Figure 2-1. Kiln used for temperature conditioning and for some moisture levels (left); and preservation cylinder for saturation (right)

Conditioning the boards to temperatures below freezing was carried out using three different freezers: two at of the School of Forestry and one freezer located in Biological Sciences used for storage of Antarctic samples (Figure 2-2). The freezers were set to -3, -20 and -80°C, respectively. For temperatures of -3 and -20°C, boards were conditioned for at least 48 hours, whereas for -80°C boards were left for 72 hours. These time periods were determined by preliminary tests in which the changes of temperature on the surface of the boards were monitored over time. The actual final temperatures achieved by the boards differed slightly from the target temperatures stated above. Results presented below are reported based on average actual temperatures.

Conditioning to the nominal temperature of 4°C was done in a cool room, and conditioning to 20°C was conducted in a controlled environment room (20°C, RH 65%). In both cases the boards were conditioned for a minimum period of 24 hours as indicated by preliminary tests in which the changes of temperature on the surface of the boards were monitored over time. For conditioning to 40° and 60°C the kiln provided a high humidity environment which impeded excessive moisture loss during the process. It was also important to avoid any moisture change so schedules with a very low bulb depression were used. Schedules used for temperatures 40° and 60°C were 39/41°C and 59/61°C, respectively. The period utilised to heat the boards to these temperatures was about 10 hours, which was a compromise between the ideal time length and avoiding the risk of excessive alterations in moisture content.

Figure 2-2. Freezers used for conditioning to -71°(left) and -20°(right), boards are tightly wrapped with cling film

For practical reasons, the sequence of temperature conditioning differed slightly between moisture levels, and also between groups of boards (Table 2-1). Moreover, in order to avoid physical damage to the boards, it was necessary to provide a rest period between temperatures below and above freezing (or *vice versa*). This consisted of at least 48 hours in the controlled environment room (20°C, RH 65%).

Table 2-1. Sequence of conditioning for nominal moisture contents and temperatures for each group of boards

Boards group	Target MC	Nominal temperature (°C)						
		-70	-20	-2	4	20	40	60
One	Fresh (start)	Start	→					End
	partial saturation	End					←	Start
	near FSP	End					←	Start
	well below FSP	End					←	Start
Two	well below FSP	Start	→					End
	near FSP	End					←	Start
	partial saturation	End					←	Start
	Full saturation (end)			←	Start	From -72	→	End

The actual temperatures were measured on the surface of the boards using a thermocouple. In the first sequences of conditioning only a few boards were measured according to their position within the pile: on the top, bottom, sides and in the middle. In the second half of the experiment all the boards were temperature measured for every conditioning sequence. In all cases, differences in temperature among boards were small.

2.2.2 Determination of actual moisture content, saturation and density of boards

After all the stages of moisture content and temperature, the boards were oven dried at 103°C for several days until they achieved constant weights. Oven dry weights of the boards were then recorded. Next, the boards were resaturated following the procedure described in section 2.2.1., which was repeated two times in order to ensure maximum saturation. Once the process was completed, saturated weight and volume of boards were measured, the later by water displacement.

The basic density (BD) of the boards was then calculated using the common definition: BD (kg/m^3) = ODW / SV, where ODW = ovendry weight and SV = saturated volume. This calculation was conducted only once for each board. Actual moisture contents for each of the boards throughout the experiment were then calculated using formula (4) below, where AW was the actual weight of the board at every stage of the experiment.

$$MC_{ODW}(\%) = \frac{AW - ODW}{ODW} \times 100 \tag{4}$$

Next, the saturation percentage was determined. This was defined as the percentage of space occupied by free water in the cell lumens. This measure of moisture is particularly useful for green wood as it is related to the amount of water above the fibre saturation point (free water). Contrary to the moisture content expressed as the percentage of ovendry weight (MC_{ODW}), saturation percentage is based on volume relations rather than weight, and has a maximum of 100%. Similar to the actual moisture contents, the saturation percentage of the boards was calculated for each of the experimental sequences. The calculation required first the determination of the components of green wood, from which formulas were developed and discussed in Chapter 3, Section 3.2.1. These are listed as follows,

$$\text{Wood substance } \% = \frac{BD}{r_{wood}} \times 100 \tag{5}$$

$$B\ water\ \% = \frac{BD}{r_{Bwater}} \times 30\% \tag{6}$$

$$F\ water\ \% = \frac{BD}{r_{Fwater}} \times (MC_{ODW}\,\% - 30\%) \tag{7}$$

$$Air\ \% = 100 - (wood \text{ substance } \% + B\ water\ \% + F\ water\ \%) \tag{8}$$

Where BD and MC_{ODW} have been already defined; $?_{wood}$ = density of wood substance (1500 kg/m^3); Bwater = bound water, $?_{Bwater}$ = density of bound water (1018 kg/m^3); Fwater = free water, $?_{Fwater}$ = density of free water (1000 kg/m^3). Once these calculations are completed the determination of saturation percentage is straight forward,

$$Saturation\,\% = \frac{Fwater\%}{(Fwater\% + Air\,\%)} \times 100 \tag{9}$$

The density of the boards in kg/m^3 at every sequence of the experiment was determined by adding the amounts of mass for wood substance, bound water, and free water contained per unit volume of resaturated wood. The first term is equivalent to the basic density (BD) and is a constant for each board. The second and third terms were obtained by multiplying the volumetric percentages (equations 6 and 7) of bound water and free water by their respective densities. In the case of moisture contents lower than 30%, the density of the boards only considered the amounts of mass of wood substance and bound water. The latter was calculated also with equation (6) but using the current value of MC_{ODW} rather than 30%.

2.2.3. Acoustic velocity and dynamic MOE

Acoustic velocity was determined using WoodSpec: a resonance based instrument developed by Industrial Research Limited (IRL), New Zealand. This tool has been intensively used and validated by the School of Forestry (Grabianowsky 2003, Hsu 2003, and Chauhan 2004). WoodSpec has a maximum inbuilt frequency of 15 kHz but in this experiment the maximum frequencies obtained were about 2.5 kHz.

WoodSpec was operated in the impulse mode (trigger) where a stress wave was launched in the sample by hitting one end of the board with a small bearing ball. The signal was detected by a microphone on the other end of the board. The system requires maximum velocities and starting frequencies to be assigned *a priori*. For example, for saturated wood and high temperatures the maximum velocity was typically set at 3 km/s and a frequency of 800 Hz. In contrast, for dry wood and the lowest temperatures maximum velocity was typically set at 5 km/s and a frequency of 1500 Hz. As mentioned above, the boards remained cling-wrapped throughout the different stages of the experiment in order to avoid changes in moisture. As a consequence, it was necessary to open a window in the film at each end of the board (Figure 2-3), one for hitting the board and the other for capturing the signal with the microphone.

The full set up for the acoustic measurement is shown in Figure 2-3. Samples were supported at two points with special frames covered with bubble wrap at the contact areas. The two points corresponded roughly to the theoretical nodal points of the second harmonic, where node location = sample length / 4 = 26 cm, as measured from the ends of the board. Nodes have the property of being areas "undetected" by the multiple resonance reverberations, hence are appropriate points to support the samples.

Figure 2-3. Full set up for acoustic measurements with WoodSpec (left); and windows opened at the end of the boards for launching and detection of acoustic signal (right)

WoodSpec determines acoustic velocity from the frequency of reverberations of the stress wave within the sample. Frequency is related inversely to the time it takes the acoustic wave to travel along the sample length (IRL 2001). Acoustic velocity was then calculated automatically by WoodSpec with the equation:

$$\mathrm{V} = f\ \ 2\,l \times 0.001 \tag{10}$$

Where V is acoustic velocity in km/s, f is the first fundamental frequency (Hz) and l is length of sample (m). Depending on the acoustic properties and conditions of the sample the system may provide the second, third and higher order frequencies. The number of harmonic frequencies (overtones) obtained was generally two and sometimes three. There was no consistent effect of moisture content, temperature or combination of both in the number of frequencies obtained. Nevertheless, it was observed that saturated wood at high temperatures sometimes yielded poor spectra and it was hard to get good readings (even of the fundamental frequency).

The speed of sound (V) in long solid rods is defined by the equation (8) below, where MOE is the modulus of elasticity and ? is density. From this basic relationship the so-called dynamic MOE (DMOE) is commonly defined by equation (9).

$$V = \sqrt{\frac{MOE}{r}} \qquad (11)$$

$$\text{DMOE} = V^2\ ? \qquad (12)$$

2.2.4 Data analysis

As mentioned, the two groups of 18 boards were conditioned in inverse order with regard to moisture levels. Once the actual moisture contents were calculated it was noted that the average values differed significantly between the groups of boards. Additionally it was observed that for the nominal level of moisture close to FSP some of the individual data points showed values greater than 30%. These were arranged as a separate moisture level above the FSP. As a result, there were in the end five different moisture levels for both groups of boards: two below FSP and three above FSP. Because the paired moisture levels differed between groups, these were considered separately giving as a result ten different moisture levels.

Average values of acoustic velocity, density and DMOE were obtained for every combination of moisture level and temperature within each group of boards. Thus there were in the end 70 mean values = 2 groups of boards x 5 moisture levels x 7 temperature levels. This method of grouping the data was used by James (1961) for studying the influence of temperature and moisture content on vibrational properties of wood; the author suggested this approach to reduce the noise caused by the differences between specimens for each sequence of the experiment. In the present study, mean values were used for graphical analysis and for modelling the effects of temperature and moisture content.

The effects of temperature and moisture content on acoustic velocity were examined for the four ‘quadrants’ defined by the moisture content at FSP (30%) and the temperature at freezing point (0°C). This included analysis of trends and determination of variation in rates of velocity and DMOE in relation to both moisture content and temperature. Modelling the simultaneous effects of temperature and moisture content on acoustic velocity was done separately for temperatures below and above the freezing point. The variation in DMOE for wood above FSP was further investigated for selected temperatures above 0°C; including relationships between acoustic velocity and saturation percentage above the FSP. The method developed by Sobue (1993) for adjusting DMOE above FSP was used with saturation percentage as a surrogate for the mobility of free water ratio.

2.3 RESULTS

2.3.1 Influence of moisture content and temperature on acoustic velocity and dynamic MOE

There was an overall inverse effect of moisture content and temperature on acoustic velocity which differed considerably below and above FSP as shown in Figure 2-4. Below the FSP changes in acoustic velocity were approximately linear across the whole range of moisture contents and temperatures (Figure 2-4). In contrast, for wood above the FSP there was a considerable interaction effect between moisture content and temperature giving as a result differences in velocity patterns (Figure 2-4). Moreover, results indicated that the simultaneous effects of temperature and moisture content on acoustic velocity differed among the four ‘quadrants’ defined by the moisture content at FSP (30%) and the temperature at freezing point (0°C). These are discussed below. Note that for ease of comparison, in the results discussed below the rates of decrease of velocity have been calculated in m/sec (velocity is expressed in km/s in the Tables and Figures).

Below the FSP two main temperature effects were observed: first, there was an inverse effect of temperature on acoustic velocity; second, this effect differed slightly for temperatures below and above freezing (Figure 2-4a). The rate of decrease of velocity with increasing temperature in the frozen wood varied from 5.1 m/s per °C for wood at 17% moisture content to 6.1 m/s per °C for wood at 25% moisture content. Above 0°C, the rate of decrease of velocity with increasing temperature varied from 5 m/s per °C for wood at 17% moisture content to 1.9 m/s per °C for wood at 23% moisture content.

Above the FSP the effects of temperature on acoustic velocity followed the same trends as those observed in wood below FSP, but changes were slightly greater (Figure 2-4a). Namely the rate of decrease in velocity with increasing temperature in the frozen wood varied from 6.3 m/s per °C for wood at 38% moisture content to 8.4 m/s per °C for wood at 159% moisture content. Above 0°C, the rate of decrease of velocity with increasing temperature varied from 3.6 m/s per °C for wood at 38% moisture content to 2.9 m/s per °C for wood at 159% moisture content. The most noticeable effect of temperature on wood above FSP occurred at the freezing point where there was a significant discontinuity in velocity (Figure 2-4a). The drop in acoustic velocity at the freezing point was 133 m/s for wood just above the FSP, 456 m/s for partially saturated wood, and 710 m/s for nearly saturated material (Table 2-2). Although not noticeable, wood below the FSP also showed a small drop in velocity at the freezing point; this ranged from 24 to 51 m/s and increased with increasing moisture content.

Table 2-2. Mean values of acoustic velocity (km/s) with moisture content as percentage of ovendry weight (MC_{ODW}), and saturation percentage (Sat) for temperatures below and above 0°C

MC_{ODW} (%) Mean	(SD)†	Sat (%)	Board group	Avg. obs.	Temperature (°C) -72	-20	-3	4	20	39	58
17	(3.1)	0.0	1	18	4.58	4.31	4.23	4.20	4.12	4.01	3.92
21	(1.8)	0.0	2	18	4.48	4.20	4.10	4.07	4.01	3.89	3.79
23	(2.5)	0.0	2	15	4.39	4.16	4.02	4.02	3.94	3.83	3.65
25	(3.9)	0.0	1	15	4.36	4.05	3.94	3.89	3.83	3.73	3.78
38	(4.8)	4.8	2	3	4.23	3.95	3.79	3.70	3.63	3.52	3.51
46	(15.9)	9.7	1	3	4.34	3.96	3.75	3.58	3.51	3.42	3.49
78	(9.1)	35.6	2	18	4.12	3.81	3.59	3.19	3.13	3.07	2.97
89	(18.3)	41.0	1	17	4.16	3.81	3.66	3.15	3.10	3.03	3.02
149	(26.0)	81.9	1	17	3.90	3.67	3.51	2.79	2.76	2.66	2.55
159	(23.5)	92.2	2	18	3.91	3.63	3.33	2.63	2.57	2.53	2.47

† Standard deviation for MC_{ODW} considering individual data from all temperatures

Below the FSP, the effects of moisture content on acoustic velocity were as follows: first, velocity decreased rapidly with increasing moisture content; second, this effect differed little between temperatures below and above freezing as indicated by the similar slopes of the best-fit lines (Figure 2-4b). The rate of decrease in velocity with increasing moisture content for frozen wood varied from 26.3 m/s per unit moisture for wood at -72°C to 34.6 m/s per unit moisture for wood at -3°C. Above 0°C, the rate of decrease of velocity with increasing moisture content varied from 36.4 m/s per unit moisture for wood at 4°C to 16.8 m/s per unit moisture for wood at 58°C.

Above the FSP, the effects of moisture content on acoustic velocity were markedly different to those observed in the hygroscopic range (Figure 2-4b). These are summarized as follows: firstly, trends of velocity differed greatly between frozen and unfrozen wood as indicated by the differences in the slopes of the predicting lines; secondly, acoustic velocity of frozen wood showed gradual decreases as moisture increased above the FSP; thirdly, acoustic velocity of unfrozen wood decreased at changing rates as moisture content increased. The rate of decrease in velocity with increasing moisture content for frozen wood varied from 2.5 to 3.1 m/s per unit moisture. On the other hand, the average rate of decrease in velocity with increasing moisture content for unfrozen wood was as follows: 11.2 m/s per unit moisture between wood at low saturation and wood at medium saturation, and 6.6 m/s per unit moisture between wood at medium saturation and wood close to full saturation.

Models to predict acoustic velocity as a function of temperature and moisture content were developed and fitted separately for temperatures below and above freezing because of the large discontinuity at the freezing point for wood above FSP (Figure 2-4a). Furthermore, a separate fit was needed for wood below and above FSP in the case of temperatures below 0°C (Table 2-3). A logarithmic transformation of moisture content was necessary to straighten out the curvilinear trend of velocity with moisture, thus allowing the prediction of linear relationships between acoustic velocity and temperature. Because of the number of moisture levels (ten in total) fitted lines for temperature effects considered paired levels of moisture content (see moisture groupings in Figure 2-4a).

For wood below 0°C, the lines that connect data above and below FSP in Figures 2-4b and 2-5b are just “connecting lines” linking the predicting equations above and below FSP; these “connecting lines” were not the best-fit lines for this range of moisture. Similarly, the lines that appear between -3° and 4°C in Figures 2-4a and 2-5a are just “connecting lines” between predicted values above and below 0°C for each of the paired moisture levels. The situation is different for wood above 0°C in Figures 2-4b and 2-5b where the regression equations covered the whole range of moistures.

Table 2-3. Equations for predicting acoustic velocity (V=km/s) in terms of temperature (T°C) and moisture content as percentage of ovendry weight (MC_{ODW}), all parameters significant at P>0.0001

Temperature range	Moisture range	Equation	n	R^2
Below 0°C	Below FSP	$V = 5.96619 - 0.00558 \times T - 0.62194 \times \log_e(MC_{ODW})$	12	0.99
Below 0°C	Above FSP	$V = 4.75535 - 0.00701 \times T - 0.25736 \times \log_e(MC_{ODW})$	18	0.94
Above 0°C	All	$V = 6.06085 - 0.00407 \times T - 0.65275 \times \log_e(MC_{ODW})$	40	0.99

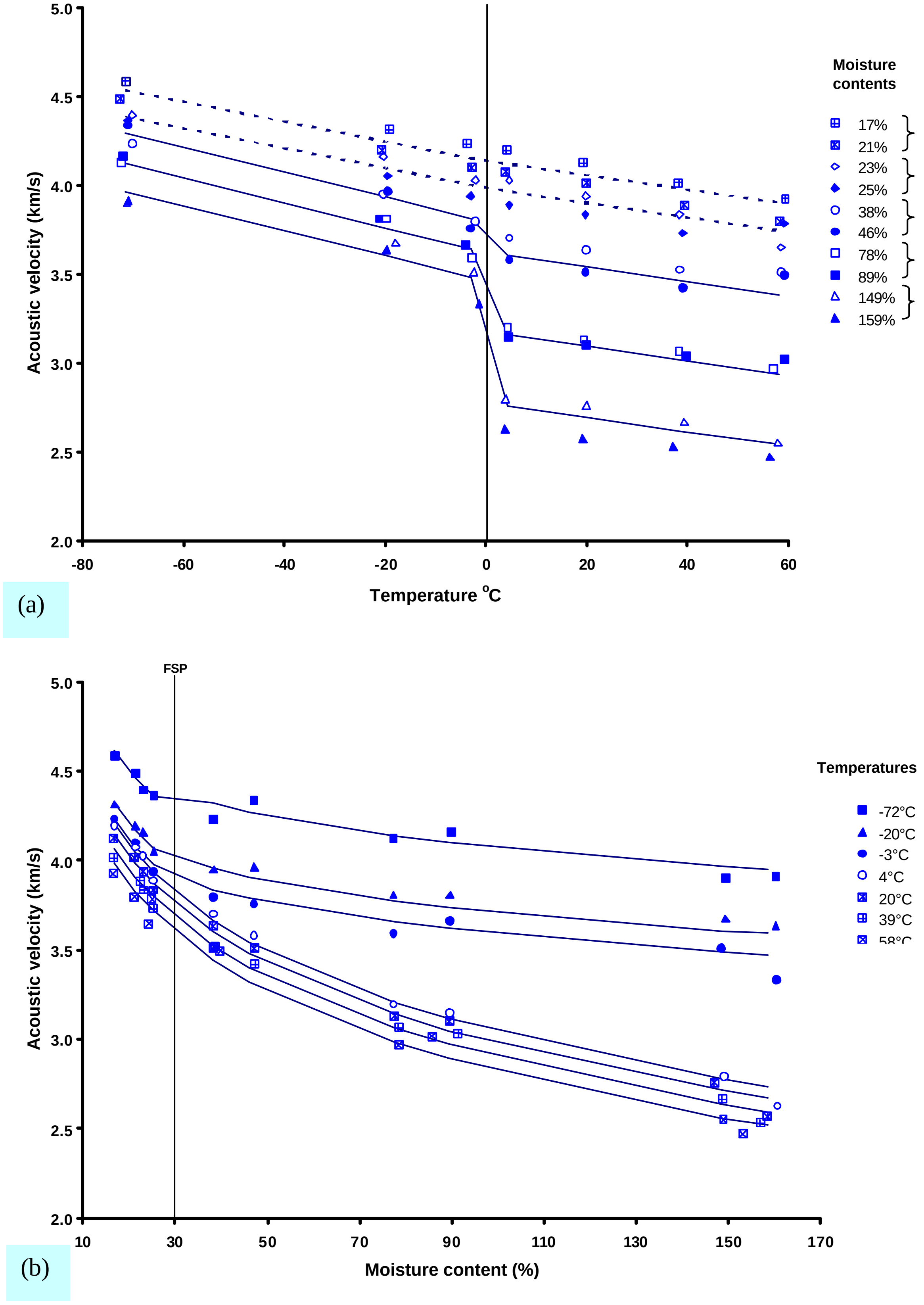

Figure 2-4. Effects of temperature (a) and moisture content (b) on acoustic velocity; points represent mean values and lines represent fitted values. In (a) dotted lines denote moisture contents below FSP and solid lines denote moisture contents above FSP, and each fitted line uses data points from paired sets of moisture contents (pairs indicated in the legend).

Below FSP, the variation patterns of DMOE (Figure 2-5a) with temperature were as follows: first, DMOE decreased with increasing temperature; second, decreasing rates differed slightly between temperatures below and above freezing; third, there was a small discontinuity in DMOE at the freezing point (Figure 2-5a). The average rate of decrease in DMOE with increasing temperature for frozen wood was 25 MPa per °C, whereas for unfrozen wood the average rate of decrease in DMOE with increasing temperature was 19 MPa per °C. For ease of comparison, the rates of decrease of DMOE have been calculated in MPa (note that DMOE is expressed in GPa in the Tables and Figures).

Above FSP, decreasing rates of DMOE with increasing temperature were higher than those below FSP and there was a large discontinuity at freezing point (Figure 2-5a). For frozen wood the average rate of decrease in DMOE with increasing temperature was 57.1 MPa per °C, whereas for unfrozen wood the average rate of decrease in DMOE with increasing temperature was 20.1 MPa per °C. The drop in DMOE at the freezing point was 0.6 GPa for wood just above the FSP, 2.4 GPa for partially saturated wood, and 4.7 GPa for nearly saturated material (Table 2-4).

Table 2-4. Mean values of dynamic MOE (GPa) with moisture content as percentage of ovendry weight (MC_{ODW}), saturation percentage (Sat) and density, for temperatures below and above 0°C

MC_{ODW} (%)	Sat (%)	Density (kg/m^3)	Board group	Avg. obs.	Temperature (°C)						
					-72	-20	-3	4	20	39	58
17	0.0	495	1	18	10.3	9.1	8.7	8.6	8.3	7.9	7.6
21	0.0	520	2	18	10.4	9.1	8.7	8.6	8.3	7.9	7.5
23	0.0	536	2	15	10.3	9.2	8.6	8.6	8.2	7.8	7.1
25	0.0	536	1	15	10.1	8.7	8.2	8.0	7.8	7.4	7.5
38	4.8	545	2	3	9.8	8.5	7.9	7.5	7.2	6.8	6.5
46	9.7	583	1	3	10.9	9.1	8.2	7.4	7.2	6.8	6.0
78	35.6	762	2	18	12.9	10.9	9.7	7.6	7.4	7.1	6.7
89	41.0	788	1	17	13.6	11.4	10.5	7.8	7.5	7.3	7.0
149	81.9	1032	1	17	15.7	14.0	12.7	8.0	7.7	7.3	6.7
159	92.2	1097	2	18	16.9	14.6	12.3	7.6	7.3	7.0	6.5

Below FSP, there was an average decrease of 0.4 GPa in DMOE with increasing moisture content from 17 to 25% across the different temperatures studied (Figure 2-5b and Table 2-4). Above FSP, variation of DMOE with moisture showed two distinct patterns depending on whether temperatures were below or above 0°C. For unfrozen wood there was an average increase of 0.3 GPa in DMOE between wood at low saturation (4.8 and 9.7%, Table 2-4) and wood at the highest saturation (81.9 and 92.2%, Table 2-4). Also for unfrozen wood above FSP, the maximum changes in DMOE across temperatures ranged from 0.5 to 1 GPa (Table 2-4). For frozen wood, increases in DMOE between wood at low saturation and wood at the highest saturation ranged from 4.5 GPa for wood at -3°C to 6 GPa for wood at -72°C.

Results revealed that changes in DMOE with temperature and moisture content were well explained by the counteracting effects of acoustic velocity and density, which was in agreement with the definition of DMOE (DMOE=V^2?). Nevertheless this relationship was not straightforward; some examples are discussed as follows.

There were large differences in DMOE between wood above FSP (green) and wood below FSP (dry) at temperatures below 0°C which contrasted to the relatively small differences observed above 0°C (Figure 2-5a). This can be explained as follows: below 0°C, the acoustic velocity of frozen dry wood was higher than frozen green wood but differences were rather small (Figure 2-4a); in contrast, the density of frozen green wood was much higher than frozen dry wood (Figure 2-6a); as a consequence, the DMOE of frozen green wood was considerably higher (Figure 2-5a). Above 0°C, the acoustic velocity of dry wood was considerably higher than green wood (Figure 2-4a), but in contrast the higher densities of green wood matched the differences in velocity (Figure 2-6a) giving as a result relatively small differences in DMOE (Figure 2-5a). Note that above 0°C the DMOE of dry wood was higher than that of low-saturated wood (38-46% moisture content) (Figure 2-5a). This can be explained by the fact that the higher acoustic velocity of dry wood offset the slightly higher density of low-saturated wood (Figures 2-4a and 2-6a).

For wood below FSP at temperatures below and above freezing the rapid decreases in velocity with increasing moisture content were well offset by the increases in density giving as a result small changes in DMOE (Figures 2-4b, 2-5b, and 2-6b). Above FSP the curvilinear decreases in velocity with increasing moisture content for unfrozen wood were slightly offset by the linear increases in density giving as a consequence small increases in DMOE (Figures 2-4b, 2-5b, and 2-6b). In the case of frozen wood above the FSP the very gradual decreases in velocity with increasing moisture content were overridden by the usual linear increases in density giving as a result considerably increases in DMOE (Figures 2-4b, 2-5b, and 2-6b).

Another example was the higher variation in DMOE for wood above FSP at 58°C (Figure 2-5b). This effect was caused partly by some variable moisture losses while heating the boards to the highest temperature of the experiment as indicated by the trends in density for this temperature level (Figure 2-6b). The other cause was the irregularities in acoustic velocity for wood above FSP at 58°C (Figure 2-4b). This was due to the difficulty in sometimes obtaining acoustic readings for green wood at high temperatures.

Divergences in trends of acoustic velocity and density with moisture content prevented direct modelling of DMOE. As a result, DMOE could only be indirectly predicted in a two-stage procedure. Firstly, acoustic velocity was obtained using equations shown in Table 2-3; the second stage consisted of predicting density in terms of moisture content using the equation below, where MC_{ODW} has been previously defined. Fitted lines of DMOE are shown in Figure 2-5; note that in the case of variation of DMOE with temperature fitted lines considered paired moisture levels (see moisture groupings in Figure 2-5a).

$$\text{Density} = MC_{ODW} \times 4.185\ (\pm\ 0.09) + 419\ (\pm\ 8) \qquad R^2=0.99 \qquad n=70$$

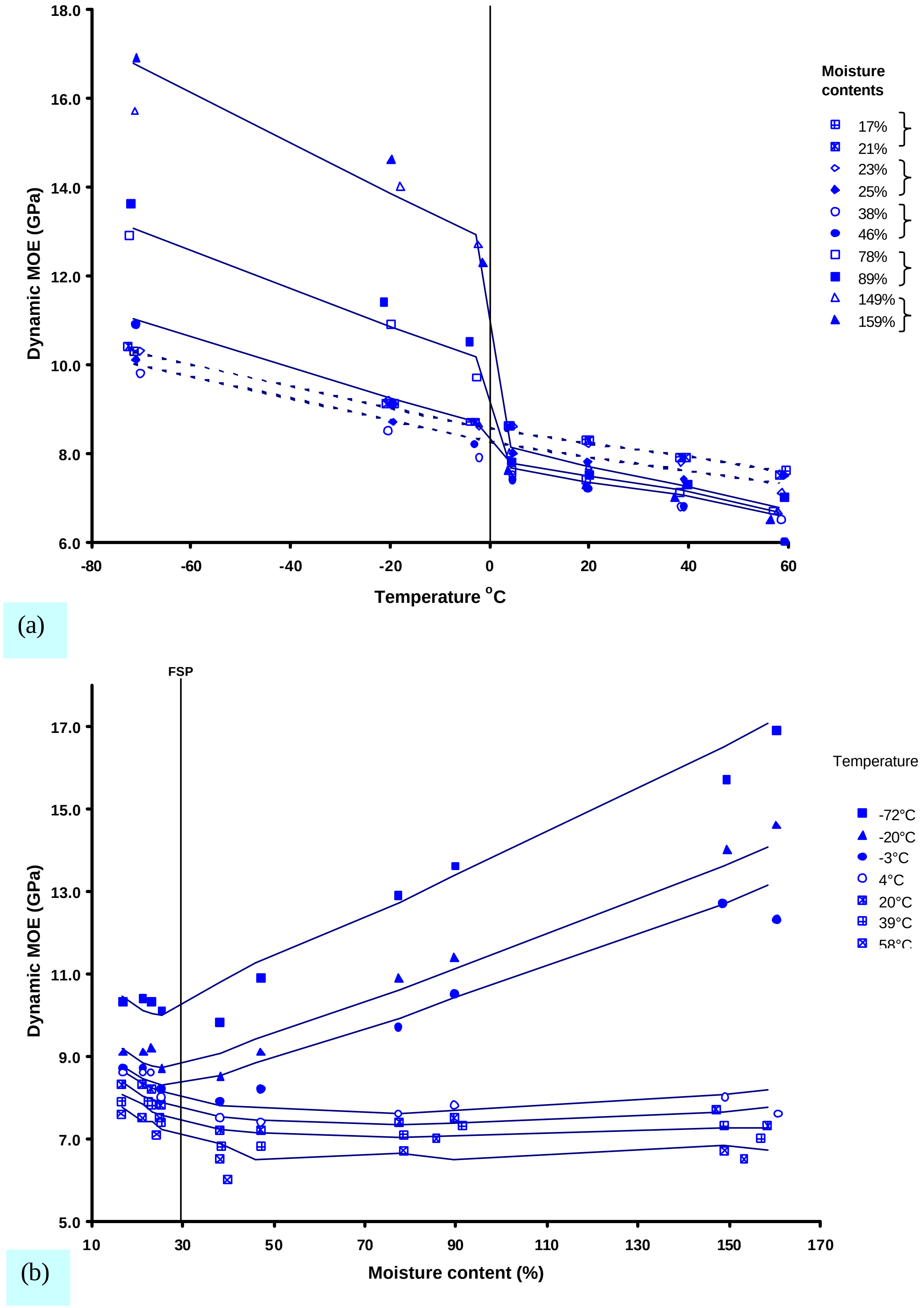

Figure 2-5. Variation of DMOE with temperature (a) and moisture content (b); points represent mean values and lines represent fitted values. In (a) dotted lines denote moisture contents below FSP and solid lines denote moisture contents above FSP, and each fitted line uses data points from paired sets of moisture contents (pairs indicated in the legend).

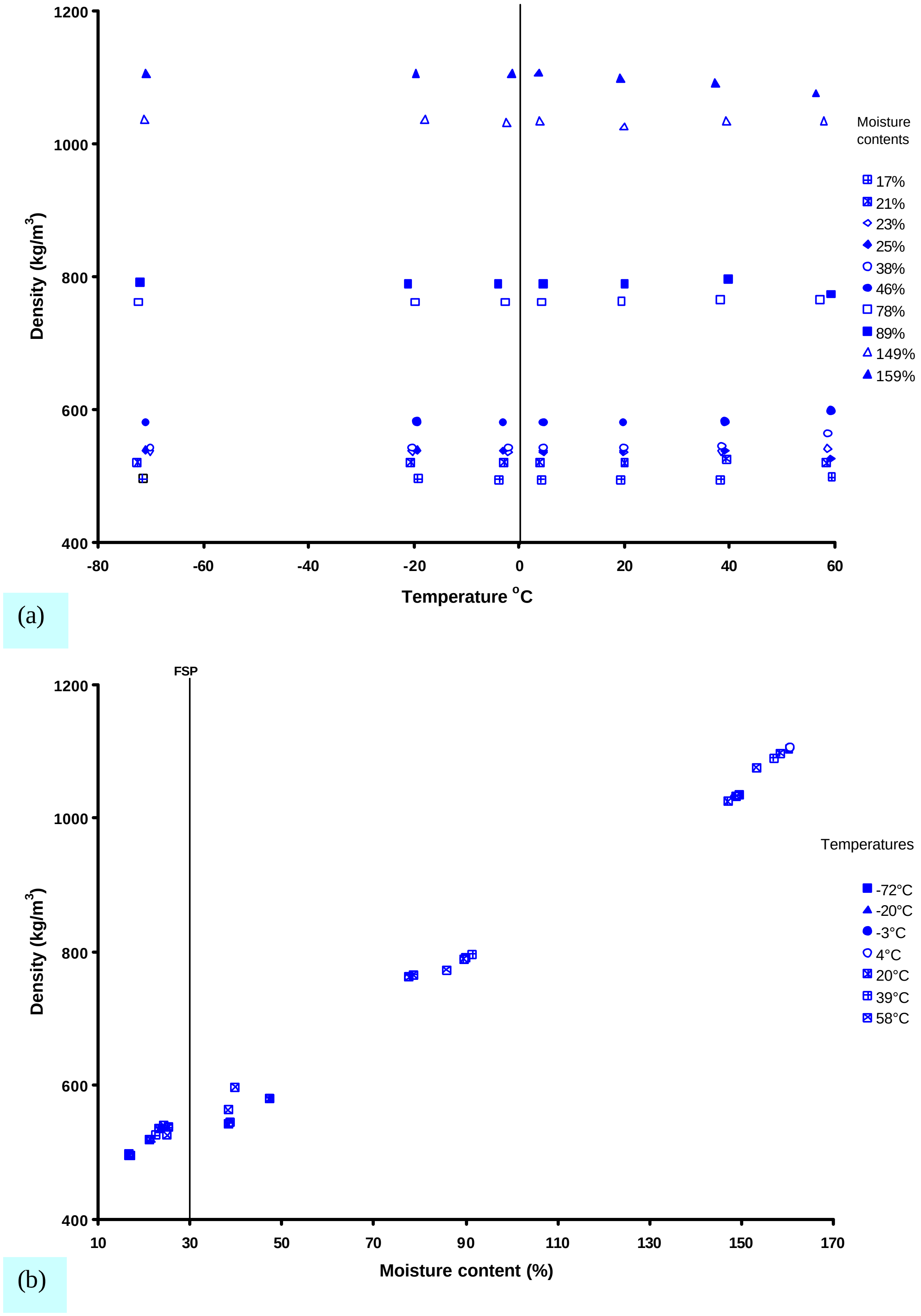

Figure 2-6. Mean values of density across the different stages of temperature and moisture content

2.3.2 Adjustment of DMOE on wood above FSP for selected temperatures above 0°C

The maximum changes in DMOE above FSP for unfrozen wood across temperatures ranged from 0.5 to 1 GPa (Table 2-4). This result contrasted with the significant increments in DMOE above FSP reported by Gerhards (1975), Sobue (1993), S. Y. Wang and Chuang (2000), S. Y. Wang *et al.* (2002), and S. Y. Wang *et al.* (2003). Regardless of the extent, the changes in DMOE above the FSP contradict the general assumption that mechanical properties remain constant above FSP (Gerhards 1982). This was investigated using the data of wood above FSP at three temperatures above freezing (4°, 20°, and 39°C); data at the highest temperature (58°C) was not considered because of the somewhat irregular trend of velocity for wood above FSP at this temperature (Figure 2-4b).

Sobue (1993) developed a correction factor for the estimation of DMOE above the FSP: mobility of free water (k) defined as the ratio of the weight of free water that vibrates in the same phase with wood cell walls to the total weight of free water. When k=0 no free water vibrates in phase with the cell wall substance, while for k=1 all free water vibrates simultaneously with the cell wall substance. A number of authors have validated the procedures of Sobue (1993) for correcting density above FSP and hence DMOE, including S. Y. Wang and Chuang (2000), S. Y. Wang *et al.* (2002), and S. Y. Wang *et al.* (2003). Free water mobility ratios in these reports ranged from 0.58 to 0.78 for ultrasound waves obtained at frequencies from 16 to 200 kHz, whereas for stress waves there was only one value reported, namely 0.60.

It was noted that the concept of the mobility of free water ratio of Sobue (1993) was somehow related to our definition of saturation percentage, in that they both require a determination of the proportion of free water. This idea was explored graphically with the individual data of acoustic velocity and saturation percentage (Figure 2-7). Results indicated a change in slope at 60% saturation for the relationship between acoustic velocity and saturation percentage, suggesting that this is a critical point where the decreases in velocity with saturation seem to diminish. This was further confirmed by correlation analysis between velocity and saturation percentage below and above the critical point for each of the temperatures. Correlation coefficients below 60% saturation ranged from -0.55 to -0.59 (all significant at $P<0.001$), whereas above 60% saturation correlation coefficients varied from -0.36 to -0.40 (all significant at $P<0.05$). In addition, the critical value of saturation was well in agreement with the mobility of free water ratios obtained by Sobue (1993) and subsequent reports (S. Y. Wang and Chuang 2000, S. Y. Wang *et al.* 2002, and S. Y. Wang *et al.* 2003).

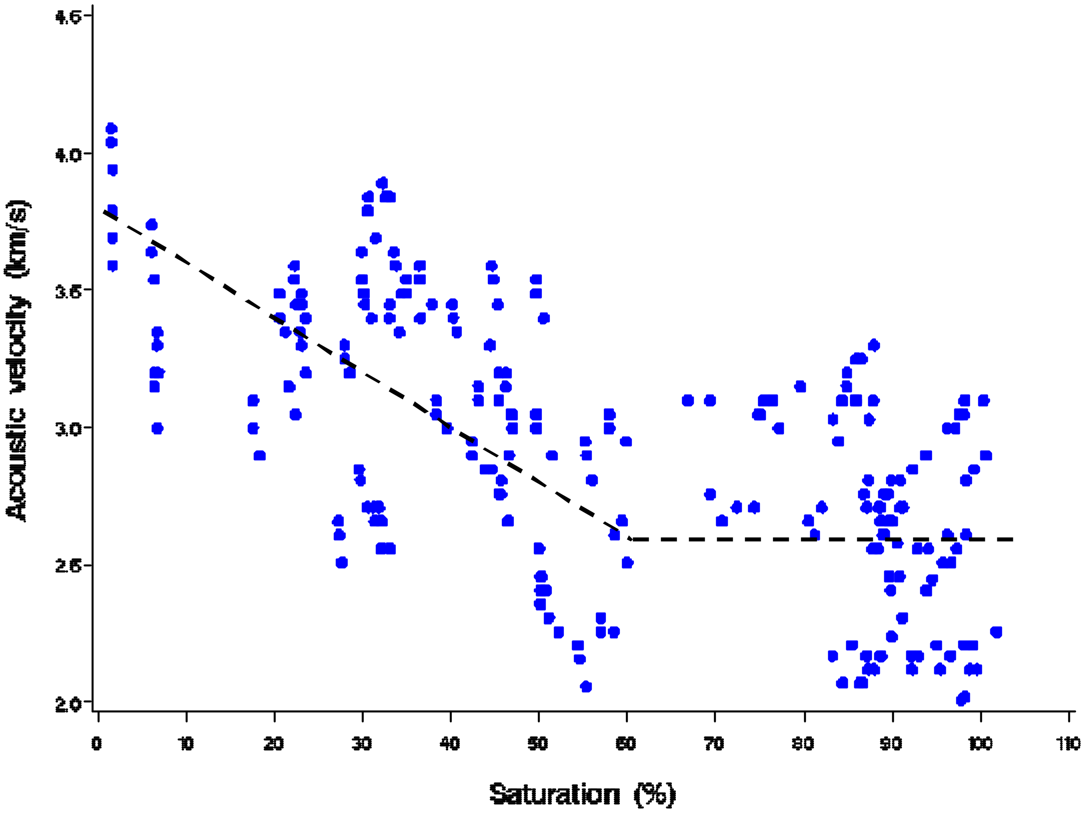

Figure 2-7. Individual observations and approximate trend (dashed line) of acoustic velocity with saturation percentage for wood above FSP (data include temperatures 4, 20, and 39°C), showing the apparent critical point for influence of moisture content on velocity at 60% saturation

The equivalent critical value of moisture content expressed as the percentage of ovendry weight (MC_{ODW}) at which there is a change for the influence of moisture content on velocity was approximately 115%. This was determined by graphical trends and also by checking data with this value of MC_{ODW}. Nevertheless, when MC_{ODW} data is plotted there is not a clear change of slope at 115% in the trend of velocity as with saturation. Note that by definition 30% MC_{ODW} (the fibre saturation point) is equivalent to 0% saturation. Further, MC_{ODW} is a measure of moisture content for the whole range of moisture in wood based on the oven dry weight, whereas saturation percentage is a measure of moisture content in wood above FSP based on volumetric calculations.

The next step consisted of using the 60% saturation of our study as a surrogate for the mobility of free water ratio (k) in the formula of Sobue (1993) to adjust the densities above the FSP and therefore DMOE. This was done using the average values of density at every stage of the experiment for wood above the FSP as recommended by S. Y. Wang and Chuang (2000). The formula to calculate adjusted density is as follows,

$$r_{Adj} = r\left[1 - \frac{(1-k)(MC_{ODW} - FSP)}{(100 + MC_{ODW})}\right] \qquad (13)$$

where ?$_{\text{Adj}}$ is the adjusted density in kg/m^3 for wood above FSP (30%), ? is the actual density, k is the mobility of free water ratio, and MC$_{\text{ODW}}$ was defined in section 2.2.2 above.

Results obtained using k=60/100 were satisfactory for DMOE at low and medium saturation, but not for DMOE of wood close to full saturation, where the adjusted values were too low. Better results were obtained using 60% for wood at low and medium saturation and 75% for wood close to full saturation (Figure 2-8b). This suggested that density and DMOE could perhaps be adjusted using the actual saturation values for the different moisture levels; i.e. using k=saturation percentage/100. Results were rather poor, namely DMOE values for wood at low and medium saturation were too low followed by a sudden increase at wood close to full saturation. According to these results it was concluded that the formula of Sobue (1993), along with the use of two critical saturation values (60% and 75%) as a surrogates for the ratio of mobility of free water (k), gave acceptable results for adjusting DMOE values above the FSP (Figure 2-8b and Table 2-5).

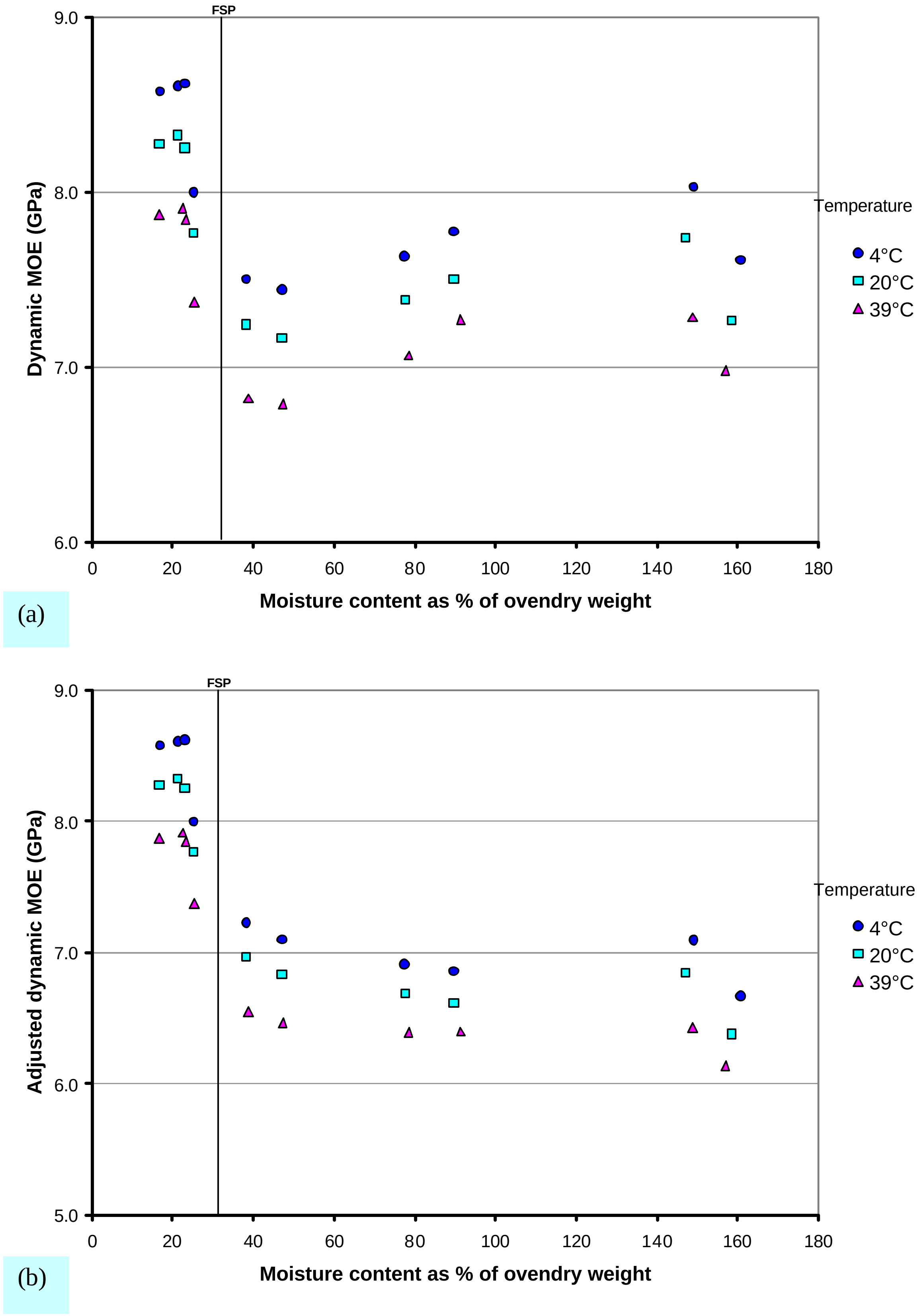

Figure 2-8. (a) Variation in dynamic MOE with moisture content for three selected temperatures above 0°C; (b) adjusted values of DMOE for moisture contents above FSP using two saturation values as surrogates for the ratio of mobility of free water (k) in the formula of Sobue (1993) (60% for wood at low and medium saturation, and 75% for wood at the highest saturation)

2.3.3 Adjustment of DMOE for frozen wood above FSP

The procedures used in the previous section for adjusting density and DMOE above FSP were applied to frozen wood. First, the individual data of acoustic velocity and saturation percentage for frozen wood above FSP was plotted (Figure 2-9). Results suggested a change of slope at 60% saturation although the trend was not as clear-cut as with the data for unfrozen wood in Figure 2-7. Because of the difficultly of establishing an unambiguous point, correlation analysis was not conducted to confirm the change in slope at 60% saturation and results presented below are merely exploratory. The second step consisted of testing 60/100 as a surrogate of k in equation (13) for adjusting density and thus DMOE. Similar to unfrozen wood, better results were obtained using 60% saturation for frozen wood at low and medium saturation and 75% for frozen wood close to full saturation; results are shown in Figure 2-10 and Table 2-5.

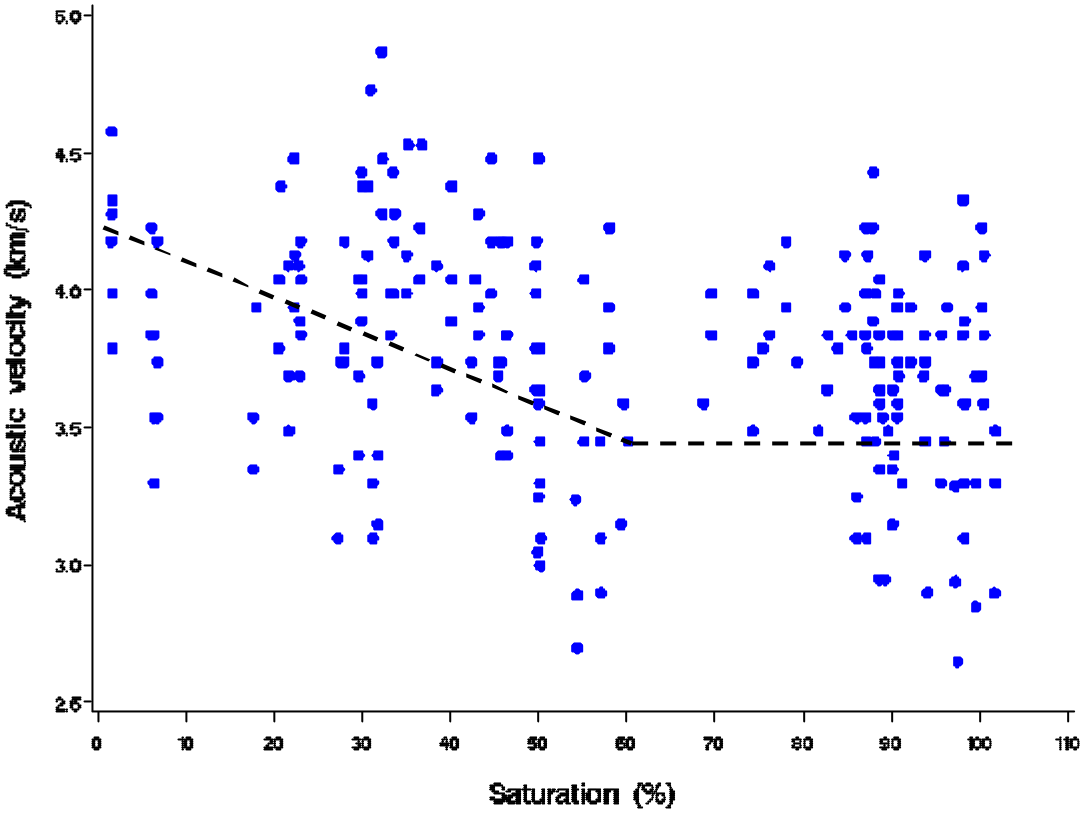

Figure 2-9. Individual observations and approximate trend (dashed line) of acoustic velocity with saturation percentage for frozen wood above FSP (temperatures: -72°, -20°, and -3°C), showing an apparent critical point for influence of moisture content on velocity at 60% saturation

Adjusted DMOE values could not be fully validated because of the insufficient information in the literature on the changes in static MOE for frozen wood at moisture contents below and above FSP. The only related report was that of Comben (1964) in which the author tested the effect of low temperatures on static MOE of ash wood at 12% moisture content and at green condition. From the graphical results in the report of Comben (1964) it was estimated an increase of about 10.8% in modulus of elasticity from 12% moisture content to green condition at a nominal temperature of -73°C. Results in our study for wood at -72°C indicated an increase in DMOE of 29.1% with increasing moisture content from 17% to 83.5%, and an increase in DMOE of 58.3% with increasing moisture content from 17% to 154%. The increases in DMOE after correction for density were significantly reduced (14.6% and 38.8%, correspondingly), yet there was no way to fully assess these results. Additionally, there was uncertainty on using the equation of Sobue (1993) for frozen wood given that the author developed his theory for correcting DMOE above FSP with liquid free water.

Table 2-5. Adjusted DMOE (GPa) for moisture contents above FSP and temperatures below and above 0°C using two saturation values as surrogates for the ratio of mobility of free water (k) in the formula of Sobue (1993) (60% for wood at low and medium saturation, and 75% for wood at the highest saturation)

MC_{ODW} (%)	Sat (%)	Density (kg/m^3)	Temperature (°C)					
			-72	-20	-3	4	20	39
38	4.8	545	9.5	8.3	7.6	7.2	7.0	6.5
46	9.7	583	10.4	8.7	7.8	7.1	6.8	6.5
78	35.6	762	11.6	9.8	8.8	6.9	6.7	6.4
89	41.0	788	12.0	10.0	9.2	6.9	6.6	6.4
149	81.9	1032	13.8	12.3	11.2	7.1	6.8	6.4
159	92.2	1097	14.8	12.8	10.8	6.7	6.4	6.1

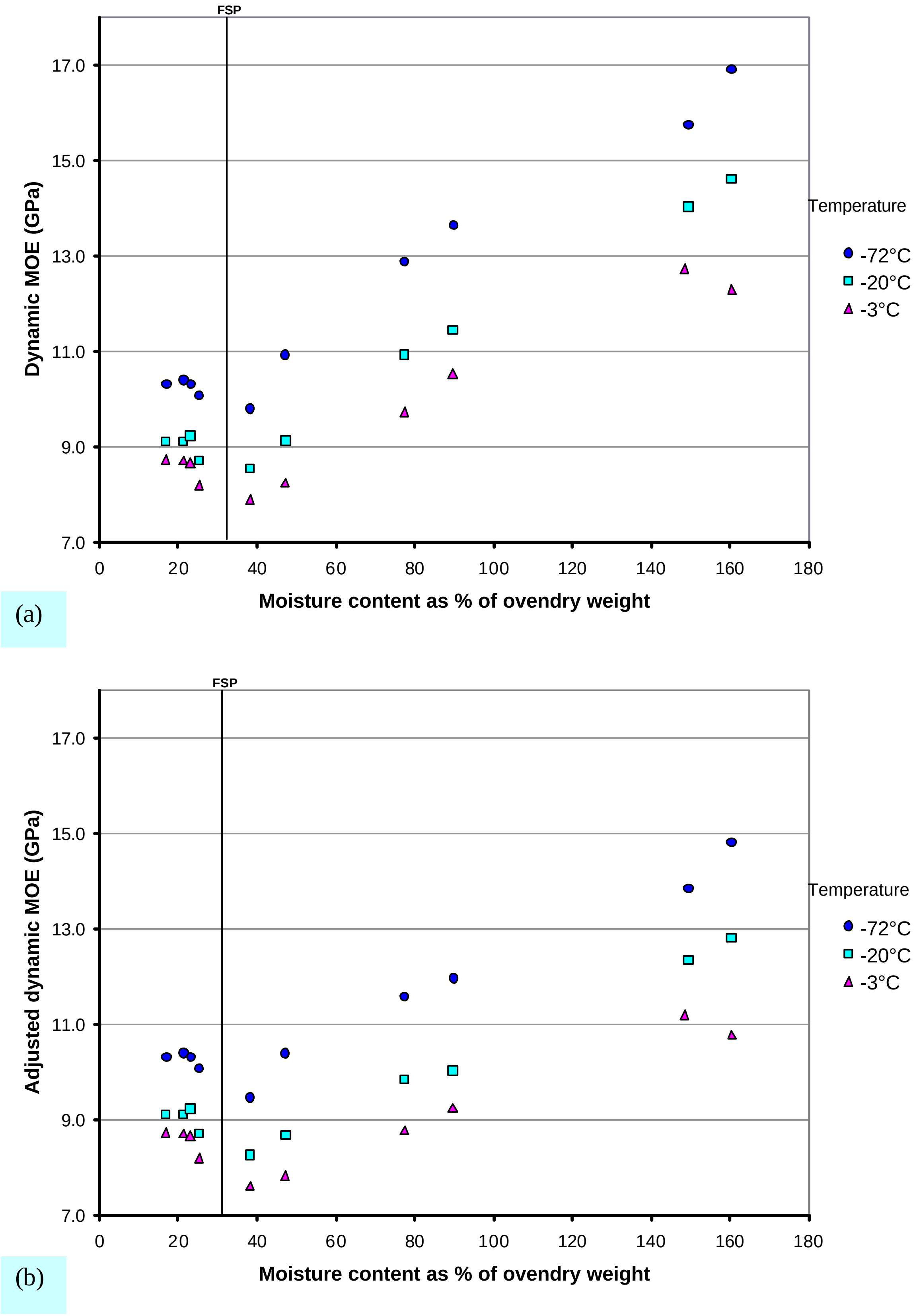

Figure 2-10. (a) Variation in dynamic MOE with moisture content for frozen wood; (b) adjusted values of DMOE for moisture contents above FSP using two saturation values as surrogates for the ratio of mobility of free water (k) in the formula of Sobue (1993) (60% for wood at low and medium saturation, and 75% for wood close to full saturation)

2.4 DISCUSSION

2.4.1 Explaining changes in acoustic velocity

The linear decreases in acoustic velocity with increasing temperature and moisture content obtained in our study for wood below FSP (Figure 2-4) were in line with James (1961), Sandoz (1993), Kang and Booker (2002), and Bucur (2006). Both effects can be related to the influence of bound water and temperature on the true Young's modulus (MOE) for the cell walls. Sakai *et al.* (1990) stated that when the fibres of cellulose adsorb water, the cell walls swell out and soften, and consequently the elastic modulus of the wood substance decreases up to the FSP. Similarly, Kollman and Coté (1968), from results obtained with static bending as well as vibration tests in previous studies concluded that below the FSP shrinkage or swelling occur thus increasing or reducing cohesion and stiffness. In regard to the effects of temperature, Kollman and Coté (1968) indicated that for wood below the melting point or below the thermal decomposition, strength and stiffness decrease with increasing temperature due to thermal expansion of the crystal lattice of the cellulose and due to the increased intensity of the thermal molecular oscillations. The U.S. Forest Products Laboratory (USDA 1999) stated that for moisture contents below FSP and temperatures under 150ºC, mechanical properties are approximately linearly related to temperature.

The consistently higher acoustic velocities of frozen wood and the rapid decrease in velocity with increasing moisture content for both frozen and unfrozen wood in the hygroscopic range (left side of the FSP line, Figure 2-4a), suggested that presence of ice in the cell walls stiffens the wood and that the inverse effect of bound water on MOE is similar whether bound water is frozen or unfrozen. Sellevold *et al.* (1975) obtained results similar to our study for two temperatures (-130° and 25°C). In contrast to our conclusion, they argued that below the FSP if ice forms it would occur in such locations where the ice does not contribute to the stiffness of the material.

The gradual changes in acoustic velocity in wood above FSP when compared to the rapid changes below FSP suggested that free water in liquid or solid phase exerted considerably less influence on acoustic propagation than bound water. This follows the logic that mechanical properties are not affected by liquid free water (Kollman and Coté 1968). Similarly, Gerhards (1975) and S. Y. Wang and Chuang (2000) discussing the results in stress wave above FSP argued that free water is unable to bear stress. In our study the presence of ice in the lumens of frozen wood had little effect on acoustic velocity as shown by the very gradual decreases in velocity as increasing moisture above FSP. This was in agreement with Sellevold *et al.* (1975) who concluded that ice in the cell lumens plays only a small part in the dynamic mechanical response of wood.

The different gradients at which acoustic velocity decreased above FSP in unfrozen wood would appear to be well related to the proportion of free water vibrating in unison with wood substance (Sobue 1993), which in our study was indirectly estimated by saturation percentage (Section 2.3.2). That is, velocity was strongly affected by the proportion of free water in the lumens up to a critical level of 60% (equivalent to approximately 115% MC_{ODW}) followed by little change thereafter. This phenomenon was also observed in frozen wood above FSP where the critical point at 60% saturation also occurred (Section 2.3.3). Nevertheless, this seemed to exert a different influence on the acoustic velocity of frozen wood as indicated by the markedly distinct trends between frozen and unfrozen wood above FSP and by the slower decreases in velocity with increasing moisture content for frozen wood (Figure 2-4b).

The abrupt discontinuity in acoustic velocity at the freezing point (0°C) for wood above FSP observed in our study and reported by Sellevold *et al.* (1975) and Bächle and Walker (2006) could be explained by the combined effects of the mechanisms discussed above. Firstly lets assume there is an increase in the stiffness of frozen wood due to the presence of ice in the cell walls; secondly, this increased stiffness remain almost constant above FSP because frozen free water contributes less to the stiffness of wood (upper lines in Figure 2-4b); thirdly, while the velocity of frozen wood remains almost constant in the capillary range, the acoustic velocity of unfrozen wood keep decreasing with increasing moisture content (lower lines in Figure 2-4b). The end results are the increased differences between frozen and unfrozen wood

(Figure 2-4b) which are the equivalent to the increasing discontinuities in velocity at 0°C shown in Figure 2-4a. Moreover, this mechanism would also explain the small drop in ultrasound velocity observed by Sandoz (1993) at freezing point for wood at moisture content just above the FSP, i.e. similar to our study with moisture contents 38% and 46% (Figure 2-4a).

2.4.2 Explaining changes in DMOE and adjustment above FSP

Results revealed that changes in DMOE with temperature and moisture content were well related to the counteracting effects of acoustic velocity and density, which was in agreement with the definition of DMOE (DMOE=V^2?). However, this relationship was not straightforward because of the following factors:

1) Changes of velocity with temperature were approximately linear with the exception of the discontinuity at freezing point (Figure 2-4a)
2) Changes of velocity with moisture were curvilinear and these varied depending on whether wood was frozen or unfrozen (Figure 2-4b)
3) Changes of density with moisture content were linear (Figure 2-6b).

Trends of DMOE for wood below FSP were in agreement with the theory of the influence of moisture content and temperature on mechanical properties. However, above FSP there were small to moderate increases in DMOE with increasing moisture content for unfrozen wood as well as large increases for frozen wood (Table 2-4 and Figure 2-5b) which contradicted the assumption advanced by Gerhards (1982) that mechanical properties should not change above the FSP. Yet it is worth noting the lack of research on the changes in static MOE for frozen wood at different moisture contents. From the only relevant report (Comben 1964) it was estimated an increase of about 10.8% in modulus of elasticity from 12% moisture content to green condition in frozen wood at -73°C, which contrasted with the increases in DMOE of 29.1% and 58.3% obtained in our study with increasing moisture content from 17% to 83.5% and 154%, respectively, for wood at -72°C.

Increases in DMOE for wood above FSP questioned the robustness of the use of DMOE for the estimation of stiffness in wood above FSP. According to the definition of DMOE below, it would be expected that the density (?) should 'cancel out itself' thus enabling DMOE to be a true estimate of the intrinsic Young's modulus (E), however, results indicated this did not occur for wood above FSP.

$$DMOE = V^2 r = \frac{E}{r} \times r \neq E$$

In the study of Gerhards (1975), on the effect of moisture content on stress wave speed and DMOE, he concluded that the variation in DMOE above FSP was driven mainly by moisture content and that DMOE should be corrected for moisture contents higher than 50%. Ross and Pellerin (1991) reanalyzing the data of Gerhards concluded that the sharp increase in DMOE above the FSP was simply due to changes in density. Sobue (1993) based on results of Gerhards (1975) and his own work, concluded that above the FSP, DMOE increases as a result of the increased density with increasing moisture content. X. Wang and Ross (2002) pointed out that according to the fundamental equation for DMOE, decreases in stress wave velocity and increases in density with increasing moisture content have opposite effects on DMOE. Moreover, above FSP the increase in density could yield a higher computed value of DMOE as published by Gerhards (1975). Based on this report and that of Sobue (1993), X. Wang and Ross (2002) concluded that DMOE required adjustments for moisture contents above the FSP.

2.5 CONCLUSIONS

- There was an overall inverse effect of moisture content and temperature on acoustic velocity which differed considerably below and above FSP. Trends are summarized as follows: 1) acoustic velocity in wood below FSP (dry) is faster than in wood above FSP (wet) because of the negative effect of free water on acoustic propagation; 2) velocity in dry frozen wood is faster than in dry unfrozen wood because the ice stiffens the cell walls; 3) velocity of wet frozen wood is faster than wet unfrozen wood because of the ice in the cell walls (not in the lumens), and because free water reduces acoustic velocity as moisture increases;

4) the drop in velocity at 0°C increases with increasing moisture content because of the negative effect of free water on velocity; 5) the gradual decrease of velocity with increasing temperature for both dry and wet wood is due to the general inverse effect of temperature on the stiffness of the cell wall.

- The marked differences in the trends of acoustic velocity across the moisture range along with the higher decreasing rates per unit moisture indicated a dominant effect of moisture content over temperature on acoustic propagation.

- Changes in DMOE with moisture content and temperature were explained by the counteracting effects of acoustic velocity and density, which was in agreement with the equation $DMOE=V^2?$. Nevertheless, this relationship was not straightforward because of the varying trends of velocity and density as follows: 1) changes of velocity with temperature were approximately linear with the exception of the discontinuity at the freezing point, 2) changes of velocity with moisture were curvilinear and these varied depending on whether the wood was frozen or unfrozen, 3) density increased linearly with increasing moisture content.

- Above FSP, the varying trends of velocity and density with increasing moisture content gave rise to variation in DMOE which showed two distinct patterns depending on whether temperatures were below or above 0°C. For unfrozen wood there was an average increase of 0.3 GPa in DMOE between wood at low saturation (4.8 and 9.7%, Table 2-4) and wood at the highest saturation (81.9 and 92.2%, Table 2-4). Also for unfrozen wood above FSP, the maximum changes in DMOE across temperatures ranged from 0.5 to 1 GPa (Table 2-4). For frozen wood above FSP, increases in DMOE between wood at low saturation and wood at the highest saturation ranged from 4.5 GPa for wood at -3°C to 6 GPa for wood at -72°C.

- These results contradicted the theory that mechanical properties should not change above FSP and suggested adjustments to the calculation of DMOE for this range of moisture. Such adjustments should consider that changes in acoustic velocity and density with increasing moisture content are not proportional.

- The large increases in DMOE obtained for frozen wood above the FSP as compared to the increases in static MOE from the only report available, questioned the reliability of the dynamic determination of stiffness in frozen green wood. This would include grading of frozen logs with acoustic tools or situations where frozen and unfrozen logs are mixed during the grading process. Research is suggested for further validation of the DMOE calculated in green frozen wood, including static tests.

- The formula developed by Sobue (1993) for correcting densities above FSP and hence DMOE gave good results in the present study for unfrozen wood using two critical saturation values (60% and 75%) as a surrogates for the ratio of mobility of free water (k). In contrast, adjustment of DMOE for frozen wood above the FSP could not be fully validated because of the insufficient information in the literature for changes in static MOE of frozen wood at different moisture contents.

CHAPTER 3

Destructive methods to determine the green density and moisture condition in live trees

3.1 INTRODUCTION

Green density is a fundamental variable for the estimation of dynamic MOE (DMOE) of standing trees and logs when using acoustic methods; namely DMOE = V^2?, where V=acoustic velocity and ?=green density. Surprisingly, to date there is no established methodology for measuring green density of standing trees or logs for resource evaluation. Instead it has been common practice to use a nominal value for green density of about 1000 kg/m^3 when this variable is not known. However; as shown in Chapters 5 and 6 and Appendix 3 there is considerable variation in this trait that needs to be considered when conducting broad-acre assessments.

Recent reports in the literature show a variety of methods to estimate green density in acoustic studies. For example, in the report of X. Wang *et al.* (2001) green density for standing-tree DMOE was determined destructively by 0.61-m-long bole sections taken from selected trees. Green density was calculated from the weight and dimensions of the bole sections. The study of X. Wang *et al.* (2001) included DMOE of small clear specimens for which green density was also measured by weight and dimensions. In a different study, X. Wang *et al.* (2002) determined green density for DMOE of small logs from the weights and dimensions of the logs. Lasserre *et al.* (2005) determined green density for standing-tree DMOE by disks taken at 1.4 m from a subsample of trees. In a detailed study of the radial variation of DMOE in logs by Booker *et al.* (2000) green density was determined from the weight and dimensions of small clear specimens across the diameter.

In this thesis there are two reasons for quantifying moisture condition in living trees and logs. On one hand moisture content affects directly green density and is related inversely to acoustic velocity, so it is important to have a measure of this parameter when using dynamic MOE for resource characterization. On the other hand, according to results in Chapter 7 the moisture condition of trees expressed as saturation percentage may have potential for monitoring drought and water-stress response, and for breeding for dry environments.

In similar fashion to green density, there is no standard methodology for measuring moisture content in living trees. There are a few early reports concerning the variation of moisture condition of several conifer species and temperate hardwoods, from the utilization perspective and also to explain seasonal changes. These include Chalk and Bigg (1956), Clark and Gibbs (1957), Gibbs (1958) and discussions by Skaar (1988). Published work for radiata pine include Hughes and Mackney (1949), Loe and Mackney (1953), Fielding (1952), Cown and McConchie (1980, 1982), Harris (1961), and unpublished work by Harris and Cown (1991) and Kininmonth (1991) as well as discussions by Bamber and Burley (1983). The common experimental approach has been destructive sampling using disks of a range of thicknesses. Such studies have commonly reported the moisture content of live trees as a percentage of the ovendry weight. However more appropriate methods for expressing the moisture condition in live trees include the volumetric percentage of water content (Fielding 1952, Clark and Gibbs 1957, Borghetti *et al.* 1991, Cinnirella *et al.* 2002), and saturation percentage or moisture saturation (Chalk and Bigg 1956, Harris 1954a and 1961, Kininmonth 1991). The latter was the method selected for this study.

Saturation percentage is especially useful for green wood as it is more related to the water above the fibre saturation point (free water). Unlike the moisture content expressed as percentage of ovendry weight (MC_{ODW} %), saturation percentage has the advantage that it is uninfluenced by basic density; so it is possible to compare more accurately moisture changes within the tree, with age, site, etc. (Fielding 1952, Clark and Gibbs 1957, Kininmonth 1991). The advantages of saturation over other moisture measures for living trees are extensively demonstrated in Chapter 5.

This part of the thesis deals with the development of destructive methods to correctly measure green density and saturation. Results of preliminary work provided the framework for refining the procedures used to collect and process the samples. This Chapter introduces components of green wood as a better approach for assessing green density. The main aims were to test the influence of thickness and surface preparation of samples plus additional comparison for some of the samples after surface resaturation. For this purpose two different experiments were devised; one aimed to test the influence of sample thickness and cross-cut method on green density and saturation of young sapwood; and the second was aimed to test the influence of cross-sectional and along-the-grain cutting methods on green density and saturation of mature sapwood and heartwood.

3.2 METHODS

3.2.1 Theoretical considerations and development of formulas for green wood components and saturation

Wood in green condition contains 1) cell wall or wood substance, 2) bound water contained in the cell walls, 3) free water partially or completely filling the cell cavities or lumens, and 4) vapour/air or void space in the empty cell cavity spaces (Figure 3-1). The common definition of green density as the amount or mass of green wood per unit volume (GD = GW / GV) tells little about the actual nature of this property.

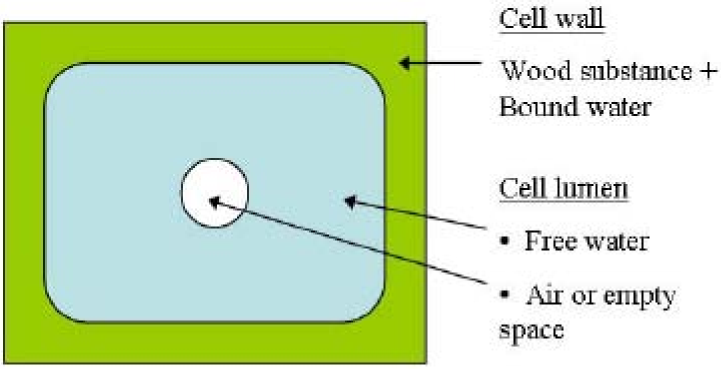

Figure 3-1. Components of green wood in the living tree (after Skaar 1988)

It was postulated that measuring the proportion of the different components of green wood is relevant for the correct assessment of green density. Similarly, instead of comparing different methods empirically on the basis of the simple definition of green density it may be more accurate to include all the components.

To date there is no tool or method to determine directly the proportion of each of the components of wood in green condition, namely cell wall (wood substance), bound water (B water), free water (F water), and air. However these can be estimated indirectly by measuring the green weight (GW), green volume (GV) and ovendry weight (ODW) of the sample.

The approach used was to derive the volumetric percentage occupied by each component with respect to the green volume of the sample. This is not a straightforward procedure as we can only measure weights (of wood and water) so these values need to be converted to volume using the respective densities of wood substance, bound water and free water. The principles underlying the formulas developed here have been discussed by Stamm (1938, and 1964 p. 63-64), MacLean (1952 p. 18, 28-30) Fielding (1952), and Clark and Gibbs (1957)

1) Percentage of wood substance in green wood

$$From\ fundamental\ relation\ M = D\,V, \quad V = \frac{M}{D}$$

This is a basic relationship for common materials where M = mass, D = density, and V = volume. In the case of wood, mass can be determined from the ovendry weight (ODW) and the density of wood substance which is taken to be 1.5 g/cm^3 or 1500 kg/m^3 (?$_{\text{wood}}$) (Walker 2006 p. 74). So volume of wood would be = ODW/?$_{\text{wood}}$. But we need this volume to be calculated in respect to green volume of the sample (GV). Algebraically this becomes:

$$\text{wood substance } \% = \frac{\left(\dfrac{ODW}{r_{wood}}\right)}{GV} \times 100 = \frac{ODW}{r_{wood}} \times \frac{1}{GV} \times 100 \quad = \quad \frac{ODW}{GV} \times \frac{1}{r_{wood}} \times 100$$

But ODW/GV is the basic density of wood (BD) so the above expression is simplified as follows and represents the percentage of wood substance in green wood,

$$\text{wood substance }\% = BD \times \frac{1}{\rho_{wood}} \times 100 = \frac{BD}{\rho_{wood}} \times 100 \qquad (1)$$

2) Percentage of water in green wood

For the purposes of this research we need to estimate the amount of water contained in the cell walls or bound water (B water), and the amount of water contained in the lumens or free water (F water). Bound water is the water adsorbed in the cell walls up to the fibre saturation point (FSP). The fibre saturation point of radiata pine is 30% for both sapwood and heartwood (Kininmonth 1991). When water is adsorbed into the cell wall it becomes slightly compressed so its density is slightly higher than that of 'normal' water (Walker 2006 p. 75). The value for the density of bound water at FSP differs in the literature; however the value used in this study was 1018 kg/m^3 as quoted by Walker (2006 p. 76). Above FSP free water is not compressed in the lumens and has a 'normal' density of 1 g/cm^3 or 1000 kg/m^3.

As in the case of wood substance, we need to refer the volume of water to the green volume of the sample (GV). We can measure the weight of water (W$_{water}$) and we know the different values for density of water (?$_{water}$) so the formulas can be developed as follows:

$$water\ \% = \frac{\left(\dfrac{W_{water}}{\rho_{water}}\right)}{GV} \times 100 = \frac{W_{water}}{\rho_{water}} \times \frac{1}{GV} \times 100$$

This expression can be algebraically rearranged introducing ODW (ovendry weight) as dummy variable,

$$water\,\% = \frac{W_{water}}{r_{\,water}} \times \frac{1}{GV} \times 100 \times \frac{ODW}{ODW} = \frac{W_{water}}{ODW} \times 100 \times \frac{ODW}{GV} \times \frac{1}{r_{\,water}}$$

But (W_{water} / ODW) x 100 is the moisture content of wood respect to its ovendry weight (MC_{ODW}%), and ODW/GV is the basic density of wood, so the above expression becomes:

$$water\,\% = MC_{ODW}\,\% \times BD \times \frac{1}{r_{\,water}} \quad or \quad \frac{BD}{r_{\,water}} \times MC_{ODW}\,\%$$

The above formula can be used for calculating both bound water (B water) and free water (F water) contents as follows:

$$B\ water\,\% = \frac{BD}{1018} \times 30\% \tag{2}$$

$$F\ water\,\% = \frac{BD}{1000} \times (MC_{ODW}\,\% - 30\%) \tag{3}$$

3) Percentage of air or void space in green wood

Having calculated the percentages of wood substance, bound water and free water then the remaining space should be occupied by air/vapour. Some authors call this the void volume in wood (Stamm 1938, and 1964 p. 63-64). This is calculated as follows:

$$Air\,\% = 100 - (wood\ \text{substance}\ \% + B\ water\,\% + F\ water\,\%) \tag{4}$$

4) Saturation percentage

Having determined the components of green wood the calculation of saturation percentage is straightforward; the definition used in the study was that of Harris (1954a) because of its biological context,

$$Saturation\,\% = \frac{Fwater\%}{(Fwater\% + Air\,\%)} \times 100 \qquad (5)$$

3.2.2 Experiments with young trees to examine the effect of sample thickness and sectional cutting method

This study was conducted during June – August 2005 (winter) in the Hume region of Forests NSW, Australia. As the experiment required young trees containing mostly sapwood and with long internodes, regeneration trees were used. Straight trees were selected in order to avoid compression wood as much as possible. Eighteen trees were felled and 2 m logs cut near the base of the tree and brought immediately to the laboratory (Figure 3-2a). Two subsets of disks of four different thicknesses (25 mm, 50 mm, 100 mm, and 150 mm) were obtained from each log; one set cut with chainsaw and the other with a fine dropsaw. The total number of disks utilized was 144 = 18 trees x 4 thickness x 2 cutting methods.

Disks were cut within 24 hours of the logs arriving at the laboratory. Each disk was placed immediately into water in order to avoid any moisture loss. This was in response to preliminary work in which some moisture loss was observed in spite of wrapping the disks with plastic bags and also because of the lack of a freezing or cool room. The next step was to assure that the samples contained only sapwood. The pith and any heartwood or dry sapwood in the centre of the disks was removed by drilling with bores of different sizes (Figure 3-2b). Frequently a very thin layer of dry sapwood remained in the samples because if the wet sapwood near the dry centre was reached while drilling it would cause strands of loose fibres. After removing the dry centre the disks were thoroughly debarked and loose fibres cut with chisel.

Each disk was dried with absorbent paper in order to eliminate any extra surface water and then weighed for green weight. Volume was measured using the water displacement method, with samples immersed in water using a long needle attached to a special-adapted stand so the balance readings were steady. After green measurements, disks were ovendried for 48 hours at temperatures around 103 – 105° C until constant weight was reached. All weight and volume measures were done with the same balance which had a resolution of 1 g or 1 cm^3 for weight and volume, respectively.

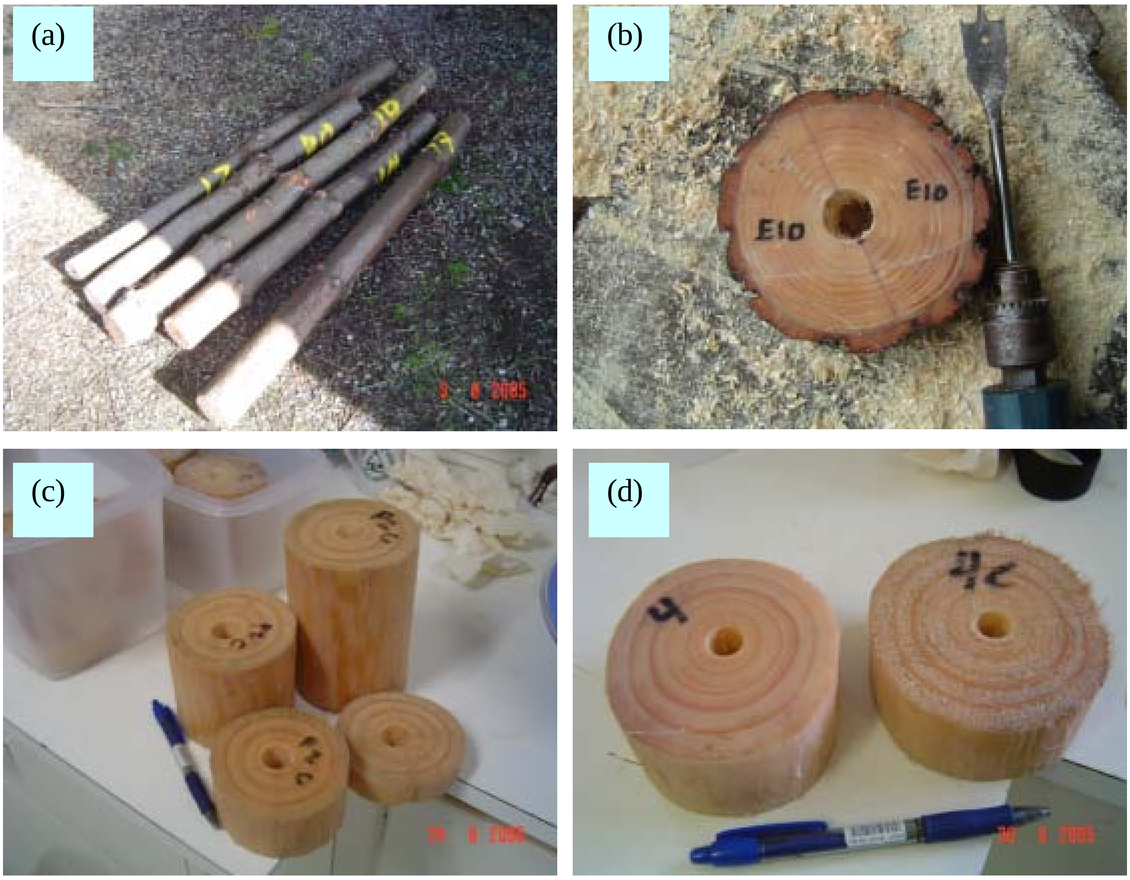

Figure 3-2. Details of sample processing: a) fresh logs, b) removal of dry centre with drill and speedbore, c) samples of the four thicknesses tested, d) cross sections showing cutting methods, fine dropsaw on the left and chainsaw on the right

Resaturation of cross-sectional surfaces was undertaken for the 50 mm disks after initial measurements of green weight and volume, using a portable vacuum chamber in which vacuum was generated with a Venturi tube powered by running water (Figure 3-3). The vacuum obtained was about -70 kPa. Samples were immersed in water inside the chamber and vacuum was applied for 20 minutes. During this time the samples were gently shaken and flipped over. Due to the small size of the chamber, samples were treated one by one. After resaturation, 50 mm disks were surface dried and weighed immediately so a ‘resaturated’ green density could be obtained.

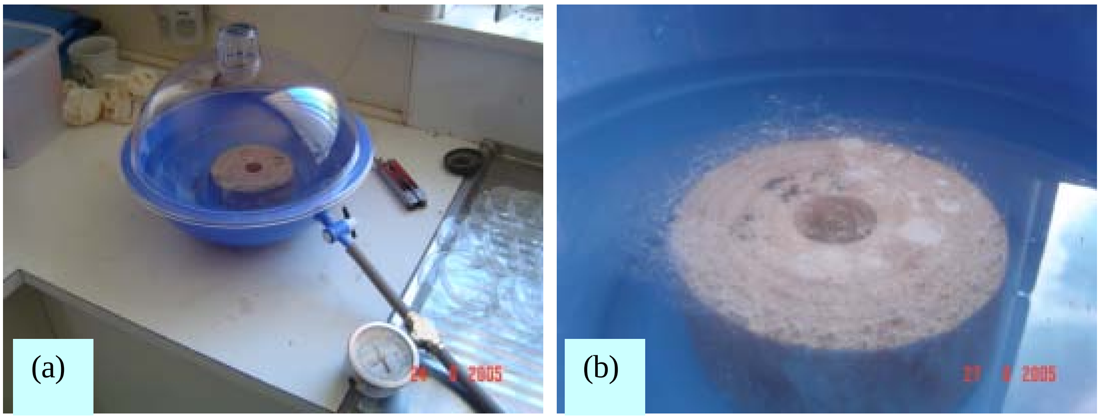

Figure 3-3. a) Vacuum chamber used for surface resaturation of the 50mm samples, b) close-up of the resaturation process showing air bubbles

3.2.3 Experiments with mature sapwood and heartwood to study the effect of surface preparation

This experiment was conducted in September 2005 (late winter) in the Hume region of Forests NSW, Australia. Wood samples came from ten mature trees (35 years old). Trees selected were healthy, straight and with moderate branching. From each of the trees two disks of 75 - 80 mm thickness were cut at two heights: 1.3 and 10.5 m. For most of the disks, wedges of about 30% cross section were obtained using an axe (Figure 3-4a), while small disks were left whole. In both cases material was placed immediately in drums with water so they could be transported with no moisture loss (Figure 3-4b). Disk sections were further kept in water at the laboratory while waiting to be processed, which occurred within the following 48 hours. As with the study of young material, this was done in response to preliminary work in which some moisture loss was observed in spite of wrapping the disks and also because of the lack of a cool room.

Once in the laboratory, two kinds of slice-or-wedge-shaped samples were obtained from the disk segments as follows,

1) Fine dropsaw samples (Figure 3-5a). The cross sectional surfaces were trimmed (3-4 mm) and the side-grain surfaces were dressed with a fine

dropsaw (Figure 3-4c). Samples had a thickness of about 70 mm after trimming the cross sections. The sapwood/heartwood boundary was carefully identified and the curved transition zone (1 or 1.5 rings with both sapwood and heartwood) was removed with the dropsaw.

2) Chainsaw and chisel samples (Figure 3-5b). The cross sectional surfaces were left with their original chainsaw rough surface, while the side-grain surfaces were dressed with chisel and mallet while splitting the samples from the original disks. The sapwood/heartwood boundary was also carefully identified and marked but the transition zone was not removed so both sapwood and heartwood were split out and separated with a single chisel cut.

Figure 3-4. Details of sample processing for mature trees material: a) Sections of disks, b) Transportation in drums with water, c) Portable dropsaw with thin kerf, d) Heartwood (top) and sapwood (below) dropsaw samples after green measurements

The number of samples used in the experiment was 80 = 10 trees x 2 heights x 2 methods x 2 materials (sapwood / heartwood). After processing, each sample was immediately measured for green weight and volume in order to avoid any moisture loss. Volume measurement was done by water displacement in similar fashion to the young material. After green measurements, samples were ovendried for 48 hours at around 103 – 105° C until constant weight was reached; sapwood and heartwood were oven-dried separately. All weight and volume measures were done with the same balance which had a resolution of 1 g and 1 cm^3 for weight and volume, respectively.

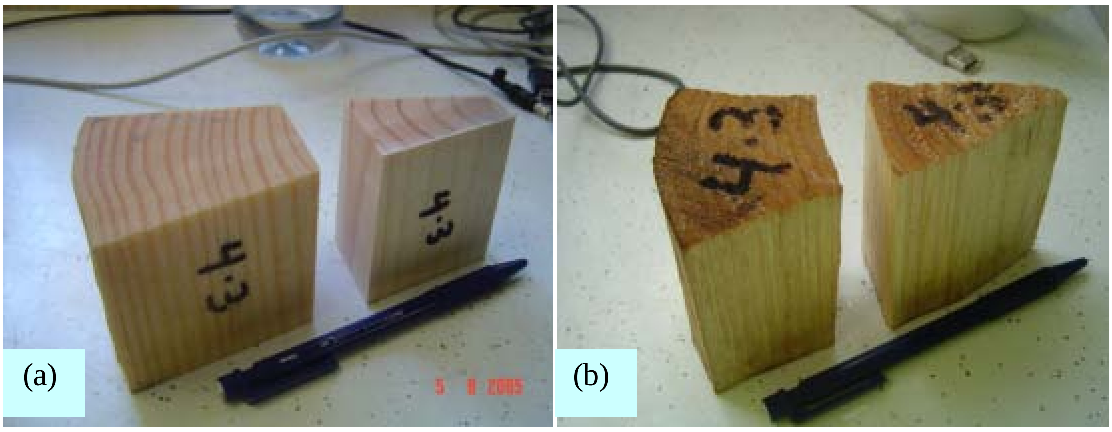

Figure 3-5. a) Samples dressed by a fine dropsaw in cross sectional and grain direction; b)Samples with cross sectional chainsaw cut and dressed with chisel in grain direction. Sapwood appears on the left and heartwood on the right side in both photos. Note: photo of chainsaw-chisel samples was taken after ovendrying whereas dropsaw samples photo was in the green condition.

3.2.4 Data analysis

Statistical effects of thickness on sapwood green density, saturation, and the green wood components for the young trees were determined separately for each cutting method, whereas the effects of cutting method were tested for each of the thicknesses. In both cases one-way analysis of variance analysis was used. The significance of cutting method was re-tested for 50 mm samples after surface resaturation using same approach.

For mature trees, the statistical effects of cutting method on sapwood green density, saturation, and the green wood components were determined separately for sapwood and heartwood obtained at two different heights in the stem (1.3 and 10.5 m). Similar to the young trees, one-way analysis of variance analysis was used.

3.3 RESULTS

3.3.1. Experiments with sapwood from young trees

Surprisingly thickness had no significant influence on green density or saturation for either of the cutting methods (Table 3-1). It was observed that the green density of 25 mm dropsaw, and 25 and 50 mm chainsaw samples were slightly lower than the rest of treatments (Figure 3-6). However these trends were not observed for saturation (Figure 3-7) so contrary to expectation, there was no relation between proportion of fibres severed and green density or moisture condition, at least for close-to-saturation material.

On the other hand, results revealed that green density was influenced by cutting method although differences were small and statistically significant only for 25 and 150 mm samples (Table 3-1). These two thicknesses also showed greater variation (Figures 3-6 and 3-7); in consequence, samples between 50 and 100 mm appear to be more robust for green density and moisture determination.

Table 3-1. Means and statistical effects of thickness and cutting method on sapwood green density and saturation from young trees

Thickness (mm)	Cutting method	Green density (kg/m^3)	ANOVA cutting method	Saturation (%)	ANOVA cutting method
25	Chainsaw	1105	*	98.1	ns
	Dropsaw	1094		96.6	
50	Chainsaw	1105	ns	97.7	ns
	Dropsaw	1100		97.5	
100	Chainsaw	1108	ns	97.9	ns
	Dropsaw	1099		97.2	
150	Chainsaw	1109	*	97.9	ns
	Dropsaw	1099		96.9	
ANOVA thickness	Chainsaw	--	ns	--	ns
	Dropsaw	--	ns	--	ns

* Significance at $P < 0.05$, ns = not significant

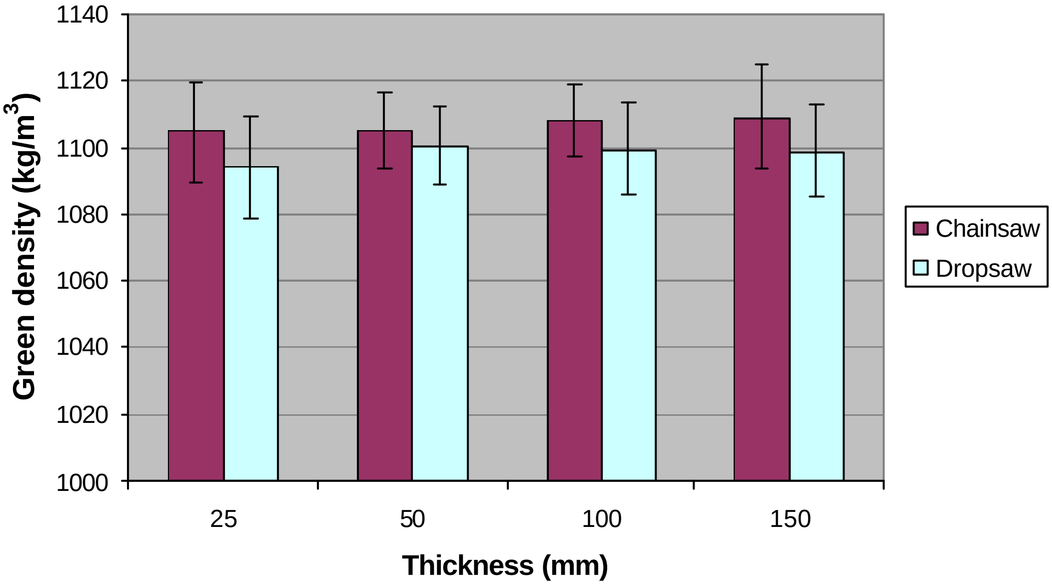

Figure 3-6. Sapwood green density across thickness and cutting methods for young trees (vertical bars = ±1 standard deviation)

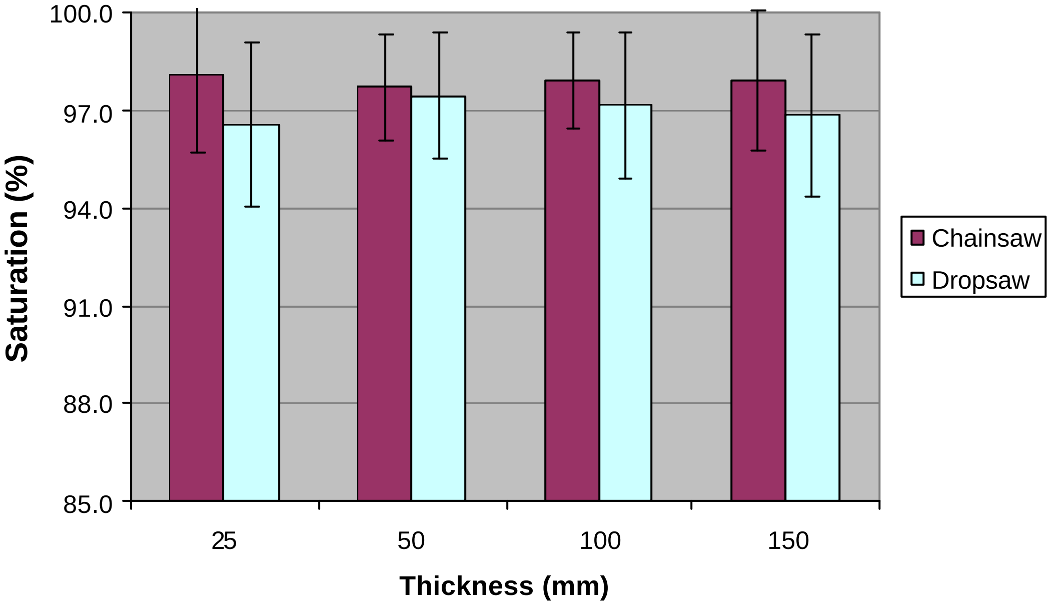

Figure 3-7. Sapwood saturation across thickness and cutting methods for young trees (vertical bars = ±1 standard deviation)

Although differences were small, green density and saturation were consistently higher for chainsaw samples which indicated some fundamental differences between cutting methods. This effect was further investigated in terms of green wood components and results are shown in Table 3-2. Results indicated small and non-significant differences in wood substance and free water content across treatments. In contrast, there were considerable differences in air content especially for 25 and 150 mm samples which suggested that any major differences between cutting methods was mostly influenced by air content.

Table 3-2. Means and statistical differences between cutting methods for green wood components of sapwood from young trees

Thickness (mm)	Cutting method	Wood substance %	†	Free water %	†	Air %	†
25	Chainsaw	23.1	ns	65.4	ns	1.3	ns
	Dropsaw	23.0		64.6		2.3	
50	Chainsaw	23.6	ns	64.5	ns	1.5	ns
	Dropsaw	23.1		65.0		1.7	
100	Chainsaw	23.9	ns	64.2	ns	1.4	ns
	Dropsaw	23.2		64.6		1.9	
150	Chainsaw	24.1	ns	63.8	ns	1.4	ns
	Dropsaw	23.5		64.1		2.0	

† ANOVA cutting method
ns = not significant

Interestingly and contrary to expectation was the fact that air content was lower –and consequently saturation was greater– for chainsaw samples. This suggests that the chainsaw samples are picking up extra water in the cross-section surface (trapped between the severed fibres presumably). This is causing two effects: 1) Extra water adds to the green weight of the sample thus inflating green density, and 2) Extra water with 'no air' in it causes the air content of the sample to decrease, altering the true air content of the wood. Consequently saturation appears to be higher. The extra water picked up in the chainsaw samples surface must have been only minute particles since all samples were dried with absorbent paper before having their green weight and volume measured.

Results after surface resaturation of the 50 mm samples, as a further comparison between cutting methods are shown in Table 3-3. These revealed that chainsaw samples still gave significantly higher green density than dropsaw samples, although the difference was minute. There were no statistical differences between methods for any of the green wood components and results were similar to those obtained at fresh condition (Table 3-2). Differences in free water after resaturation did not shed any new light to explain why the chainsaw samples gave slightly higher green densities than dropsaw samples with smooth cross sections. The only explanation remained that microscopic water trapped in the rough chainsaw surfaces increased green weight (hence green density) and altered the true free water and air content balance for these samples.

Table 3-3. Means and statistical differences between cutting methods for 50 mm samples after surface resaturation

Cutting method	Green density kg/m^3	†	Saturation %	†	Wood substance %	†	Free water %	†	Air %	†
Chainsaw	1116	*	99.4	ns	23.6	ns	65.6	ns	0.4	ns
Dropsaw	1108		98.6		23.1		65.8		0.9	

† ANOVA cutting method
* Significance at $P < 0.05$, ns = not significant

3.3.2 Experiments with material from mature trees

For sapwood material the chainsaw-chisel method showed slightly higher green density and saturation at breast height, but in contrast higher up the stem both methods gave practically identical results (Table 3-4). This was explained by the higher free water and lower air content for the chainsaw-chisel samples at breast height (Table 3-5) confirming the effect of rough surfaces observed previously with young trees but in this case to a lesser extent. In spite of this, the question still remained: why was this effect not observed higher up the stem?

Table 3-4. Means and statistical effect of cutting method on green density and saturation for sapwood and heartwood material at two heights in the tree (mature trees)

Material	Height (m)	Method	Green density (kg/m^3)	ANOVA cutting method	Saturation (%)	ANOVA cutting method
Sapwood	1.3	Chainsaw-chisel	1138	ns	94.5	ns
		Dropsaw	1131		93.2	
	10.5	Chainsaw-chisel	1115	ns	94.1	ns
		Dropsaw	1114		94.0	
Heartwood	1.3	Chainsaw-chisel	659	ns	15.2	**
		Dropsaw	610		8.8	
	10.5	Chainsaw-chisel	594	**	15.1	**
		Dropsaw	524		6.0	

** Significance at $P < 0.01$, ns = not significant

On the other hand, for heartwood material the chainsaw-chisel method showed significantly increased values for both green density and saturation (Table 3-4). However this effect was not related to the method of surface preparation *per se*; instead it was observed that the heartwood sections absorbed some moisture while the discs sections were stored in water waiting to be processed. This was a natural outcome as the heartwood of mature trees was just above the fibre saturation point. For the dropsaw samples this represented no problem as the surfaces were trimmed off but that was not the case for chainsaw-chisel samples which were left undressed. The comparison of green wood components between methods for heartwood in Table 3-5 showed that chainsaw-chisel samples contained about double the amount of free water compared to dropsaw samples resulting in the same difference in saturation and inflating green density. This clearly confirmed that the increased values for the heartwood samples of the chainsaw-chisel method were caused by the extra moisture absorbed by the samples while being stored in water.

Table 3-5. Means and statistical effect of cutting method on green wood components for sapwood and heartwood material at two heights in the tree (mature trees)

Material	Height (m)	Method	Wood substance %	†	Free water %	†	Air %	†
Sapwood	1.3	Chainsaw-chisel	32.9	ns	49.6	ns	2.9	ns
		Dropsaw	32.8		49.1		3.6	
	10.5	Chainsaw-chisel	29.2	ns	54.4	ns	3.4	ns
		Dropsaw	29.2		54.4		3.5	
Heartwood	1.3	Chainsaw-chisel	29.3	ns	8.7	**	49.0	ns
		Dropsaw	28.6		5.1		53.6	
	10.5	Chainsaw-chisel	25.6	ns	9.6	**	53.6	**
		Dropsaw	24.9		3.9		60.2	

† ANOVA cutting method
** Significance at $P < 0.01$, ns = not significant

3.4 DISCUSSION

The lack of effect of sample thickness on green density and saturation suggested that the number of fibres in lengthwise direction and the proportion of fibres severed don't bear significant influence on these traits at least for sapwood near to saturation. This may also indicate that, contrary to expectation, the proportion of fibres whose lumens have been drained has no effect on the determination of green density and saturation. Nonetheless it was noticed that thinner or thicker samples gave more variation.

Unlike thickness, cutting method showed a consistent yet small effect across material from different ages. This indicated that the way the fibres are perpendicularly cut, and therefore the smoothness/roughness of the cross-sectional surface of the samples plays some role in the determination of green density and saturation. It was particularly interesting that the rough samples apparently trapped extra water on the surface giving as a result slightly higher sapwood green density and saturation than the smooth dropsaw samples. In this study the effect was only minor because the samples were carefully chainsawed; however under operational conditions or using samples taken directly from mechanically harvested logs, this effect may potentially be far worse.

After complete resaturation of 50 mm dropsaw disks, green density and saturation were still slightly higher for chainsaw samples confirming the intrinsic differences between the two cutting methods.

The last factor to consider was that in all cases sapwood material used in the study was near to saturation (mean saturation ranged from 94 to 98%) so results may change for samples collected in the dry months. In addition, heartwood results indicated that trimming of all surfaces would be required on samples with lower levels of saturation. Finally, there has not been similar work published with which to compare these results; further research in the subject is encouraged.

3.5 CONCLUSIONS

- Transporting and keeping the samples in water during processing proved to be a satisfactory procedure where large freezing or cooling facilities are unavailable. This method is recommended when working during hot months to avoid any moisture loss. However the drawback is that the heartwood sections would need to be trimmed to remove the film of absorbed water.

- Using the individual components of green wood aided in interpreting fundamental differences between the methods, as opposed to simply making empirical comparisons with the values of green density and saturation.

- Samples between 50 and 100 mm appear to be adequate for obtaining precise measures of green density and saturation. Either of the surface preparation methods studied were adequate for material of any age. However, in future work the accuracy of chainsaw samples could be improved by taking care to ensure clean cuts when sectioning the samples. In the subsequent sections of the thesis, dropsaw samples with smooth surfaces were preferred because they permitted a clear observation of the wood surface and allowed identification of signs of cavitation in the sapwood.

CHAPTER 4

Predicting the green density and moisture condition of live trees from increment cores

4.1 INTRODUCTION

The lack of standard methods for determining green density and moisture condition of live trees was highlighted in Chapter 3. Increment cores have been reported as giving good results for moisture content determination according to the early work of Huckenpahler (1936), Smith (1954), and Chalk and Bigg (1956). Interestingly, Smith (1954) developed the maximum moisture content method to determine basic density using ½ inch (ca. 12 mm) increment cores; however, there is no published work on the use of increment cores for green density determination.

Downes *et al.* (1997) have indicated that the use of increment cores is the most common non-destructive method. They pointed out that for wood quality studies, 12 mm cores are normally used, especially because these are the standard size for detailed studies with SilviScan, NIR analysis, mechanical and kraft pulping. According to Downes *et al.* (1997), this size of cores offers difficulties for manual extraction and these become much worse when applied to eucalyptus species so motorized methods have been developed.

Given the lack of references to this area in the literature, the methodological bases for conducting this study were set by preliminary work in which the use of increment cores was compared to the use of destructive samples of sapwood from two large datasets. One experiment included 5 mm increment cores and different types of blocks from sapwood of mature trees; whereas the second experiment involved motorized 12 mm cores, manual 5 mm cores, and blocks of sapwood from 10-year old trees. In both experiments unexpectedly low values of green density for 5 mm increment cores were obtained as well as poor correlations with the rest of the methods. These poor results were mainly attributed to moisture loss during storage due to delays in processing. Further, the 12 mm motorized cores gave considerably higher green densities than 5 mm cores; however, their relationship with the rest of the methods was rather weak. Again, this was thought to be influenced by handling and storage plus some effect of frictional heating caused by using the motorized borer. Unfortunately no definite conclusions could be drawn from these two experiments because there was some loss of moisture from the destructive samples which were acting as the control treatments.

Accordingly, a new series of experiments was devised and described in this Chapter. The general objective was to develop a reliable procedure to measure non-destructively the green density and moisture condition of standing trees. The experiments included material from different ages and seasons so robust inferences could be made. The first objective of the study with material from young trees was to make a closer examination of the possible causes of the lower values and discrepancy of increment cores with respect to destructive samples for green density and saturation. The second purpose was to test the effectiveness of the increment cores for predicting sapwood green density and saturation as measured destructively. The purpose of the study with material from matures trees was to validate the procedures developed with young material, and also to test the relationships between cores and destructive samples. Unlike the study with young trees, the study with mature material included green density from sapwood, heartwood, and whole-section. Additional traits included sapwood sectional percentage, and number of heartwood rings. Analysis for mature trees was conducted at breast-height and whole-tree levels.

4.2 METHODS

4.2.1 Experiments with sapwood from young trees

Material for the experiments with sapwood of young trees came from a stand located in intermediate climatic conditions of the Hume region of Forest NSW, Australia. The location of the stand is described in Table 5-1 of Chapter 5. Material for the first part of the experiments came from a batch of 10 trees gathered in winter 2005. Age of material varied because regeneration trees were used but it was 8 years on average.

For this experiment it was preferable to have a small dataset in order to retain close control of the processing of samples and also to allow physical observations of the samples themselves. Trees were felled and billets 1.5 m long were cut at breast height (axial centre of the billets at about breast height) and brought to the laboratory. For each of the billets, three different paired samples were obtained: 50 mm dropsaw disks, and 12 mm and 5 mm cores. Dropsaw disks were first obtained and processed according to procedures described in Section 3.2.2. Secondly, the 5 mm and 12 mm cores were extracted using manual borers from near where the disks had been cut out. Both cores were taken from bark to pith on one side of the billet and the dry-area close to the pith was removed with a sharp knife.

Green weights and volumes of all samples were immediately measured, the latter by water displacement. This aspect was important as in the preliminary experiments it was suspected that some moisture loss occurred during storage of increment cores. After fresh weights and volumes had been measured, increment cores were soaked in water for two different periods: 24 hours and 3 weeks. Weights and volumes were remeasured after each soaking period with resolutions of 0.001 g and 0.001 cc, respectively. After all weight and volume measurements had been completed all samples were ovendried for 48 hours at temperatures of around 103 – 105^o C until a constant weight was reached. Green wood components and saturation were calculated using the formulas of Chapter 3 Section 3.2.1.

The effectiveness of increment cores gathered in winter 2005 was tested against dropsaw disks both in the fresh condition, and after the two periods of soaking. Analysis included a detailed comparison using ANOVA for green density, saturation, and green wood components. Physical observations on both 12 and 5 mm cores were made during processing and while conducting the measurements.

Because the initial results with the 12 mm cores were obtained with a small and close-to-saturation sample, it was of interest to make a further validation with a larger dataset. For this purpose 26 new trees were selected the following summer at the same site. The age of the new material was 12 years on average. In this instance cores were first extracted on the standing trees as this eased the operation. After extraction the cores were immediately put in water for transport. Once they were in the laboratory the dry centre of the cores was removed and cores were maintained in water for another 24 hours. After the extraction of cores, trees were felled and billets about 1 m long were cut at breast height and brought to the laboratory. Dropsaw disks were then obtained and processed according to the procedures described in Section 3.2.2.

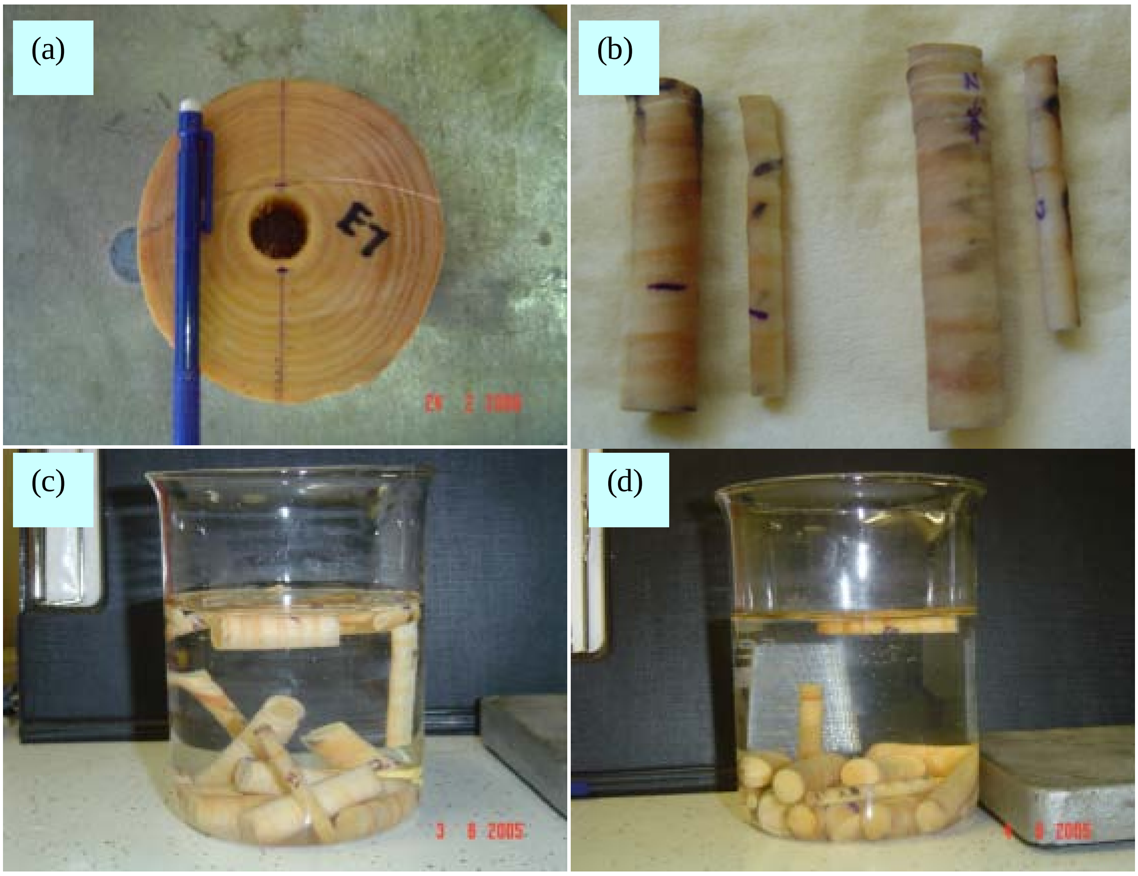

Figure 4-1. Details of samples from young trees gathered in winter 2005: a) 50 mm dropsaw disks with dry centre removed; b) 12 and 5 mm cores extracted manually; c) Fresh cores immersed in water: note the number of samples floating just below the surface; d) Cores after 24 hours soaking: note that all except one 5 mm core sank

Dropsaw disks were green weighed and their volumes measured in fresh condition; while green measurements for 12 mm cores were conducted after soaking in water for 24 hours. After this, both types of samples were ovendried according to the procedures described above. Green wood components and saturation were then calculated using the formulas of Section 3.2.1, Chapter 3. ANOVA analysis was subsequently conducted to test for differences in green density, saturation, and green wood components between methods.

The efficacy of 12 mm cores for predicting green density and saturation was tested by regression analysis. Linear relationships between cores and dropsaw disks were obtained separately for each of the datasets gathered in winter and summer, and then for the joint data. Finally, tests of parallel regressions were conducted for both green density and saturation to test for influence of season.

Figure 4-2. Details of the second set of samples collected in summer 2006 for further validation of 12 mm cores: a) manual borer; b) dropsaw for extraction of disk from billets; c) batch of 12 mm pith-to-bark cores, and the corresponding (paired) dropsaw disks (d)

4.2.2 Study with material from mature trees

Material for this experiment came from a 36-year old unthinned stand located on a warm-dry inland climate site of the Hume region of Forests NSW, Australia (Carabost SF, Rosewood Trig Rd. Sec., Cpt. 174; 35°40’25”S, 147°46’7”E, 528 m.a.s.l). The location and climatic conditions of the stand was similar to the stands of mature trees reported in Chapters 5 and 7 for the “warm-dry site” (Figure 5-1). This stand was also used for the experiment reported in Appendix 3. The study included 29 mature trees covering the whole range of diameters of the stand. Trees were grouped into three sizes: large, average, and suppressed (Table 4-1). The first part of the experiment consisted of taking 12 mm manual increment cores at breast height followed by felling and destructive sampling a few days later. The study was conducted in January 2007 (middle of summer). Detailed procedures are described below.

Table 4-1. Characteristics of mature trees used to study the prediction of green density, moisture condition and related traits from increment cores

Tree size	No. of trees	DBH mm (Std dev)	Height m (Std dev)
Large	10	454 (37)	30.9 (2.4)
Average	10	367 (26)	26.8 (2.7)
Suppressed	9	243 (32)	24.0 (4.4)

Because of the large size of some of the trees and because it was of interest to obtain bark-to-bark cores, a new set of 12 mm manual borers was acquired specifically for this study. Previously in the experiments with young trees, manual borers 300 mm long were enough, whereas in this case 300 mm and 450 mm borers had to be utilized. Also for the purpose of making the process more efficient it was necessary to build a custom-made steel handle. The procedure consisted of engaging and starting the borer as normal. Once the threaded bit had firmly penetrated the tree, the handle bar was swapped for the custom-made one (Figures 4-3a, 4-3b). The custom-made handle allowed driving in the borer much more efficiently without causing excessive stress on the sample and the operator. As a result it was possible to obtain damage-free and smooth bark-to-bark cores even from the largest trees (Figures 4-3c, 4-3d).

Unlike the cores taken for young trees, in which the dry centre was purposely removed, in the case of mature material it was of interest to measure both sapwood and heartwood material. Because of this, the cores could not be immersed in water immediately after being taken so they were wrapped tightly in plastic and kept in a cooler box with ice. Processing of cores in the laboratory was done in the following hours after collecting the cores in the field and it started with the identification of sapwood and heartwood. The staining test[1] consisted of spraying Variamine blue RT

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[1] Joe, B., Research officer, Land Management and Technical Services, Forests NSW, Beecroft NSW, Australia, March 2005, email: billj@sf.nsw.gov.au

(VBRT) salt solution on batches of 10 cores and then allowing it to dry out for 10 min (Figure 4-4a). Next the cores were sprayed with 4% Ammonia solution which immediately stained any heartwood in the centre of the cores an intense red-pinkish colour (Figure 4-4a). After the staining test, heartwood and pith-to-cambium radii were measured in order to obtain the cross-sectional percentages of sapwood and heartwood. At this point the number of heartwood rings was also determined. Next the cores were cut-sectioned into sapwood and heartwood and the former were immersed in water for 24 hours. Heartwood sections were immediately weighted and volume measured whereas for sapwood samples this was done after the soaking period. Finally all core sections were ovendried according to the procedures already described.

Figure 4-3. Procedures for extraction of 12 mm cores showing: a) Initial engaging and coring using normal handle; b) custom-made steel handle; c) coring a large mature tree; d) damage-free and smooth bark-to-bark core obtained from a large tree

The trees were felled a few days after the cores were obtained. The lower 1.3 m section of the trees was discarded and from that point upwards the stem was sectioned into logs of commercial dimensions. Disks about 80 mm thick were cut from 3 locations: the bottom end of the first log (nominally breast height) and the top ends of the first and second logs (with a log length of 5.5 m). Subsequent handling, storage, machining of disks into wedge-shaped samples and processing for green density assessment was conducted according to the procedures described in Section 3.2.3. Pith-to-bark wedges were then stain-tested in order to identify the boundary sapwood/heartwood in similar fashion as that described for the cores (Figure 4-4b). Next pith-to-cambium and heartwood radii of the wedges were recorded and the number of heartwood rings counted. Subsequently, wedges were split into sapwood and heartwood sections and these were weighed and the volume measured. Finally all sections were ovendried following the same procedures previously described.

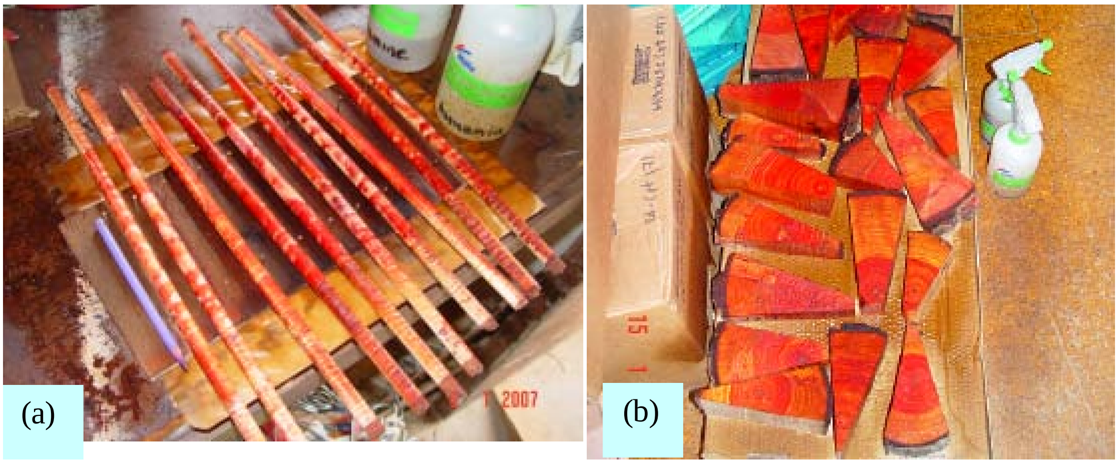

Figure 4-4. a) Bark-to-bark 12 mm cores; and (b) pith-to-bark wedges immediately after staining to detect heartwood (wedges shown before dressing to separate sapwood and heartwood sections)

For both the 12 mm cores and wedges, green density, saturation and green wood components were calculated separately for sapwood and heartwood using the formulas of Section 3.2.1. Whole-section values were the weighted averages of sapwood and heartwood sections, allowing for their respective cross-sectional percentages. An approximation of whole-tree values was also calculated from the weighted averages of the three samples taken per tree. The efficacy of 12 mm cores for predicting green density, saturation, sapwood content, and the number of heartwood rings was tested by regression analysis. It was also of interest to compare the predictions between results given by one side of the core and the average of two sides. For the latter purpose, tests of parallel regressions were conducted to test for differences between these results.

Considering that in this experiment bark-to-bark cores were used, it was also of interest to check whether there would be any differences between the 'entry' side and the 'exit' side of the cores. In particular it was suspected that the entry side may give less accurate results because of the greater amount of pressure exerted during first engaging the borer in the wood which would cause some extra water loss. To answer this question, the entry and exit sides were compared on the basis of saturation and green wood components.

4.3 RESULTS

4.3.1 Material from young trees measured in winter

Results indicated that in the fresh condition both 12 and 5 mm increment cores gave noticeably lower and more variable green density and saturation than the dropsaw disks (Table 4-2 and Figure 4-5). Interestingly the averages obtained for increment cores in this experiment were very similar to those obtained in preliminary work with 10 year-old trees. In the earlier experiments the lower values for increment cores were attributed to moisture loss during storage and handling; however this effect was removed in this new experiment as cores were immediately processed hence differences were attributed to intrinsic features of the increment cores as discussed below.

The major cause for the poor performance of the increment cores in fresh condition was the considerably decreased amount of free water and the subsequently increased amount of air, which occurred at a considerably larger extent with the 5 mm cores (Table 4-2). Two possible causes were examined to explain this. The first cause lies in the damage –at microscopic scale– suffered by the cores presumably while coring. This was mainly present for the 5 mm cores and consisted of fractures at some of the boundaries early/latewood, as well as small torn sections in the surfaces. The rationale was that the cracks and torn surfaces created void spaces that increased the air content in the samples. However, this was contradictory with the effect obtained on disks and wedges in Chapter 3, where rough surfaces seemed to trap extra water and showed slightly lower air contents compared to samples with smooth surfaces.

The second and perhaps more reasonable explanation lies in the loss of moisture due to squeezing of wood during the coring process. Increment cores are obtained by exerting considerable amount of pressure in radial and grain directions both inside and outside the borer cylinder. During the boring process the threaded bit penetrates the wood slowly and squeezes green wood inside the tree leading inevitably to some moisture loss. In the case of the 5 mm cores it would appear that the pressure exerted in a smaller cross sectional area led to higher loss of water and mechanical damage.

Table 4-2. Means in young sapwood green density, saturation, and green wood components at breast height sampled in winter for dropsaw 50 mm disks versus 12 and 5 mm cores in fresh condition, and after soaking in water for 24 hours and 3 weeks (n=10 trees). LSD test only for disks and cores soaked 24 hours; different letters are significant at P < 0.01

Method/samples condition	Green density (kg/m^3)	(SD) †	Saturation (%)	(SD) †	Wood substance (%)	(SD) †	Free water (%)	(SD) †	Air (%)	(SD) †
Dropsaw Disks 50 mm thick	1099	(9) a	97.5	(1.6) a	22.8	(0.7) a	65.5	(1.8) a	1.6	(1.0) b
<u>Fresh condition</u>										
12 mm cores	1045	(45)	88.2	(6.7)	24.1	(1.3)	57.5	(4.7)	7.7	(4.4)
5 mm cores	993	(57)	79.9	(8.3)	24.3	(1.3)	52.0	(5.6)	13.1	(5.5)
<u>Soaked 24 h</u>										
12 mm cores	1092	(22) a	95.5	(3.0) ab	23.9	(1.3) a	62.6	(2.7) ab	3.0	(2.0) ab
5 mm cores	1073	(39) a	92.7	(5.3) b	23.8	(1.3) a	60.9	(3.4) b	4.8	(3.6) a
<u>Soaked 3 weeks</u>										
12 mm cores	1126	(9)	100	(0)	23.9	(1.3)	66.0	(1.7)	0	(0)
5 mm cores	1134	(6)	100	(0)	23.9	(1.3)	66.9	(2.1)	0	(0)

† Results of LSD test
SD=Standard deviation

Results after soaking in water for 24 hours indicated that the 12 mm cores gave a close match to the dropsaw disks for both green density and saturation; in contrast the 5 mm cores still showed somewhat low and more variable results (Table 4-2 and Figure 4-5). Improvement of cores was in direct relation to the increased amount of free water and reduced air content (Table 4-2) suggesting that soaking for 24 hours gave a close approximation to the amount of water lost during the process of coring, especially for 12 mm cores. Statistical results revealed that green densities of both 12 and 5 mm cores soaked 24 hours were similar to the dropsaw disks; however the amount of free water and so the saturation of the 5 mm cores was considerably and statistically lower than dropsaw disks. These results and the elevated variability of the 5 mm cores (Figure 4-5) indicated that this method was not appropriate.

Results after soaking for 3 weeks indicated that for both 12 and 5 mm cores green density values were close to dropsaw samples and showed low variability; however results were biased by the fact that both cores reached complete resaturation (Table 4-2). It was evident that 3 weeks was an excessive period of time but the aim was to explore two extremes of soaking.

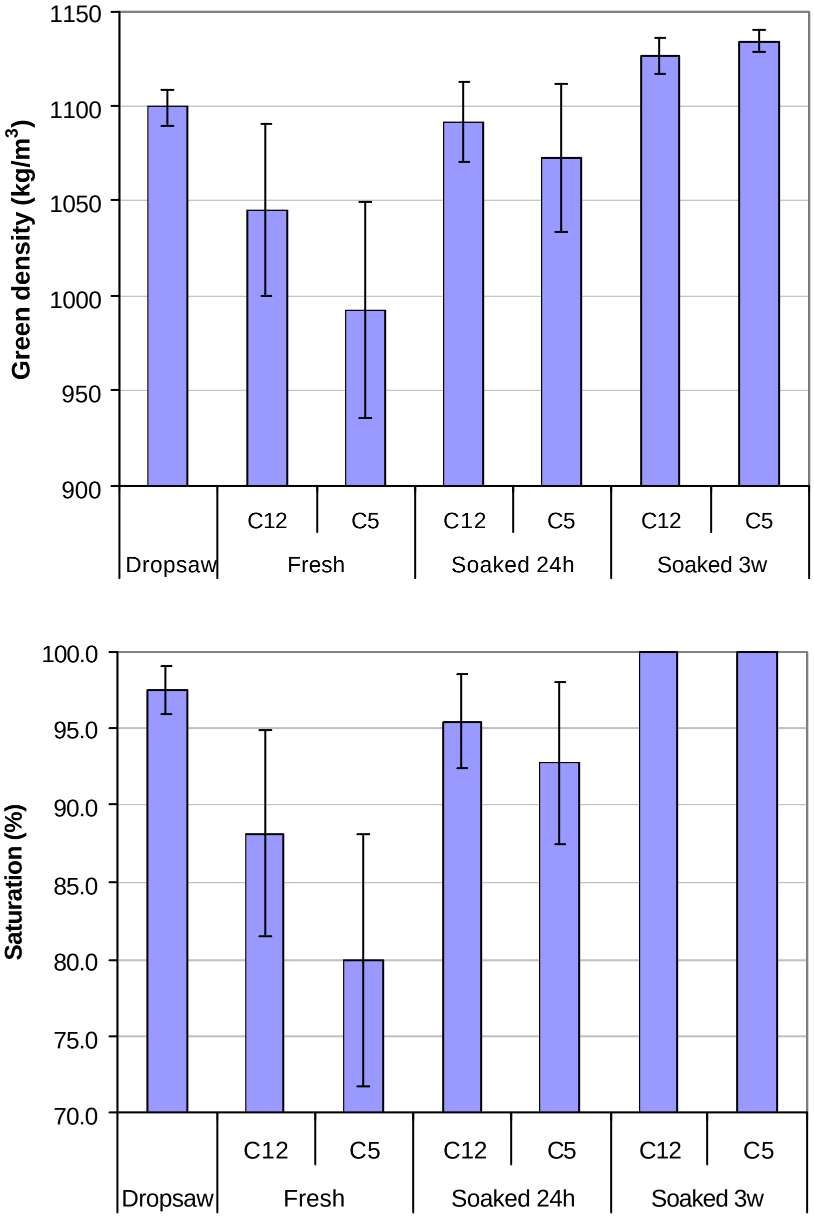

Figure 4-5. Means and variation in young sapwood green density and saturation sampled in winter for dropsaw 50 mm disks versus 12 and 5 mm cores (C12 and C5) in the fresh condition, and after soaking in water 24 hours and 3 weeks. (Vertical bars = ±1 standard deviation)

4.3.2 Material from young trees measured in summer and regression analysis for material of young trees across seasons

Average values for material from young trees collected in summer are shown in Table 4-3. There was a fairly good approximation in green density and saturation for the 12 mm cores soaked in water 24 hours with respect to dropsaw disks, and differences between methods were not statistically significant (Table 4-3). Values of 12 mm cores for green wood components were statistically similar to those of the dropsaw disks yet the air content was somewhat higher and caused saturation to decrease (Table 4-3).

Table 4-3. Means and statistical differences in young sapwood green density, saturation, and green wood components at breast height sampled in summer for dropsaw 50 mm disks versus 12 mm cores soaked in water 24 hours (n=26 trees)

Method	Green density (kg/m^3)	(SD)	Saturation (%)	(SD)	Wood substance (%)	(SD)	Free water (%)	(SD)	Air (%)	(SD)
Dropsaw 50 mm	1079	(58)	90.4	(9.7)	26.9	(2.8)	55.3	(7.5)	5.8	(5.8)
12 mm cores	1050	(49)	86.8	(7.8)	26.1	(2.5)	54.2	(6.3)	8.2	(4.8)
ANOVA method	ns		ns		ns		ns		ns	

ns = not significant
SD=Standard deviation

Results of regression analysis revealed that young sapwood green density and saturation measured destructively at breast height with smooth disks can be acceptably predicted from 12 mm cores soaked 24 hours (Table 4-4 and Figure 4-6). In the case of green density, cores explained between 64% and 69% of the variation in green density measured destructively with disks for each season, and 66% of variation across seasons (joint data) (Table 4-4 and Figure 4-6a). Similarly, cores explained between 51% and 72% of the variation in saturation measured destructively with disks for each season, and 74% of variation across seasons (Table 4-4 and Figure 4-6b). Results in Table 4-4 showed that relationships between cores and disks varied noticeably between seasons; however tests of parallel regressions for both green density and saturation revealed no statistical influence of season. It is suggested to use the regression obtained in summer due to the following reasons: 1) the summer data covers the whole range of sapwood green density and saturation, 2) unlike the joint data in which the winter points have some leverage, data is better 'balanced' for the summer regressions, and 3) slightly higher accuracy (R^2) (Table 4-4).

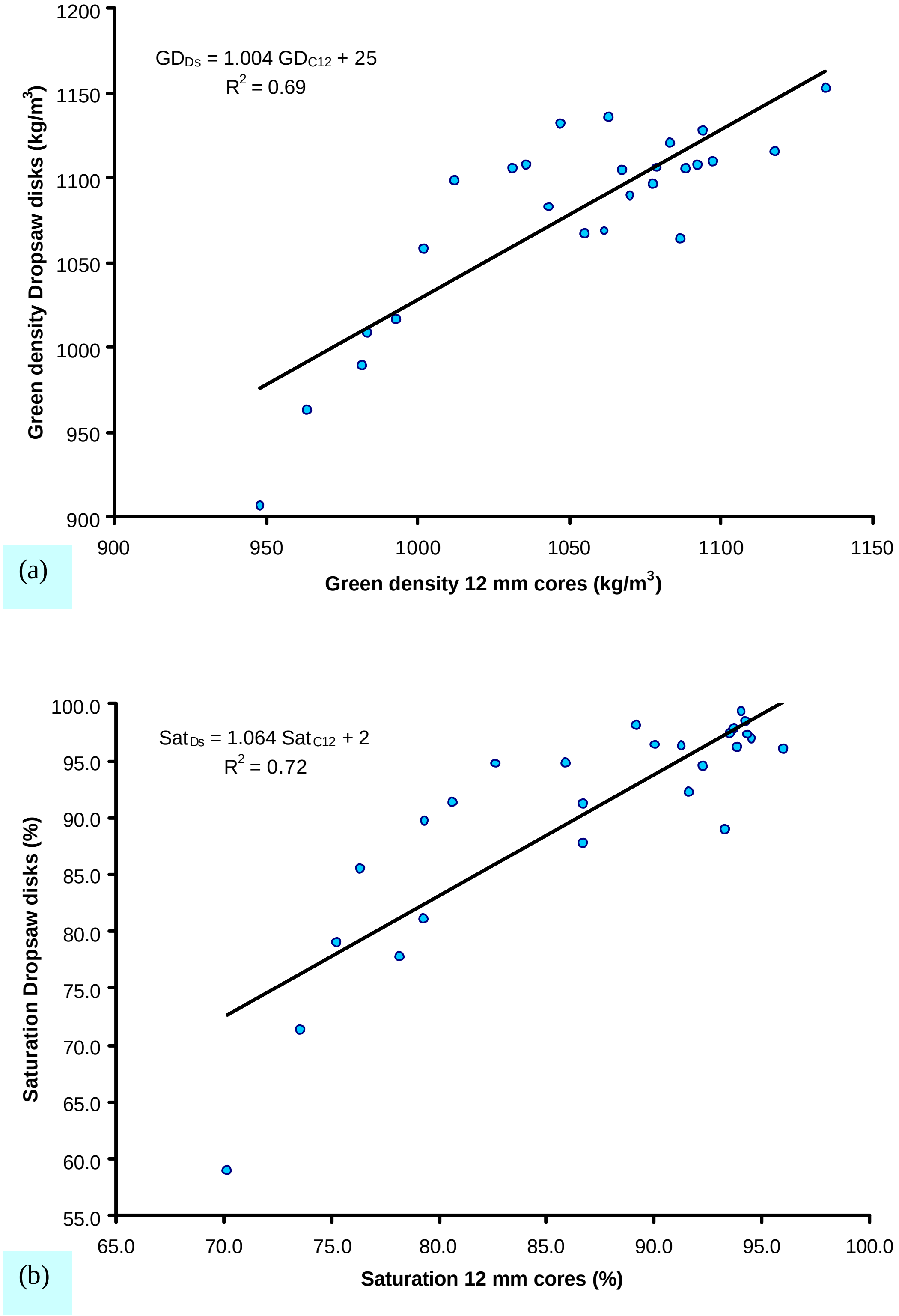

Figure 4-6. Linear relationships between dropsaw disks and 12 mm cores soaked in water 24 hours for sapwood green density (a) and saturation (b) of young trees measured at breast height in summer (n=26 trees)

Table 4-4. Regression equations for breast-height sapwood green density (GD_{Ds}) and saturation (Sat_{Ds}) of young trees measured destructively with dropsaw disks, and predicted by 12 mm cores soaked in water 24 hours (GD_{C12} and Sat_{C12}, respectively); 95% confidence intervals for coefficients in brackets

Trait / Season	Regression equation		adj-R^2	n
Green density (kg/m^3)				
winter	GD_{Ds} =	GD_{C12} × 0.359 (± 0.199) + 707 (± 217)	0.64	10
summer	GD_{Ds} =	GD_{C12} × 1.004 (± 0.274) + 25 (± 288)	0.69	26
joint	GD_{Ds} =	GD_{C12} × 0.886 (± 0.216) + 144 (± 230)	0.66	36
Saturation (%)				
winter	Sat_{Ds} =	Sat_{C12} × 0.385 (± 0.277) + 61 (± 26)	0.51	10
summer	Sat_{Ds} =	Sat_{C12} × 1.064 (± 0.272) - 2 (± 24)	0.72	26
joint	Sat_{Ds} =	Sat_{C12} × 0.977 (± 0.198) + 5 (± 18)	0.74	36

In Figure 4-6 there was one point with very low sapwood green density and saturation which was attributed to a considerably amount of dry (cavitated) sapwood observed in the disk. There were six trees in total out of the 26 collected in summer which also presented cavitation bands and thus lower green densities and saturations. The presence of cavitation in the sapwood is extensively discussed in Chapter 7. If the point with the lowest values is removed from the regression analysis, the corresponding R^2=0.65 and 0.71 for sapwood green density and saturation, respectively.

4.3.3 Material from mature trees

Regression analysis for predicting values at breast height of mature trees revealed that in the case of sapwood green density and saturation, good results were obtained by bark-to-bark coring and averaging the two sides. 12 mm cores soaked 24 hours in water explained 73% of variation in sapwood green density, and 56% of sapwood saturation as measured by destructive wedges (Table 4-5). Results for the same traits indicated that coring only one side of the tree was not reliable and differed statistically from sampling two sides (Table 4-5).

12 mm cores soaked 24 hours gave good results for predicting whole-section green density (Table 4-5). Cores explained 72% and 80% of the variation in whole-section green density as measured by destructive wedges when coring one or two sides of the

tree, respectively. These results were in close agreement with the good results obtained for predicting sapwood sectional percentage; namely 12 mm cores explained 70% and 79% of the variation in sapwood content measured destructively using wedges (Table 4-5). Furthermore, tests for statistical differences between regressions indicated that reliable results for whole-section green density and sapwood sectional percent can be obtained by coring either one or two sides (Table 4-5).

Results also revealed that the number of heartwood rings can be reliably predicted from 12 mm cores, especially if averages from two sides are considered (Table 4-5). One and two-side averages from cores explained 57% and 71% of the variation in number of heartwood rings measured with wedges, respectively. Finally, prediction of heartwood green density from cores was poor either by sampling one or two sides, and contrasted with the good results obtained for sapwood and whole-section. From the practical point of view this result was not so critical because for the purposes of this investigation it was more important to estimate the green density for sapwood and whole-section material.

Table 4-5. Regression equations for breast-height green density, sapwood saturation sapwood %, and number of heartwood rings of mature trees measured destructively with wedges (Wg), and predicted by 12 mm cores soaked in water 24 hours (C12); 95% confidence intervals for coefficients in brackets (n = 29 trees)

Trait / material	No. Sides		Regression equation	R^2	Test Reg[†]
Green density					
Sapwood	One	$GD_{Wg} =$	$GD_{C12} \times 1.470\ (\pm 0.631) - 421\ (\pm 616)$	0.46	*
	Two	$GD_{Wg} =$	$GD_{C12} \times 2.389\ (\pm 0.567) - 1311\ (\pm 552)$	0.73	
Heartwood	One	$GD_{Wg} =$	$GD_{C12} \times 0.406\ (\pm 0.493) + 334\ (\pm 250)$	0.10	ns
	Two	$GD_{Wg} =$	$GD_{C12} \times 0.724\ (\pm 0.515) - 171\ (\pm 263)$	0.24	
Whole-section	One	$GD_{Wg} =$	$GD_{C12} \times 1.237\ (\pm 0.307) - 166\ (\pm 254)$	0.72	ns
	Two	$GD_{Wg} =$	$GD_{C12} \times 1.418\ (\pm 0.280) - 320\ (\pm 233)$	0.80	
SW Saturation	One	$Sat_{Wg} =$	$Sat_{C12} \times 1.294\ (\pm 0.721) - 15\ (\pm 51)$	0.33	*
	Two	$Sat_{Wg} =$	$Sat_{C12} \times 2.530\ (\pm 0.890) - 103\ (\pm 63)$	0.56	
Sapwood %	One	$SW\%_{Wg} =$	$SW_{C12} \times 0.840\ (\pm 0.215) + 9\ (\pm 15)$	0.70	ns
	Two	$SW\%_{Wg} =$	$SW_{C12} \times 0.933\ (\pm 0.190) + 2\ (\pm 13)$	0.79	
Heartwood rings	One	$HWr_{Wg} =$	$HWr_{C12} \times 1.040\ (\pm 0.355) + 0.9\ (\pm 3.2)$	0.57	ns
	Two	$HWr_{Wg} =$	$HWr_{C12} \times 1.174\ (\pm 0.293) - 0.3\ (\pm 2.6)$	0.71	

[†] Test of differences for paired regressions: * significant at $P < 0.05$; ns = not significant

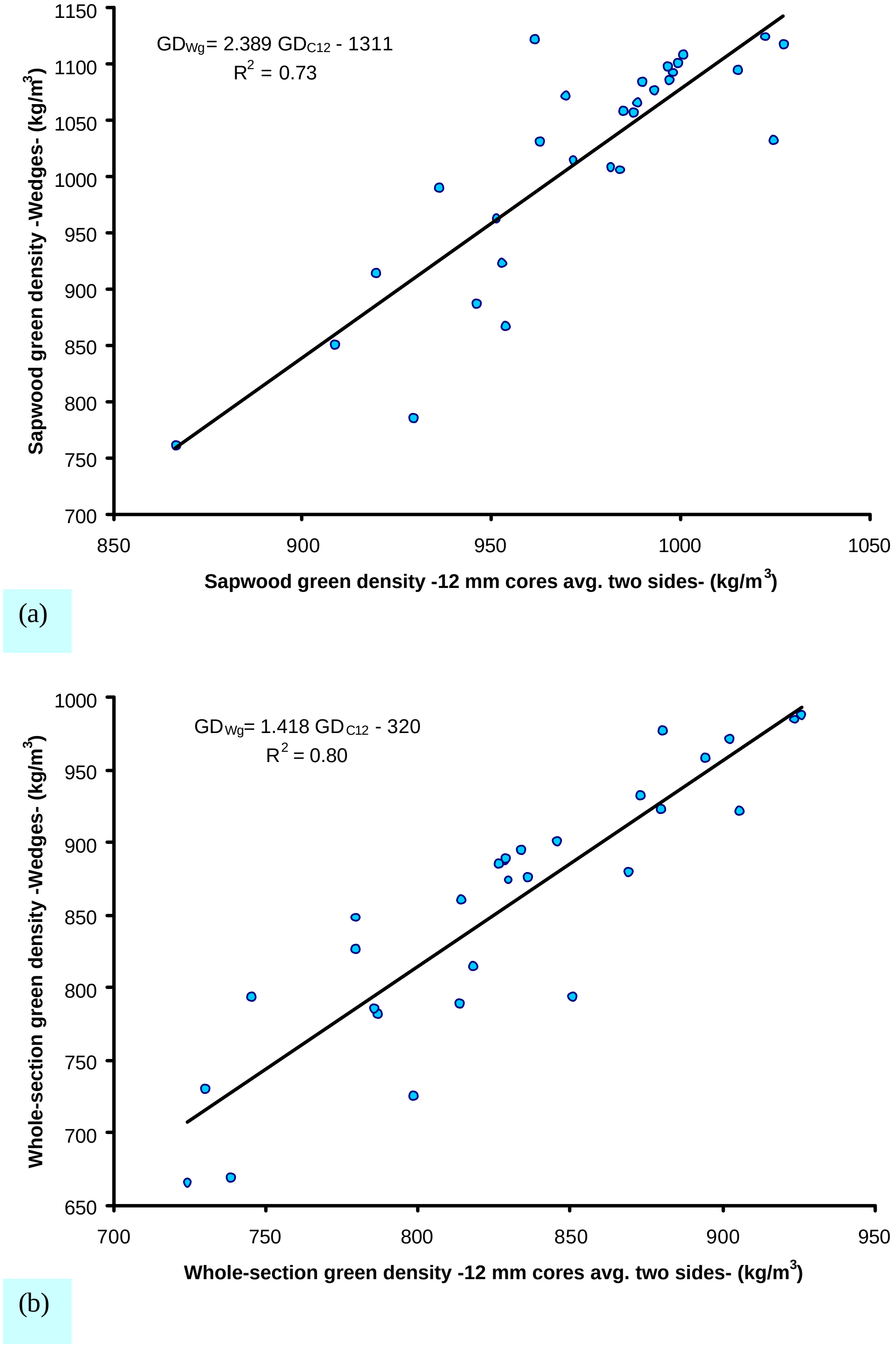

Figure 4-7. Linear relationships between destructive wedges and 12 mm cores soaked in water 24 hours –average of two sides– for sapwood (a) and whole-section (b) green density of mature trees measured at breast height (n = 29 trees)

Comparison between the entry and the exit side of the cores indicated no statistical differences in saturation or any of the green wood components (Table 4-6). On the contrary, results indicated virtually the same values across the sides. This revealed that there was no greater water loss in the entry side of the core as suspected. In the same way, based on the better results in green density and saturation obtained by averaging the two sides, it would appear that coring from side to side of the tree would capture more variation in moisture content within the cross section, and therefore would give more accurate results.

Table 4-6. Means and statistical comparison in saturation and green wood components between entry and exit sides of bark-to-bark 12 mm cores for mature sapwood as measured in summer of

Core side	Saturation (%)	(SD)	Wood substance (%)	(SD)	Free water (%)	(SD)	Air (%)	(SD)
Entry	70.9	(7.1)	28.8	(2.0)	41.5	(4.4)	17.0	(4.3)
Exit	70.8	(4.9)	28.3	(1.9)	41.9	(2.9)	17.3	(3.3)
ANOVA side	ns		ns		ns		ns	

ns = not significant
SD=Standard deviation

Regression analysis for predicting whole-tree values (lower two logs) from 12 mm cores taken at breast height and soaked 24 hours in water, revealed that reliable results in sapwood green density and saturation can be obtained by averaging the two sides of the cores (Table 4-7, Figure 4-8). Two-side averages explained 76% of variation in whole-tree sapwood green density and 57% of saturation, as measured by destructive wedges (Table 4-7). Also for the same traits results indicated that coring only one side of the tree was not as reliable as indicated by low R^2's and differed statistically from sampling two sides (Table 4-7).

Whole-tree values of whole-section green density could be reliably predicted either by one side or the average of two sides from 12 mm cores taken at breast height and soaked 24 hours in water: one and two-side averages from cores explained 77% and 81% of the variation in whole-section green density, respectively (Table 4-7, Figure 4-8). Further, whole-tree sapwood volumetric percent measured destructively could be acceptably related to the sapwood sectional percentage at breast height measured by cores (Table 4-7). Better results were obtained by averaging two-sides as opposed to only one side coring; however regressions were not different statistically (Table 4-7).

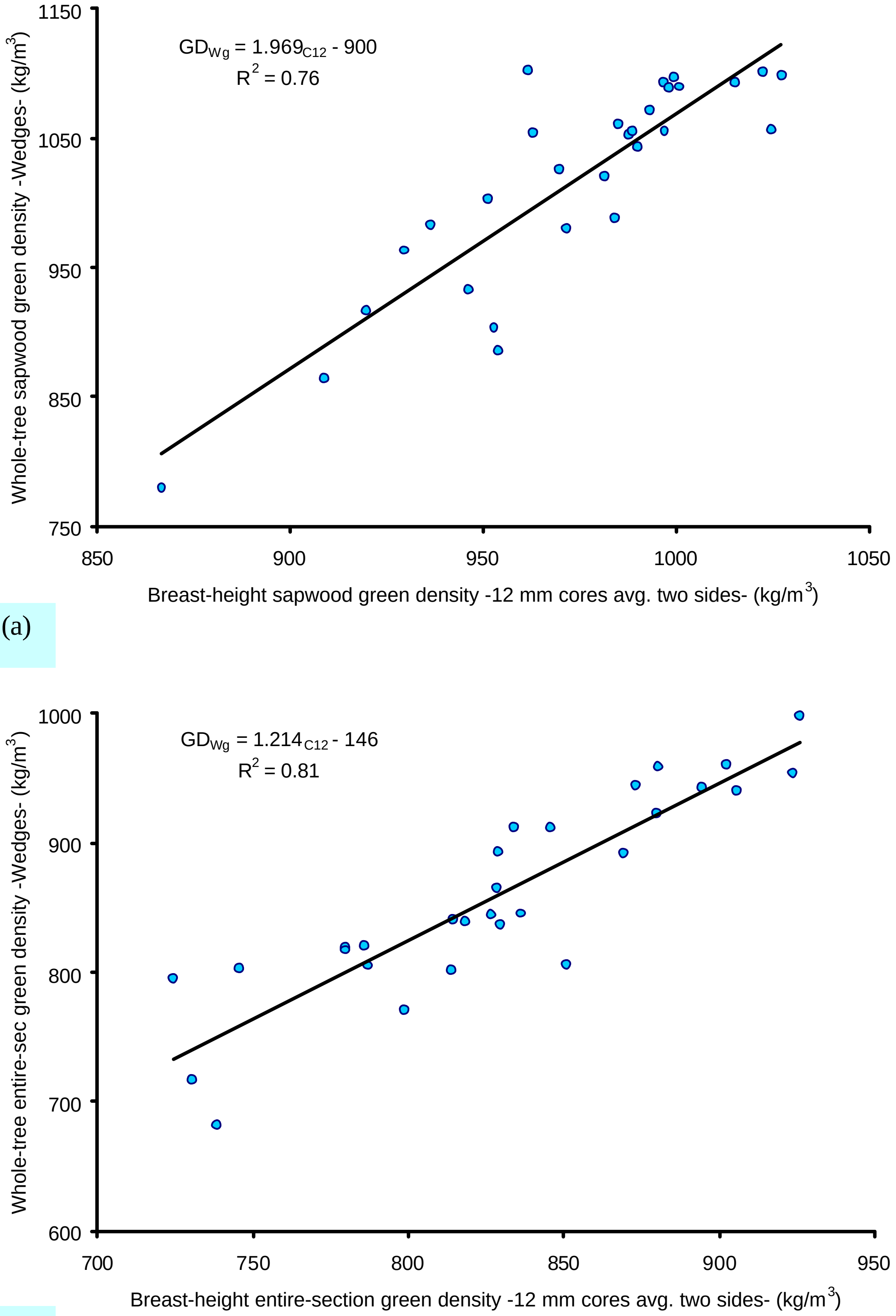

Figure 4-8. Linear relationships between destructive wedges and 12 mm cores soaked in water 24 hours –average of two sides– for whole-tree sapwood green density (a); and whole-section green density (b) of mature trees (n = 29 trees)

Table 4-7. Regression equations for whole-tree (lower two-logs) green density, sapwood saturation, and sapwood volumetric % of mature trees measured destructively with wedges (Wg), and predicted by 12 mm cores taken at breast height and soaked in water 24 hours (C12); 95% confidence intervals for coefficients in brackets (n = 29 trees)

Trait / material	No. Sides		Regression equation	R^2	Test Reg†
Green density					
Sapwood	One	$GD_{Wg} =$	$GD_{C12} \times 1.264\ (\pm 0.484) - 217\ (\pm 473)$	0.52	*
	Two	$GD_{Wg} =$	$GD_{C12} \times 1.969\ (\pm 0.437) - 900\ (\pm 426)$	0.76	
Whole-section	One	$GD_{Wg} =$	$GD_{C12} \times 1.090\ (\pm 0.238) - 41\ (\pm 198)$	0.77	ns
	Two	$GD_{Wg} =$	$GD_{C12} \times 1.214\ (\pm 0.236) - 146\ (\pm 196)$	0.81	
SW Saturation	One	$Sat_{Wg} =$	$Sat_{C12} \times 1.011\ (\pm 0.588) + 7\ (\pm 42)$	0.32	*
	Two	$Sat_{Wg} =$	$Sat_{C12} \times 2.049\ (\pm 0.710) - 67\ (\pm 50)$	0.57	
Sapwood %	One	$SW\%_{Wg} =$	$SW_{C12} \times 0.728\ (\pm 0.202) + 18\ (\pm 14)$	0.67	ns
	Two	$SW\%_{Wg} =$	$SW_{C12} \times 0.838\ (\pm 0.163) + 10\ (\pm 11)$	0.81	

†Test of differences for paired regressions: * significant at $P < 0.05$; ns = not significant

4.4 DISCUSSION

The use of increment cores for non-destructively measuring green density and moisture condition was the first choice given their availability and widespread use for measuring basic density in standing trees. Nonetheless, initial experiments revealed intrinsic deficiencies with using increment cores that had to be overcome in order to give good predictions of measurements attained destructively.

The most obvious question when using increment cores for green density and moisture content lies on the loss of moisture on the surface of the cores during the boring process. In this study it was conjectured that moisture is squeezed out of the cores by the indenting pressure of the borer. Presumably, the amount of water squeezed out of both 12 mm and 5 mm cores occurred to a greater extent for the latter due to the pressure exerted on a smaller cross sectional area. Ranatunga (unpublished 1954) quoted by Chalk and Bigg (1956) reported some indications of moisture squeezed out from increment cores while boring. However, the loss of moisture from the surface of the cores may be caused also by other factors such as frictional heating; the latter effect has been ignored. Whereas motorised borers generate noticeable heat during cutting, in this work the manual corer took 2-5 minutes and the heating effect was thought to be minimal.

It is practically impossible to avoid loss of moisture in the cores while boring. So the approach used in this study was to replace empirically the loss of moisture by soaking the cores in water. Results for both young and mature sapwood indicated that 24 hours seemed to give a good approximation; however, for practical reasons the actual amount of water replaced per unit time was not measured. Instead, the quantity of bubbles coming out of the cores while being soaked in water was monitored using two batches of samples from an independent experiment conducted in the middle of summer of 2007 after an extended drought period. Photographic sequence is shown in Figure 4-9 below. Observations revealed that a large number of bubbles occurred in the first one or two hours; after this time the rate decreased considerably but remained steady for the following period up to the 24-hour cut-off point. After this, bubbles still emerged at about the same rate. Based on this evidence it was concluded that if the moisture squeezed out while coring is indeed replaced while soaking in water, then this is mainly happening during the first hour or two but continues more slowly thereafter and the choice of a 24-hour period is an arbitrary and pragmatic decision.

According to results for young trees, the 24-hour soaking period seemed to work well for 12 mm cores collected in different seasons. Expectations were that perhaps less accurate results would be obtained in summer because of the higher between-tree variability in saturation as compared to winter (Tables 4-2 and 4-3). Results however, indicated slightly better results in summer for breast-height sapwood green density and noticeably better for saturation. Differences may have been also related to the improvement in the procedures or possibly the larger sample size used.

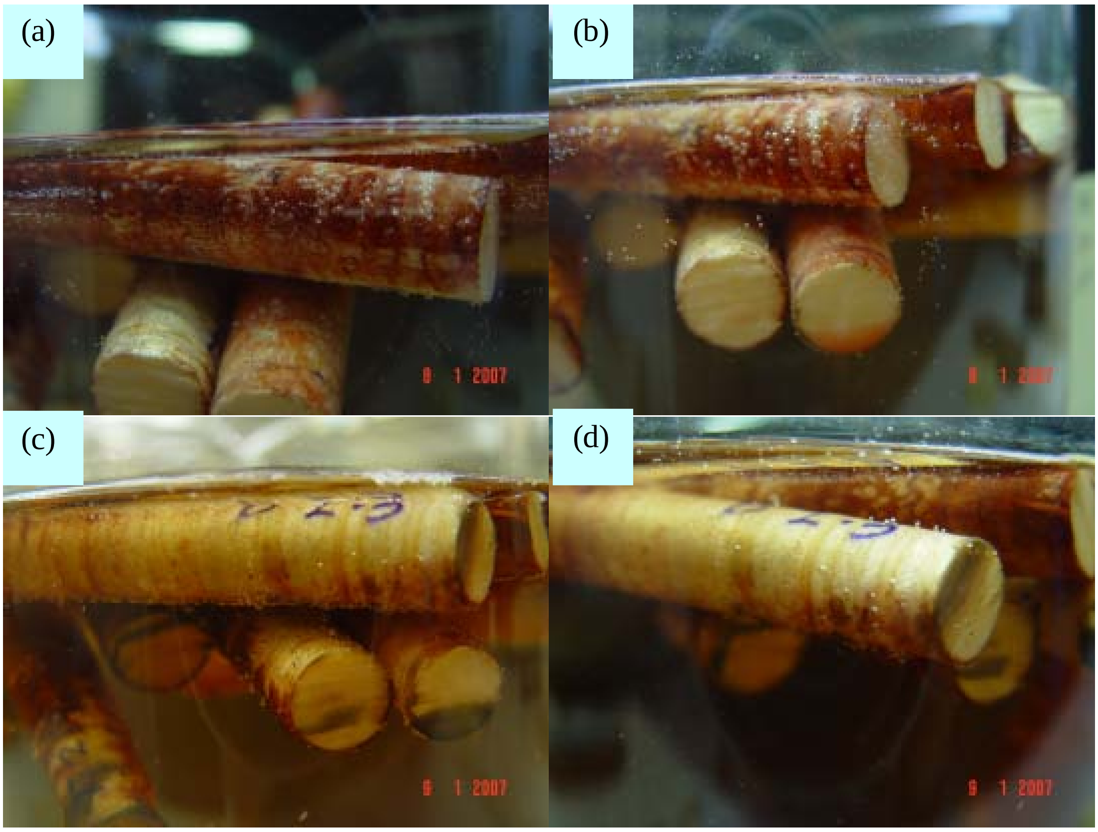

Figure 4-9. Sequence of 12 mm cores soaked in water to replace moisture lost during the coring process: a) start of soaking; b) after one hour; c) after 14 hours; and d) after 22 hours

Better results were obtained for sapwood green density and saturation of young trees by using one-side cores in comparison to results obtained for the mature trees (Table 4-4 vs. Table 4-5). Indeed prediction accuracy for mature trees was very poor when considering only the entry side of the cores. This was attributed to the lower proportion of volume sampled by a single radius core for the mature trees. For example for a mature tree of 40 cm diameter (DBH) and 70% sapwood, measured destructively with a sample of 70 mm thickness, the proportion of cross-sectional sapwood volume sampled by a single radius 12 mm core would be about 0.2%. The same proportion of sapwood volume sampled for a young tree of 10 cm DBH and measured destructively by a 50 mm thick disk would be about 1.4%. For the same reason, coring bark-to-bark and averaging the two sides of the cores in the case of mature trees improved considerably the prediction of both sapwood green density and saturation (Table 4-5). This was especially important for the study with mature trees which was conducted in the middle of the summer 2007 and after a long period of drought. These particular conditions caused a high between-tree variation in moisture content expressed as saturation (Table 4-6) and a high occurrence of xylem cavitation.

During the course of the study it was observed that the entry side of the cores showed a small squeezed area immediately underneath the bark as a result of the pressure exerted by the borer. At first it was believed that this effect may have influenced the poorer results given by the entry side of the cores. However, after comparison with the 'exit' side of the cores there were no differences in saturation and green wood components. This confirmed that the increased accuracy on prediction by coring bark-to-bark was due to the higher proportion of volume sampled. In fact for large trees and during the dry seasons for trees of any age, it would be highly recommended to obtain bark-to-bark cores and average the two sides.

Mechanical damage on the surface of the cores is another factor hard to avoid using this method, even when sharpening the coring bits regularly. Nonetheless, experiments with destructive samples in Chapter 3 to measure the effect of rough surfaces indicated that this was far from being a factor that affects negatively the effectiveness of cores. Smith (1954) developed the maximum moisture content method for measuring basic density using ½ inch (ca. 12 mm) increment cores. Interestingly, the author indicated that cores had to be surfaced in order to remove the crushed surface fibres before further measurements. On the other hand, close examination of the 5 mm cores revealed that the mechanical damage suffered by this method made it completely inadequate for determination of green density or saturation.

As a result of the gradual improvement in procedures and the use of the custom-made handle for large trees it was possible to obtain high quality and free-of-damage 12 mm cores. This may have also been in part the cause of the considerable improvement in prediction accuracy obtained for the study with mature trees. Given the robust results with the method developed in this study with 12 mm cores when using the custom-made extended handle, this may be an alternative to the use of motorized devises, such as the Trecor at least for softwood species: carrying a motorized unit in difficult field conditions can be a major drawback. One of the practical reasons for developing Trecor was the low efficiency of 12 mm cores using manual borers[2]. Our preliminary

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[2] Raymond, C.A., Senior research officer, Forests NSW, Land Management and Technical Services PO BOX 46 Tumut, NSW 2720, Australia. January 2006, Personal comm.

work using the motorized borer gave a high frequency of broken samples which did not occur after improving the manual procedures. Nevertheless, the comparison between the manual corers and Trecor was not fully validated and results may vary; it is also worth to consider that other motorized corers may give also good results.

Experiments discussed in this study revealed that contrary to early expectations and preliminary work, loss of moisture during handling and storage was not a critical factor where using increment cores. Provided this is done properly this should not be a factor that negatively affects the usage of the method.

Finally, there is no published work on the use of increment cores for green density determination, therefore it was not possible to contrast the findings obtained here for this property. On the other hand, this method has been reported with good success for moisture content determination especially in early works (Huckenpahler 1936, Smith 1954, Chalk and Bigg 1956). Huckenpahler (1936) used 12-year-old *Pinus echinata* trees to obtain whole-section increment cores, disks, and radial segments for moisture content determination (expressed as a percentage of oven-dry weight). Whole-section cores were highly correlated to disks (r = 0.97), but interestingly disks were very thin (thickness ranged from 6 to 19 mm) so this may have influenced the results. Chalk and Bigg (1956) compared successive radial segments of increment cores and disks using two disks of Douglas fir. Correlation coefficients calculated with data provided in the report were 0, 0.79, 0.70, 0.46, and 0.43 for five successive positions from cambium. Clearly these results were rather modest compared to those obtained by Huckenpahler (1936).

4.5 CONCLUSIONS

- Closer examination of increment cores unravelled the intrinsic deficiencies of this method for green density and moisture content determination. Contrary to initial expectations, the cores do not experience loss of moisture during handling or storage but during the coring process itself presumably due to the pressure of the borer on the wood, although other factors such as frictional heating can be a major cause. The loss of water by the 12 mm cores could be replaced empirically by soaking in water for 24 hours and this period seemed to be adequate for material collected across contrasting seasons. However later it was discovered that the time required could be considerably less. As a result of the gradual improvement in procedures and the use of the custom-made handle for large trees it was possible to obtain high quality and free-of-damage 12 mm cores. On the other hand, the mechanical damage and excessive loss of water from 5 mm cores deemed this method as completely inadequate for this purposes.

- 12 mm cores soaked in water for 24 hours explained 66% of the variation in breast-height sapwood green density and 74% of sapwood saturation across seasons for young trees, as measured by destructively sampled disks. For mature trees better results were obtained by coring bark-to-bark and averaging the two sides. Cores explained 73% of the variation in breast-height sapwood green density, and 56% of sapwood saturation as measured by destructive wedges. On the other hand, reliable results in whole-section green density and sapwood sectional percent of mature trees could be obtained by coring either one or two sides. Cores explained between 72% and 80% of the variation in whole-section green density, and between 70% and 79% of the variation in sapwood content measured destructively using wedges. More accurate prediction of the number of heartwood rings was obtained with two-side averages of cores; variation explained was 71%.

- Prediction of whole-tree values (lower two logs) from 12 mm cores taken at breast height indicated that two-side averages explained 76% of variation in whole-tree sapwood green density and 57% of saturation. Whole-tree values of whole-section green density could be reliably predicted either by one side or the average of two sides from 12 mm cores; variation explained by cores was 77% and 81%, respectively. Finally, more accurate prediction of the whole-tree sapwood volumetric percent was obtained by averaging the two-sides of the cores; variation explained was 81%.

- The robust and consistent results given by the manual-extracted 12 mm cores across the different experiments suggested that this method can be an alternative to the use of motorized devices such as the Trecor, at least for softwood species. The high quality and low damage of the manual cores can be useful not only for green density and moisture determination, but also for other wood properties and physical observations in wood.

CHAPTER 5

Influence of age, site, thinning regime, season, and height on green density and moisture condition; and the effect of sampling and moisture content method

5.1 INTRODUCTION

Traditionally, the importance of green density and moisture content in wood has been related to transport of raw material, lumber drying, and the subsequent stages in processing a range of products. For this reason, few studies on the variation of green density and moisture condition of radiata pine have been published. These include Hughes and Mackney (1949), Loe and Mackney (1953), Fielding (1952), Cown and McConchie (1980, 1982), Harris (1961), and unpublished work discussed by Harris and Cown (1991) and Kininmonth (1991) as well as discussions by Bamber and Burley (1983). Interestingly, there is only one study reported for radiata pine in Australia, namely Fielding (1952) but it refers only to moisture condition.

Apart from the importance of green density and moisture content of green wood for transport and processing, there are a number of emerging applications. One of these is the use of acoustic tools for stiffness determination of standing trees, logs or lumber. In this case green density is required to calculate the dynamic MOE (DMOE) of green wood, i.e. DMOE = V^2?, where V = acoustic velocity and ? = green density.

It was common practice in previous studies of green density and moisture content with radiata pine to obtain weighted averages for the whole cross-section and/or whole-tree values as these studies seemed to be focused on the importance of green density for transport of raw material. At the same time, early studies quite regularly explored radial changes in green density and moisture by dissecting at fixed distances from the pith or grouping growth rings; but unfortunately sapwood and heartwood green density averages and cross-sectional proportions were inconsistently reported.

There was also a noted lack of systematic information regarding the patterns of variation of green density as influenced by factors such as age, site, season, silviculture, and position in the tree. Such knowledge is necessary for resource characterization using dynamic MOE of standing trees and logs.

There are a few studies on the variation of moisture condition of live trees conducted on several conifer species and temperate hardwoods, from the utilization perspective and also to explain seasonal changes. These include Chalk and Bigg (1956), Clark and Gibbs (1957), Gibbs (1958) and discussions by Skaar (1988). More recently live-tree moisture condition has been used in physiological studies for monitoring water status in trees (Borghetti *et al.* 1991, Cinnirella *et al.* 2002, among others). This is quite distinct from the concept of moisture content for wood in utilization, where it is common to express the moisture content as a percentage of the ovendry weight. Instead, common measures of moisture content in trees include the water content expressed as the volumetric proportion occupied by water in green wood (Fielding 1952, Clark and Gibbs 1957, Borghetti *et al.* 1991, Cinnirella *et al.* 2002). Another measure of moisture condition in live trees is the ratio between the volume of water present in green wood and the maximum possible volume available for water, known as the moisture saturation (Chalk and Bigg 1956, Kininmonth 1991). Harris (1954a) related saturation percentage only to the volume of <u>ab</u>sorbed water (water contained in the lumens of the wood cells) with respect to the maximum volume available for absorbed water, i.e. ignoring the <u>ad</u>sorbed water within the cell walls.

The main purpose of this study was to determine patterns of variation of green density and moisture condition for radiata pine in the Hume region of Forests NSW, as influenced by age, site, thinning regime, height, and season. Secondly, this study compared three measures of moisture condition in live trees: percent saturation, moisture content expressed as a percentage of the ovendry weight, and the volumetric proportion occupied by water in green wood.

5.2 METHODS

5.2.1 Location and sites description

The study was carried out in the Hume region of Forests NSW, which is located towards the south east boundary with Victoria (Figure 5-1). The study included mature (34 -36 years) and young trees (9 years average). In the case of mature trees, two contrasting climate sites were studied: a high-altitude sub-alpine (Buccleuch) and a warm-dry inland site (Carabost) (Table 5-1, Figure 5-1). Environmental differences between the two sites are extensively discussed in Sections 7.2.1 and 7.3.3. For young trees only one site of intermediate climatic conditions was included (Figure 5-1, Table 5-1).

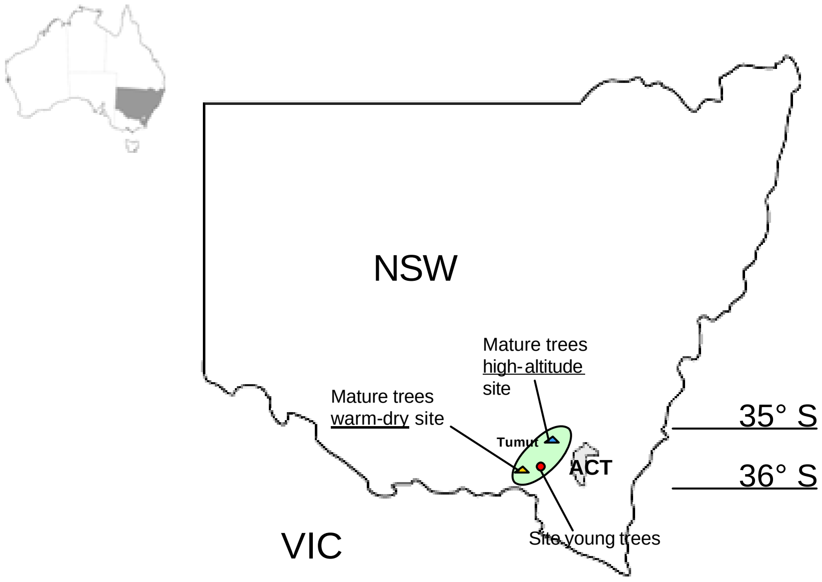

Figure 5-1. Location of the study

Table 5-1. Sites description

	Mature trees		Young trees
	High-altitude	**Warm-dry**	
Latitude (South)	35° 10.7 – 12.4’	35° 39.7 – 40.4’	35° 38.7’
Longitude (East)	148° 31.7 – 34.5’	147° 45.9 – 46.5’	147° 58.6’
Altitude (m)	896	524	723
Rainfall (mm per year) [1]	1252	923	1085
Evaporation (mm per year) [1]	1318	1394	1318

[1] Source: ESOCLIM model (run date 28/7/06), Forests NSW Sydney

5.2.2 Sampling procedures

At each of the sites there were paired stands of mature trees representing three thinning regimes: unthinned (UT), two- (T2) and three-thinnings (T3). The medium-thinned stands were sampled in winter 2005 and summer 2006 in adjacent plots in order to assess the effect of season whereas the unthinned and heavy-thinned stands were measured in spring 2005 to test for the effect of thinning regime. The effect of site and any interaction with season and thinning regime was assessed by comparing stands across sites. Characteristics of mature stands are shown in Table 5-2. Separately, the young trees were sampled both in winter 2005 and summer 2006 to test for any seasonal effect and at the same time for differences with age when compared to mature trees at breast height.

Table 5-2. Characteristics of stands measured

	Mature - high-altitude			**Mature - warm-dry**			**Young**
State forest (Section)	Buccleuch (Mitchells)			Carabost (Short Cut Rd. and Rosewood Trig Rd.)			G. Hills S. Courabyra
Stand (thinning)	UT	T2	T3	UT	T2	T3	--
Compartment	624	591	720	163	171	163	532-33
Age	36	34.5	36	36.5	35.5	36.5	9 (avg)
Season (s) sampled	spring-05	winter-05, summer-06	spring-05	spring-05	winter-05, summer-06	spring-05	winter-05, summer-06
Initial/Final stocking	1330 / 722	1330 / 220	1330 / 205	1370 / 712	1370 / 280	1370 / 193	Natural reg.
Age at thinnings	--	18, 24	14, 23, 30	--	14, 21	14, 27, 30	--
DBH (mm)	396	490 (winter) 489 (summer	581	351	420 winter 418 summer	538	119
Height (m)	35.1	32.8 summer	32.1	27.6	29.6 summer	36.3	--

At each of the mature stands a plot was established containing healthy trees without severe malformations or big branches; suppressed trees were avoided. The number of trees per plot was 10 except in the stand corresponding to the warm-dry site-winter-T2 which included 15 trees. Trees were manually felled and sectioned at 0.2, 1.3 (breast height), 5 m, and then every 5.5 m. Initially due to logistic constraints trees were sectioned up to 16 m; however for the second half of the study it was possible to include one or two more sections further up the stem (27 m). Actual lengths of logs were recorded after sectioning; these varied little between trees except for the section close to the top which varied to some extent. Nominal heights were considered for convenience of analysis and presentation. Immediately after sectioning the stem, ca. 70 mm thick disks were cut and labelled at each of the nominal heights, except at 5 m height. Handling, storage and machining of disks into wedge-shaped samples was conducted according to the procedures indicated in Section 3.2.3. Samples for mature trees are shown in Figure 5-2a.

In the case of young trees, 10 trees were sampled in winter 2005 and 26 trees in summer of 2006. Individuals selected were healthy and of good form. Billets of 1 to 1.5 m length were cut at breast height, placed in drums with water and taken immediately to the laboratory for further processing. Disks 50 mm thick were cut from the billet and processed according to procedures described in Section 3.2.2. Samples of young trees are shown in Figure 5-2b below.

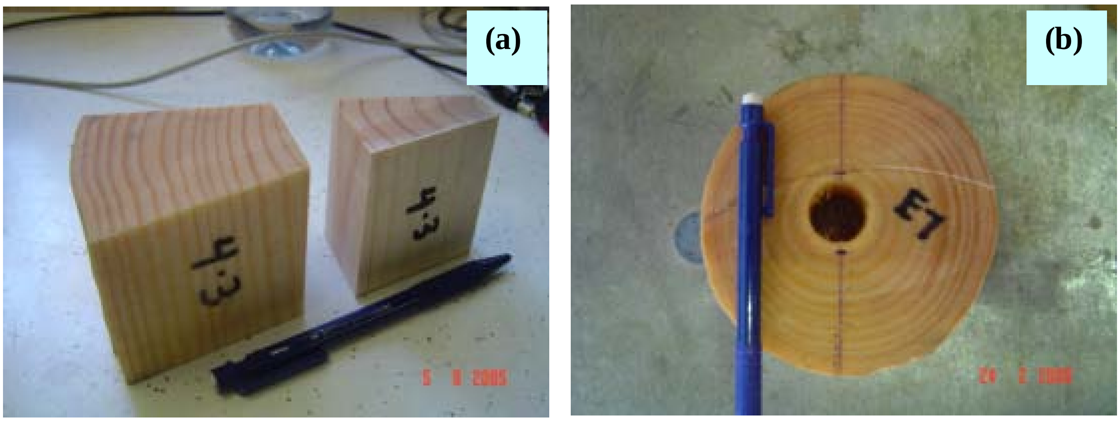

Figure 5-2. Samples of (a) mature trees showing sapwood and heartwood sections; (b) young trees showing sapwood with the pith-dry centre removed

Main variables considered were green density, basic density, and saturation percentage for pure sapwood and heartwood. All these were derived from measurements of green weight, green volume, and ovendry weight. Cross-sectional percentages of sapwood and heartwood were determined by measuring pith-to-cambium and heartwood radii. Whole-section values were the weighted averages of sapwood and heartwood by their respective sectional percentages. Results for young trees were given only for sapwood material because of their very incipient formation of heartwood. Definitions are listed in Figure 5-3 below; full discussion and development of these appear in Section 3.2.1.

a) Formulas for Tables 3 – 8

1) Green density (kg/m^3)	$GD = \frac{GW}{GV}$
2) Basic density (kg/m^3)	$BD = \frac{ODW}{GV}$
3) Wood substance (%)	$Wood\ \% = \frac{BD}{1500}\times 100$
4) Bound water (%)	$B\ water\ \% = \frac{BD}{1018}\times 30\%$
5) Free water (%)	$F\ water\ \% = \frac{BD}{1000}\times (MCODW\,\% - 30\%)$
6) Air content (%)	$Air\ \% = 100 - (Wood\ \% + Bwater\ \% + Fwater\%)$
7) Saturation (%)	$Sat\ \% = \frac{F\ water\%}{F\ water\% + Air\%}\times 100$
8) Water content (%)	$WC\ \% = B\ water\,\% + F\ water\,\%$
9) Moisture content as % of ovendry weight (%)	$MC_{ODW}\ \% = \frac{(GW - ODW)}{ODW}\times 100$
10) Heartwood and sapwood cross-sectional percentages	$HW\ \% = \frac{HW\,\mathrm{sec}\,tional\ area}{Cross\ \mathrm{sec}\,tional\ area}\times 100$ $SW\,\% = 100 - HW\,\%$

b) Formulas for footnote 2

11) Bound water (kg/m^3)	$BD \times 30\%$
12) Free water (kg/m^3)	$\left[1 - BD\times\left(\frac{1}{1500} + \frac{1}{1018}\times 30\%\right)\times 1000\right]\times Sat\%$
13) Green density (kg/m^3)	$BD + B\ water\ (kg/m^3) + F\ water\ (kg/m^3)$

Figure 5-3. Definitions used in the study, where GW=green weight, GV=green volume, ODW=ovendry weight. % values refer to volumetric percentages

5.2.3. Data analysis

Statistical analysis included one-way analysis of variance to test for the effects of age, height, season, site, and thinning regime alone. Two-way analysis of variance was used to test for interactions: age x season, site x season, and site x thinning regime. For the mature trees, analysis of variance was conducted for each of the sampling heights. Statistical effects of season, interactions of age x season, and of site x season on sapwood and heartwood green density were adjusted with basic density as covariate, whereas whole-section green density effects were adjusted using the percentage of sapwood. Regression analysis was conducted to explain changes in green density with height as influenced by height alone, and adding basic density, water content, and saturation individually. In the latter case, because multiple samples are removed from the same individual tree, another statistical technique such as the repeated measures may have been an alternative way of analysis. Finally, testing for parallel regressions was conducted for each paired stand to test for the influence of site on vertical variation of green density and saturation.

5.2.4. Monitoring of dry conditions

The Byram-Keetch Drought Index (BKDI)[1], recorded routinely by the automated weather stations of the Hume region, was used as a guide to monitor the drought conditions in the two contrasting sites of mature trees. This ensured doing the destructive measurements for the medium-thinned stands corresponding to summer 2006 in extreme dry conditions. Water stress of the two contrasting sites of mature trees was also estimated through measurements of needle water-potential on the two medium-thinned stands (T2) in summer 2006. For this purpose a pressure chamber was taken to the field and measurements were done immediately after felling the trees in the first hours of the morning. Four needle samples per tree were taken from the newest foliage at different positions of the crown. Results indicated significantly

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[1] The BKDI is an estimate of the moisture condition or dryness of the top layers of soil and is used for assessing fire risk in the forest. Australian Bureau of Meteorology. Website http://www.bom.gov.au/weather/nsw/firewx/kbdi.shtml, visited 01/08/2006

(P < 0.001) lower needle water potentials for the warm-dry site which suggested higher transpiration rates and water stress for the warm-dry site in the hottest part of the year.

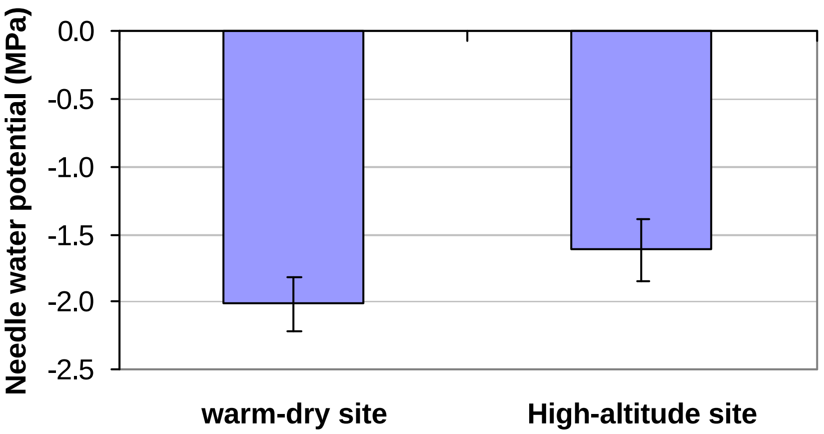

Figure 5-4. Average needle water potential for mature trees of the medium-thinned stands (T2) measured in summer 2006; vertical bars indicate ± 1 standard deviation

5.3 RESULTS

5.3.1. Influence of age

Differences in green density between mature and young sapwood were small yet statistically significant in winter (Table 5-3). Results indicated that in both seasons the higher water content of young trees was counterweighted by the higher wood substance (basic density) of mature trees so the final difference in green wood mass per unit volume was small[2].

Results indicated statistically significant differences in moisture condition between young and mature trees across seasons; mature trees were consistently drier than

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[2] In winter there was a difference of 146 kg/m^3 for basic density in favour of mature trees on the dry site, but this was counterbalanced by a difference of 115 kg/m^3 for water in young trees giving a final difference of 31 kg/m^3 green density in favour of mature trees (water content = green density – basic density). On the other hand in summer the difference in basic density was much lower (53 kg/m^3 in favour of mature trees) and for water content was 59 kg/m^3 in favour of young trees giving a final difference in green density of only 6 kg/m^3.

young trees -as indicated by saturation percentage- in both seasons at 1.3 m height (Table 5-3).

Table 5-3. Means and statistical results for age and season effects for young trees; including sapwood green density, basic density, water content, and saturation percentage at 1.3 m height during two seasons

Season	Age	Green density (kg/m^3)	Basic density (kg/m^3)	Water content %	Saturation %
Winter	Young	1100	346	75.2	97.5
	Mature (warm-dry site)	1131	492	63.6	93.2
	ANOVA age	***	***	***	***
Summer	Young	1103	404	69.7	94.4
	Mature (high-altitude site)	1120	499	61.9	90.6
	Mature (warm-dry site)	1097	457	63.8	89.8
	ANOVA age	ns	***	***	**
ANOVA interaction age x season [1]		ns	--	ns	ns
Young trees, ANOVA season effect [1]		ns	--	ns	**

* $P < 0.05$, ** $P < 0.01$, ***$P < 0.001$, ns = not significant

[1] Adjusted effects of season and interaction of age x season on green density and water content with basic density as covariate; tested only with mature trees on the warm-dry site

5.3.2. Influence of site

Results indicated that site was by far the most influential factor affecting whole-section green density and this was directly related to the differences in sapwood/heartwood percentages between sites (Figure 5-8). In all cases the high-altitude site presented higher sapwood contents and therefore higher whole-section green densities (Figure 5-8). At breast height, average differences in sapwood percentage as influenced by thinning regime ranged from 8 to 14%, whereas differences in whole-section green density varied from 46 to 84 kg/m^3.

Statistical differences in sapwood green density with site occurred only for the medium-thinned trees sampled in summer (Table 5-4) which was due to the considerably higher basic density of the high-altitude site along the stem (Table 5-6). On the other hand, heartwood green density presented considerable statistical differences with site for the unthinned and heavily-thinned stands being due to changes in basic density (Tables 5-5 and 5-7). Average differences in breast-height sapwood green density with site ranged from 5 to 23 kg/m^3, whereas differences in heartwood green density ranged from 45 to 67 kg/m^3.

There were practically no differences in sapwood saturation with site across stands. In contrast, heartwood of the warm-dry stands was consistently drier than that of the high-altitude stands –as indicated by saturation–; although differences were small and mostly non-significant (Tables 5-6 and 5-7).

5.3.3. Influence of thinning regime

Results indicated that changes in sapwood percentage with thinning were not large enough to influence differences in whole-section green density (Figure 5-8). This was true even for the heavily thinned trees on the warm-dry site which showed considerably and statistically higher sapwood proportion in the lower 1.3 m of the stem than the unthinned trees (Table 5-5). At breast height, average differences in sapwood percentage as influenced by thinning regime ranged from 2 to 8%, whereas differences in whole-section green density varied from 0 to 17 kg/m^3.

Statistical differences in sapwood green density with thinning regime occurred only for the warm-dry site at the base of the tree (Table 5-5); mainly as a result of large differences in basic density in favour of the unthinned trees (Table 5-7). Large statistical differences in heartwood green density with thinning occurred for the warm-dry site in the lower 10.5 m of the stem as influenced also by basic density (Tables 5-5, 5-7). Average differences in breast-height sapwood green density with thinning regime ranged from 2 to 21 kg/m^3, whereas differences in heartwood green density ranged from 35 to 79 kg/m^3.

Results indicated practically no influence of thinning regime on saturation for both sapwood and heartwood (Table 5-7). Nevertheless, the unthinned stands seemed to be slightly drier especially at the bottom of the tree (Table 5-7).

The large differences in diameter at breast height between unthinned and heavily-thinned trees (Table 5-2) contrasted with the small changes obtained in sapwood and whole-section green density and saturation, indicating no influence of diameter. Namely the average DBH of unthinned trees was 351 and 396 mm for the warm-dry and high-altitude sites, respectively; compared to 538 and 581 mm for the heavily-thinned trees.

5.3.4. Influence of season

5.3.4.1. Mature trees

Results indicated no statistical changes in sapwood green density with season but in contrast there were significant differences in heartwood and whole-section green density at the lower 1.3 m of the tree on the warm-dry site (Table 5-4).

Results also showed influence of season on moisture condition for the warm-dry site as indicated by saturation percentage of both sapwood and heartwood; trees of the warm-dry site were effectively drier in summer although only statistically significant at 1.3 m (Table 5-6). Average changes in sapwood saturation with season at the lower 1.3 m height were rather small (0.4 – 3.4%); and small to large for heartwood (2.9 – 8.2%) (Table 5-6). Despite the small change in average sapwood saturation with season for mature trees, during the dry season the warm-dry site presented a considerable number of samples with low saturation. These samples had prominent dry marks of different sizes and shapes within the sapwood which were associated with drought and xylem cavitation. These effects are discussed thoroughly in Chapter 7.

5.3.4.2. Young trees

Results indicated no effect of season on sapwood green density of young trees (Table 5-3). The possible influence of season was confounded by the higher basic density of trees sampled in summer (Table 5-3). Nevertheless, results after ‘correcting’ the green density of summer trees indicated that if basic density had been similar across seasons there would have been a drop of only 20 kg/m^3 in green density during the dry season which would still be a rather small decrease[3].

There was a true and statistically significant effect of season on moisture condition of young trees as indicated by saturation percentage (Table 5-3); sapwood saturation dropped from 98% in winter to 94% in summer. Further, sapwood saturation of young trees ranged from 86 to 99 % in summer, compared to 93 - 100% in winter. This indicated that during the dry season there were both moderately dry and saturated trees while in the wet season most trees were relatively close to saturation. In agreement with changes in saturation, young trees showed signs of drought during the dry season and these occurred at a greater extent than those observed in mature trees on the warm-dry site. These effects are discussed in detail on Chapter 7.

5.3.5. Variation along the stem

5.3.5.1 Sapwood

Sapwood green density generally displayed a rapid increase between the base of the tree and 1.3 m height, followed by a decrease and/or small change up to 16 m, and then a noticeable decrease towards the top of the stem (Figure 5-5). Only the heavily thinned trees on the warm-dry site ('WD site-spring-T3') presented a different trend with a gradual increase in the lower 10.5 m followed by a plateau thereafter. Trees sampled in summer presented the largest differences between the base and the top of the tree, ranging from 30 to 36 kg/m^3. Otherwise, changes in sapwood green density with height were modest and mostly non-significant (Tables 5-4 and 5-5). The range in sapwood green density along the stem among stands was around 30 kg/m^3 (Figure 5-5). Changes in sapwood green density with height were better explained by saturation and basic density as indicated by regression analysis and the vertical patterns of variation across stands (Table 5-8; Figures 5-6a and 5-6c).

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[3] 'Corrected' green density for summer trees was obtained as follows, space available for free water in winter = 1 – [346 x (1/1500 + 1/1018 x 30%)] = 0.667; from this free water in summer = 0.667 x 94.4% x 1000 = 630 kg/m^3, and bound water = 346 x 30% = 104 kg/m^3, so 'corrected' green density in summer = 346 + 630 + 104 = 1080 kg/m^3

Test for parallel regressions between sapwood green density and height for paired stands indicated significant interaction site x height for the medium-thinned trees sampled in winter (winter T2) and the unthinned trees (UT) (Table 5-9); nevertheless in the case of the former this was influenced by the lack of samples at 1.3 m for the high-altitude site in winter. Results for pooled stands indicated no interaction of site x height (Table 5-9).

On the other hand, results indicated that the sapwood at the base of the tree was consistently and statistically drier than the rest of the stem: saturation values for the base of the tree were about 90% whereas the rest of the stem presented values around 94% (Figure 5-6c; Tables 5-6 and 5-7). Lastly, the test for parallel regressions between sapwood saturation and height for paired and pooled stands indicated no interaction site x height (Table 5-9).

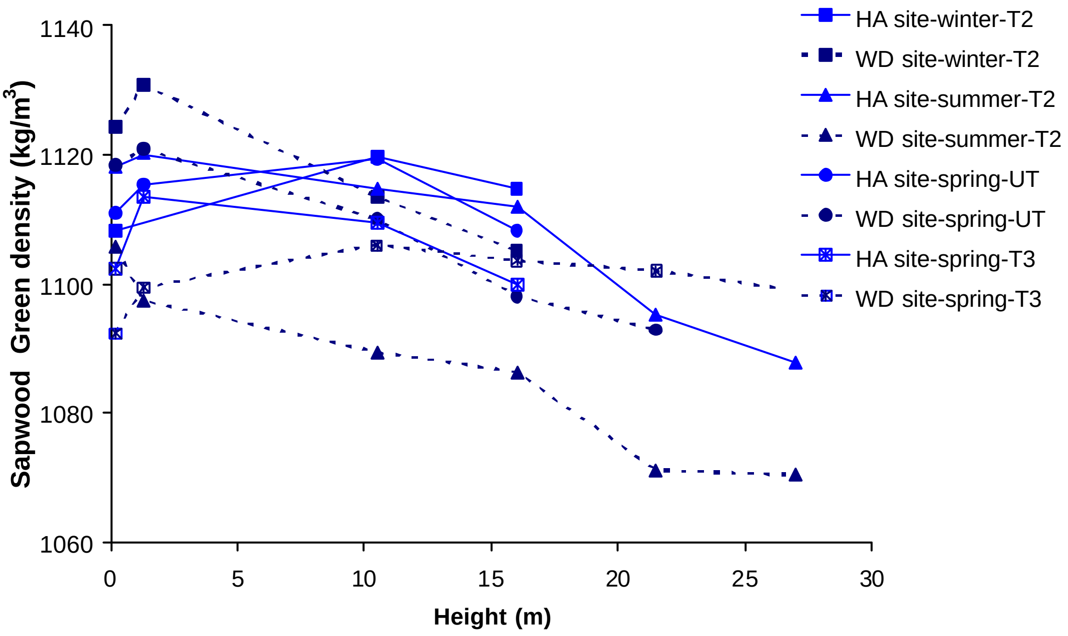


Figure 5-5. Variation in sapwood green density with height across stands; HA = high-altitude site, WD = warm-dry site; UT = unthinned trees, T2 = two thinnings, T3 = three thinnings

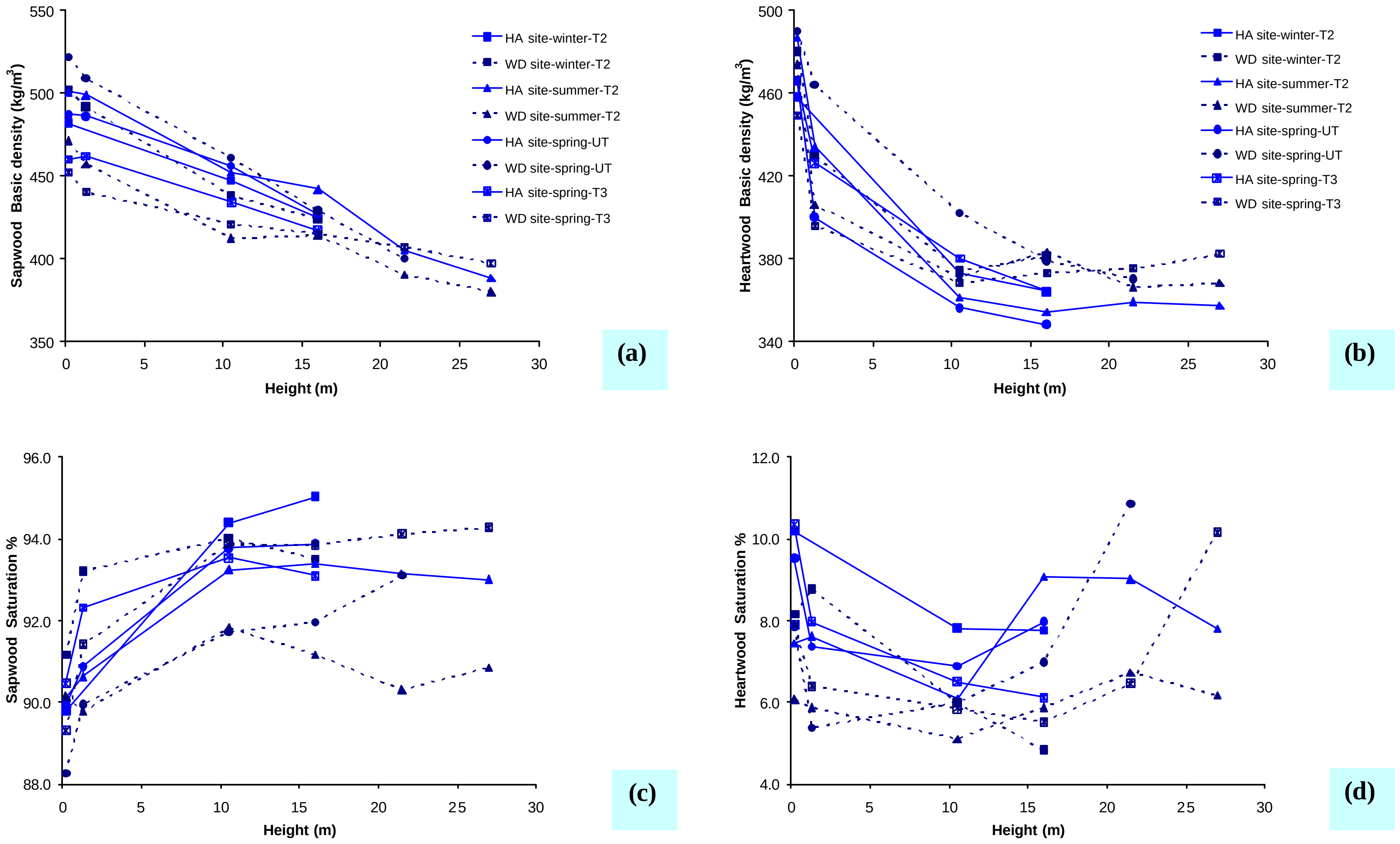


Figure 5-6. Variation in (a) sapwood and (b) heartwood basic density, and (c) sapwood and (d) heartwood saturation percentage with height across stands; HA = high-altitude site, WD = warm-dry site; UT = unthinned trees, T2 = two thinnings, T3 = three thinnings

5.3.5.2 Heartwood

Heartwood green density decreased considerably in the first 1.3 m and then showed a slower decrease up to 10.5 m; from this point there was a small change and/or sometimes a sudden increase after 16 m towards the top of the stem (Figure 5-7). Average heartwood green density decreased from 650 kg/m^3 at the base to 525 kg/m^3 at half the height and then increased to around 540 kg/m^3 at the top of the tree. Accordingly, statistical differences in heartwood green density with height were highly significant for all the stands (Tables 5-4 and 5-5). Changes in heartwood green density with height were better explained by basic density as indicated by regression analysis and the vertical patterns of variation across stands (Table 5-8 and Figure 5-6). Wood substance (basic density) occupied considerably more space than water leading to its larger influence on heartwood green density.

Testing for parallel regressions between heartwood green density and height for paired and pooled stands indicated no interaction of site x height (Table 5-9), which was in agreement with the uniformity in patterns across stands (Figure 5-7). The range in heartwood green density along the stem between sites/stands varied between 30 and 80 kg/m^3 (Figure 5-7) being largest at 1.3 m height.

Finally, heartwood saturation percentage was uniform with only small changes at the lower end of the tree whereas the upper stem showed an irregular trend among sites/stands (Figure 5-6d). Saturation values indicated that free water occupied only around 8% of lumen space, indicating that heartwood moisture content is just above the fiber saturation point and, perhaps, changes with height are of limited importance.

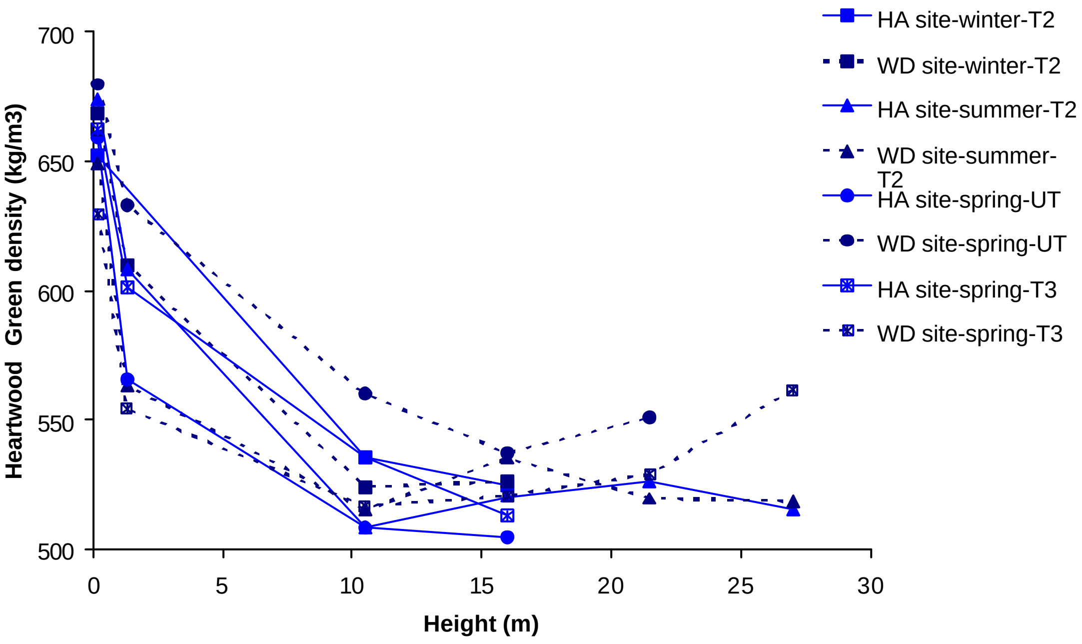


Figure 5-7. Variation in heartwood green density with height across stands; HA = high-altitude site, WD = warm-dry site; UT = unthinned trees, T2 = two thinnings, T3 = three thinnings

5.3.5.3 Whole-section

Whole-section green density showed a consistent inflection point at 10.5 m across stands; namely it decreased from the base of the stem to this point and then increased steadily towards the top of the stem. Differences between the base of the stem and 10.5 m height ranged from -37 to -77 kg/m^3, whereas differences from this point to the top of the stem varied from +42 to +100 kg/m^3 (Figure 5-8a). Accordingly, statistical differences in whole-section green density with height were mostly highly significant for all the stands (Tables 5-4 and 5-5). Changes in whole-section green density with height were mainly influenced by sapwood sectional percentage as indicated by vertical patterns of variation and regression analysis across stands (Figure 5-8 and Table 5-8).

On the other hand, testing for parallel regressions between whole-section green density and height for paired stands indicated significant interactions site x height for the heavily-thinned trees (T3) and for pooled stands (Table 5-9). This was in agreement with the differences in whole-section green density patterns between high-altitude and warm-dry stands (Figure 5-8a) especially in the first 10.5 m of the stem;

and with the differences in sapwood percentage at this same section of the stem (Figure 5-8b). On average, the whole-section green density in the high-altitude stands was between 39 and 65 kg/m^3 higher than in the warm-dry stands for the first 10.5 m whereas higher up the stem the differences narrowed to between 8 and 25 kg/m^3 (Figure 5-8a).

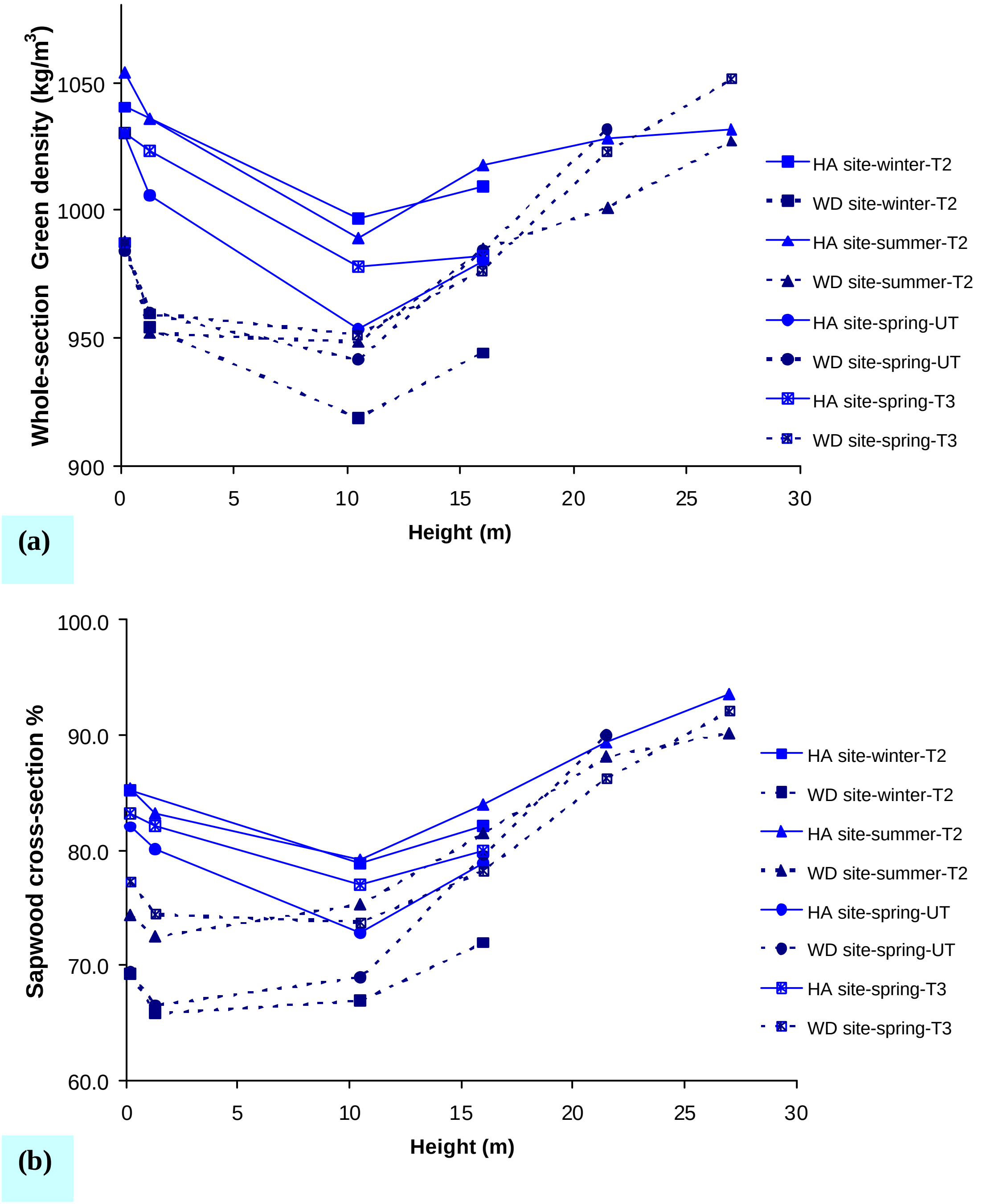


Figure 5-8. Variation in (a) whole-section green density, and (b) sapwood sectional percentage with height across stands; HA = high-altitude site, WD = warm-dry site; UT = unthinned trees, T2 = two thinnings, T3 = three thinnings

Table 5-4. Mean values and statistical effects on green density and cross section % for sapwood, heartwood, and whole-section at two contrasting sites (HA = high-altitude, WD = warm-dry), medium-thinned stands (T2)

Site	Height (m)	Sapwood				Heartwood				Whole section Green density (kg/m³)	
		Green density (kg/m³)		% Cross section		Green density (kg/m³)		% Cross section			
		Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
HA	0.2	1108	1118	85.2	85.4	652	674	14.8	14.6	1040	1054
	1.3	--	1120	--	83.2	--	608	--	16.8	--	1036
	10.5	1120	1115	78.8	79.2	535	509	21.2	20.8	997	989
	16	1115	1112	82.2	84.0	524	520	17.8	16.0	1009	1018
	21.5	--	1095	--	89.3	--	526	--	10.7	--	1028
	27	--	1088	--	93.6	--	515	--	6.4	--	1031
	height [1]	ns	***	*	**	***	***	*	***	**	***
WD	0.2	1124	1106	69.2	74.4	669	649	30.8	25.6	987	988
	1.3	1131	1097	65.8	72.5	610	563	34.2	27.5	954	952
	10.5	1114	1089	66.9	75.3	524	515	33.1	24.7	919	948
	16	1105	1086	72.0	81.4	526	535	28.0	18.6	944	985
	21.5	--	1071	--	88.1	--	520	--	11.9	--	1001
	27	--	1070	--	90.2	--	519	--	9.8	--	1027
	height [1]	**	ns	ns	***	***	***	ns	***	*	*
ANOVA Site	0.2	*	*	***	***	ns	ns	***	***	**	***
	1.3	--	*	--	***	--	ns	--	***	--	***
	10.5	ns	*	***	ns	ns	ns	***	ns	***	*
	16	ns	*	**	ns	ns	ns	**	ns	***	ns
	21.5	--	*	--	ns	--	ns	--	ns	--	ns
ANOVA Season [2]		HA site	WD site			HA site	WD site			HA site	WD site
	0.2	ns	ns			ns	*			ns	*
	1.3	--	ns			--	*			--	*
	10.5	ns	ns			*	ns			ns	ns
	16	*	ns			ns	ns			ns	ns
Site X Season [2]	0.2	ns				ns				**	
	10.5	ns				ns				ns	
	16	ns				ns				ns	

* P < 0.05, ** P < 0.01, ***P < 0.001, ns = not significant, [1] ANOVA results for height

[2] Adjusted effects of season and interaction of site x season with basic density as covariate for green density of sapwood and heartwood, and with SW% for whole-section green density

Table 5-5. Mean values and statistical effects on green density and cross section % for sapwood, heartwood, and whole-section at two contrasting sites (HA = high-altitude, WD = warm-dry) and two thinning regimes (UT = unthinned trees, T3 = three thinnings)

Site	Height (m)	Sapwood				Heartwood				Whole section Green density (kg/m^3)	
		Green density (kg/m^3)		% Cross section		Green density (kg/m^3)		% Cross section			
		UT	T3	UT	T3	UT	T3	UT	T3	UT	T3
HA	0.2	1111	1102	82.1	83.2	659	663	17.9	16.8	1030	1030
	1.3	1115	1114	80.1	82.1	566	601	19.9	17.9	1006	1023
	10.5	1119	1109	72.8	77.1	508	535	27.2	22.9	953	978
	16	1108	1100	78.9	79.9	505	513	21.1	20.1	980	982
	height [1]	ns	ns	**	ns	***	***	**	ns	***	**
WD	0.2	1118	1092	69.4	77.3	680	630	30.6	22.7	984	988
	1.3	1121	1099	66.5	74.4	633	554	33.5	25.6	960	960
	10.5	1110	1106	69.0	73.7	560	517	31.0	26.3	941	951
	16	1098	1104	79.6	78.2	537	521	20.4	21.8	984	976
	21.5	1093	1102	90.0	86.3	551	529	10.0	13.7	1032	1023
	27	--	1099	--	92.1	--	562	--	7.9	--	1051
	height [1]	*	ns	***	***	***	***	***	***	**	***
ANOVA Site	0.2	ns	ns	**	ns	ns	ns	**	ns	*	*
	1.3	ns	ns	***	*	**	**	***	*	*	**
	10.5	ns	ns	ns	ns	**	ns	ns	ns	ns	ns
	16	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ANOVA Thinning		HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site
	0.2	ns	**	ns	ns	ns	**	ns	ns	ns	ns
	1.3	ns	*	ns	*	ns	***	ns	*	ns	ns
	10.5	ns	ns	ns	ns	ns	**	ns	ns	ns	ns
	16	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	21.5	--	ns	--	ns	--	ns	--	ns	--	ns
Site X Thinning	0.2	ns		ns		*				ns	
	1.3	ns		ns		***				ns	
	10.5	ns		ns		**				ns	
	16	ns		ns		ns				ns	

* P < 0.05, ** P < 0.01, ***P < 0.001, ns = not significant, [1] ANOVA results for height

Table 5-6. Means and statistical effects on basic density, water content, and saturation percentage for sapwood and heartwood at two contrasting sites in summer and winter, medium-thinned stands (T2)

Site	Height (m)	Sapwood						Heartwood					
		Basic density (kg/m^3)[2]		Water content %		Saturation %		Basic density (kg/m^3)[2]		Water content %		Saturation %	
		Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
HA	0.2	482	501	62.4	61.5	89.8	90.1	458	487	19.2	18.4	10.2	7.4
	1.3	--	499	--	61.9	--	90.6	--	434	--	17.2	--	7.6
	10.5	447	452	67.0	66.0	94.4	93.2	373	361	16.0	14.6	7.8	6.1
	16	425	442	68.7	66.7	95.0	93.4	364	354	15.8	16.5	7.8	9.1
	21.5	--	405	--	68.8	--	93.2	--	359	--	16.5	--	9.0
	27	--	388	--	69.7	--	93.0	--	357	--	15.7	--	7.8
	height[1]	***	***	***	***	***	***	***	***	***	**	ns	ns
WD	0.2	502	471	62.0	63.2	91.2	90.1	480	474	18.6	17.3	8.2	6.1
	1.3	492	457	63.6	63.8	93.2	89.8	430	406	17.8	15.6	8.8	5.9
	10.5	438	412	67.3	67.6	94.0	91.8	374	371	14.9	14.2	6.0	5.1
	16	424	414	67.9	67.0	93.5	91.2	381	383	14.3	15.0	4.8	5.9
	21.5	--	390	--	67.9	--	90.3	--	366	--	15.1	--	6.7
	27	--	380	--	68.8	--	90.9	--	368	--	14.8	--	6.2
	height[1]	***	***	***	***	*	ns	***	***	***	*	***	ns
ANOVA Site	0.2	ns	**	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
	1.3	--	***	--	ns	--	ns	--	ns	--	ns	--	ns
	10.5	ns	**	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
	16	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	**	*
	21.5	--	ns	--	ns	--	*	--	ns	--	ns	--	ns
ANOVA Season[3]		HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site
	0.2	ns	**	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
	1.3	--	**	--	ns	--	*	--	ns	--	*	--	*
	10.5	ns	*	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
	16	ns	ns	*	ns	*	ns	ns	ns	ns	ns	ns	ns
Site X Season[3]	0.2	***		*		ns		ns		ns		ns	
	10.5	ns		ns		ns		ns		ns		ns	
	16	ns		ns		ns		ns		ns		ns	

* $P < 0.05$, ** $P < 0.01$, ***$P < 0.001$, ns = not significant

[1] ANOVA results for height; [2] unextracted basic density

[3] Statistical differences in basic density with season and interaction site x season are presented to show the influence of basic density and sampling on green density

Table 5-7. Means and statistical effects on basic density, water content, and saturation percentage for sapwood and heartwood at two contrasting sites (HA = high-altitude, WD = warm-dry) and two thinning regimes (UT = unthinned trees, T3 = three thinnings)

Site	Height (m)	Sapwood						Heartwood					
		Basic density (kg/m^3) [2]		Water content %		Saturation %		Basic density (kg/m^3) [2]		Water content %		Saturation %	
		UT	T3	UT	T3	UT	T3	UT	T3	UT	T3	UT	T3
HA	0.2	487	460	62.1	64.0	89.9	90.5	466	466	19.0	19.5	9.5	10.4
	1.3	486	462	62.7	64.9	90.9	92.3	400	426	16.3	17.2	7.4	8.0
	10.5	456	434	66.1	67.3	93.8	93.5	356	380	15.0	15.3	6.9	6.5
	16	427	417	67.9	68.1	93.9	93.1	348	364	15.5	14.7	8.0	6.1
	height [1]	***	***	***	***	**	**	***	***	***	***	ns	***
WD	0.2	522	452	59.3	63.8	88.3	89.3	490	449	18.7	17.8	7.9	7.9
	1.3	509	440	61.0	65.7	89.9	91.4	464	396	16.7	15.6	5.4	6.4
	10.5	461	421	64.6	68.3	91.7	93.9	402	368	15.6	14.6	6.0	5.8
	16	429	415	66.6	68.6	92.0	93.9	379	373	15.6	14.5	7.0	5.5
	21.5	400	407	69.1	69.3	93.1	94.1	370	375	17.9	15.2	10.9	6.5
	27	--	397	--	70.0	--	94.3	--	382	--	17.7	--	10.2
	height [1]	***	***	***	***	**	***	***	***	***	***	**	**
ANOVA Site	0.2	***	ns	***	ns	ns	ns	ns	ns	ns	**	ns	*
	1.3	ns	ns	*	ns	ns	ns	**	*	ns	**	*	ns
	10.5	ns	ns	ns	ns	ns	ns	***	ns	ns	ns	ns	ns
	16	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
ANOVA Thinning		HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site	HA site	WD site
	0.2	*	***	**	***	ns	ns	ns	*	ns	ns	ns	ns
	1.3	ns	***	**	***	ns	ns	ns	***	ns	*	ns	ns
	10.5	ns	**	ns	***	ns	ns	*	**	ns	**	ns	ns
	16	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
	21.5	--	ns	--	ns	--	ns	--	ns	--	**	--	*
Site X Thinning	0.2	**		**		ns		ns		ns		ns	
	1.3	*		*		ns		***		*		ns	
	10.5	ns		ns		ns		***		ns		ns	
	16	ns		ns		ns		ns		ns		ns	

* $P < 0.05$, ** $P < 0.01$, ***$P < 0.001$, ns = not significant

[1] ANOVA results for height; [2] unextracted basic density

Table 5-8. Adjusted-R^2 for variation of green density with height and the influence of basic density, water content, saturation percentage and sapwood percentage as measured by the change in R^2 by adding each of the variables at a time to the regression equation

Stand	Height (alone)	Added variables			
		Basic density	Water content	Saturation	Sapwood %
Sapwood					
HA site – winter – T2	0.02	0.27	0.01	0.63	--
HA site – summer – T2	0.40	0.66	0.39	0.74	--
WD site – winter – T2	0.25	0.57	0.23	0.64	--
WD site – summer – T2	0.14	0.48	0.39	0.89	--
HA site – spring – UT	0.00	0.54	0.00	0.75	--
HA site – spring – T3	0.00	0.48	0.03	0.72	--
WD site – spring – UT	0.22	0.44	0.28	0.79	--
WD site – spring – T3	0.00	0.49	0.00	0.59	--
Heartwood					--
HA site – winter – T2	0.70	0.93	0.81	0.73	--
HA site – summer – T2	0.42	0.95	0.73	0.46	--
WD site – winter – T2	0.52	0.97	0.73	0.51	--
WD site – summer – T2	0.31	0.94	0.68	0.34	--
HA site – spring – UT	0.56	0.95	0.83	0.64	--
HA site – spring – T3	0.63	0.98	0.86	0.67	--
WD site – spring – UT	0.56	0.94	0.76	0.57	--
WD site – spring – T3	0.15	0.91	0.61	0.22	--
Whole-section [1]					
HA site – winter – T2	0.12	0.18	--	--	0.86
HA site – summer – T2	0.05	0.20	--	--	0.79
WD site – winter – T2	0.08	0.19	--	--	0.80
WD site – summer – T2	0.07	0.45	--	--	0.64
HA site – spring – UT	0.20	0.36	--	--	0.79
HA site – spring – T3	0.27	0.46	--	--	0.84
WD site – spring – UT	0.06	0.15	--	--	0.83
WD site – spring – T3	0.20	0.28	--	--	0.89

[1] Whole-section basic density used in the regressions are weighted values by sapwood and heartwood sectional percentages; whole-section water content and saturation were not considered because these are composite values of pure sapwood and heartwood and are mainly influenced by the amount of sapwood

Table 5-9. Results of the test for parallel regressions green density vs. height and saturation vs. height showing significance of the interaction site x height for each paired stand and pooled stands

Stand	**Sapwood**		**Heartwood**	**Whole-Sec**
	Green density	Saturation	Green density	Green density
Summer – T2	ns	ns	ns	ns
Winter – T2	*	ns	ns	ns
T3	ns	ns	ns	*
UT	*	ns	ns	ns
Pooled stands	ns	ns	ns	**

* $P < 0.05$, ** $P < 0.01$, ns = not significant

5.3.6. Influence of sampling on the assessment of season effects

From previous results it was observed that the extent of changes in green density of sapwood and heartwood were mainly driven by the magnitude of differences in basic density. However, for the same reason this may lead to incongruent results when assessing the effects of season, and the interactions of age x season, and of site x season by measuring different trees (as in the case of destructive sampling). This situation is discussed using three different examples for sapwood green density as follows.

The first example in Figure 5-9a shows differences in sapwood green density between young and mature trees at breast height across two seasons for the warm-dry site (data shown in Table 5-3). Differences in green density were larger in winter than in summer not because of the effect of season itself but because of the larger differences in basic density between young and mature trees sampled in winter. Results after adjusting statistical effects with basic density as covariate indicated no influence of season on green density of young trees, and no interaction effect of age x season on green density (Table 5-3).

The second example in Figure 5-9b presents differences in sapwood green density between sites across seasons at the base of the tree. In this case there would appear to be an interaction effect of site x season because of the differences in basic density pattern between trees sampled in winter and summer. Results after adjusting statistical effects with basic density as covariate indicated no influence of season and the interaction of site x season on green density (Tables 5-4 and 5-6).

Finally the third example in Figure 5-9c refers to differences in sapwood green density with thinning regime at breast height for two sites. In this case a very small difference in green density was observed between unthinned and heavily-thinned trees for the high-altitude site but in contrast a large difference was present for the warm-dry site; again caused by differences in basic density patterns. In contrast to previous cases, in this instance it is valid to obtain different responses in basic density and hence in green density with different thinning regimes on different sites so there was no need to adjust statistical effects of thinning and the interaction of thinning x site (Tables 5-5 and 5-7).

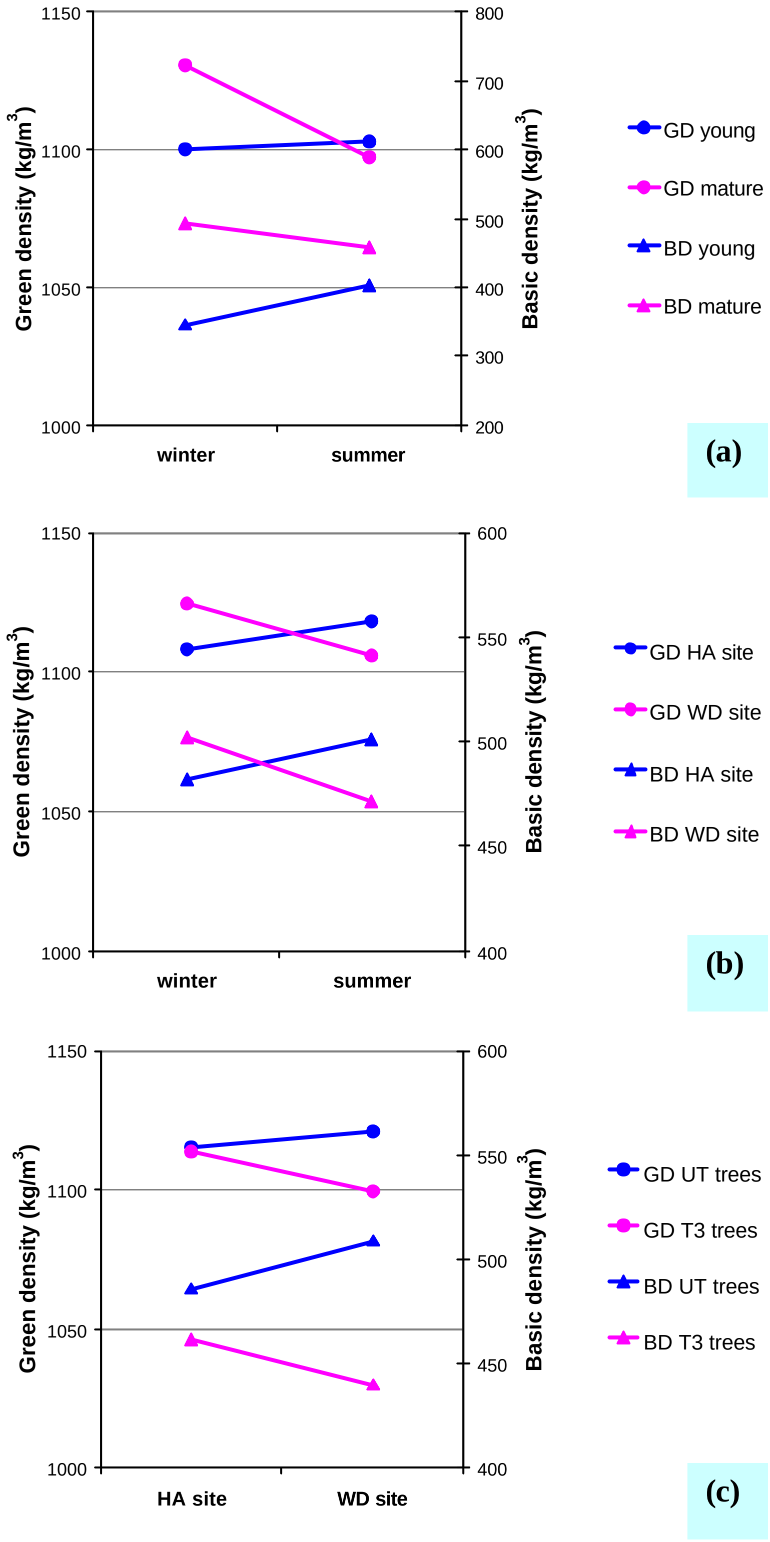


Figure 5-9. Influence of sampling and basic density (BD) on sapwood green density (GD): a) differences with age x season for the warm-dry site at 1.3 m height; b) mature trees site x season at 0.2 m (HA=high-altitude site, WD=warm-dry); c) mature trees thinning regime x site at 1.3 m (UT=unthinned, T3=3 thinnings). Data are shown in Tables 5-3 to 5-7

5.3.7. Influence of method for measuring moisture condition

Saturation percentage provided a more unbiased measure of moisture condition when compared with the moisture content expressed as the percentage of ovendry weight (MC_{ODW}), and the volumetric percentage of water (WC). This was due to the influence of sampling and basic density on both MC_{ODW} and WC as shown in the three examples below.

The first example in Figure 5-10a for sapwood moisture content at 1.3 m on the warm-dry site indicated that MC_{ODW} magnified the differences in moisture between mature and young trees and results were inconsistent across seasons. Thus in winter there was a difference of 89% MC_{ODW} in favour of the young trees whereas in summer this diminished to 35%; furthermore it would appear that the moisture content of mature trees increased during the dry season (Figure 5-10a). The water content as volumetric percentage showed the same trends as the MC_{ODW} but the changes were smaller. In both cases, this was not due to the effect of season itself but because of the larger differences in basic density between young and mature trees sampled in winter (Table 5-3 and Figure 5-10a). In contrast, changes in percent saturation were well in agreement with seasonal changes, i.e. both young and mature trees were drier in summer; and differences in saturation with age were moderate.

Another example is shown in Figure 5-10b, where there seemed to be an interaction effect of site x season for sapwood moisture content (MC_{ODW} and WC) at the base (0.2 m) of mature trees. Again this was related to the large differences in basic density pattern between trees sampled in winter and summer (Table 5-6 and Figure 5-10b). In contrast, this apparent interaction effect was not present for saturation.

A third case is presented in Figure 5-10c in which considerable larger differences in MC_{ODW} and WC with thinning regime seemed to occur for the warm-dry site at breast height. Again this was directly related to differences in basic density (Table 5-7 and Figure 5-10c). In contrast, when the percent saturation was calculated, the unthinned trees were slightly and consistently drier than the heavily-thinned trees across sites.

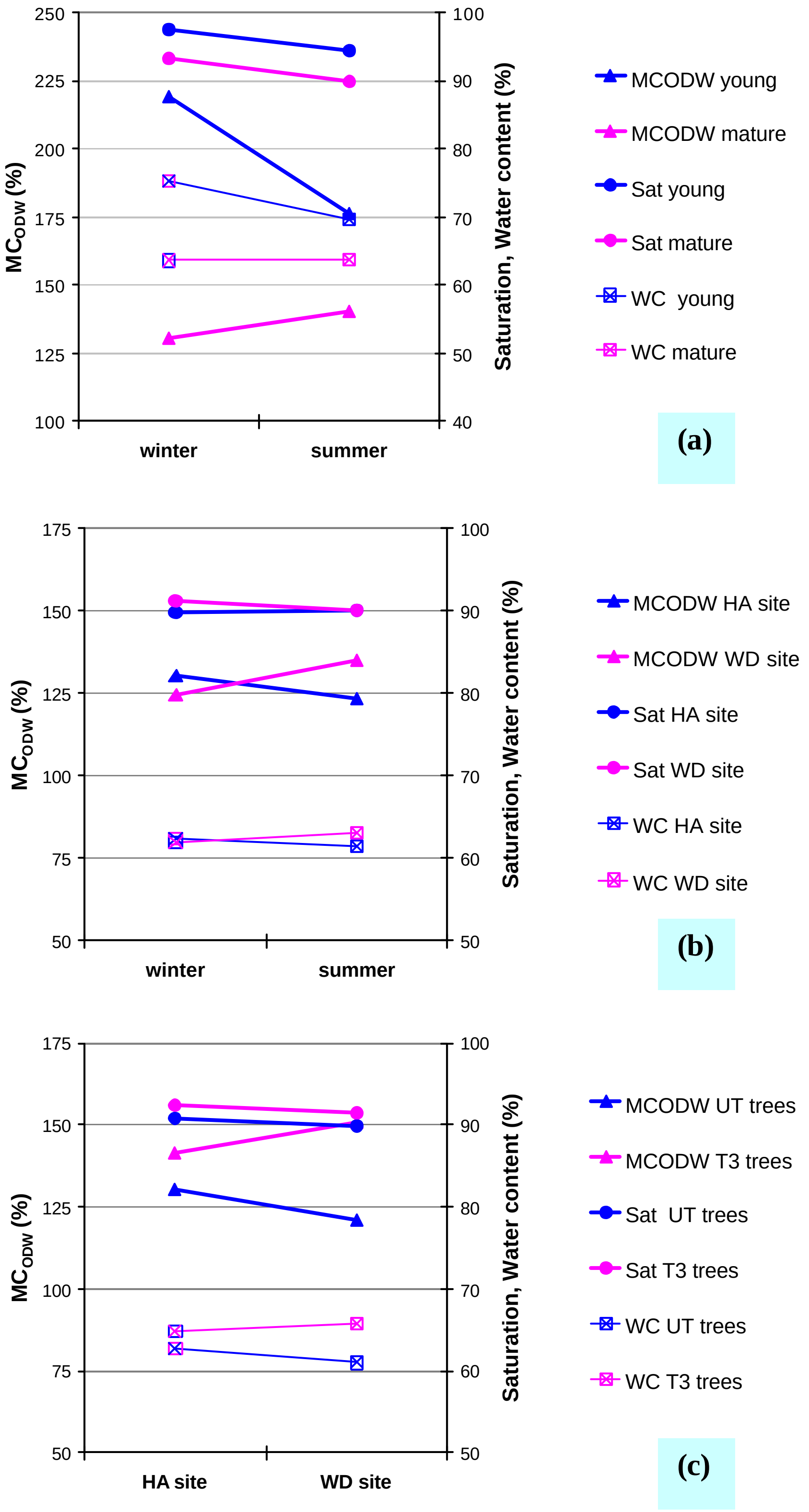


Figure 5-10. Influence of method for measuring sapwood moisture condition (MC$_{ODW}$ = moisture content as percentage of ovendry weight, saturation percentage (Sat), and water content as volumetric percentage (WC); a) age x season at 1.3 m height; b) mature trees, site x season at 0.2 m (HA=high-altitude site, WD=warm-dry); c) mature trees, thinning regime x site at 1.3 m (UT=unthinned, T3=3 thinnings)

Using whole-section values to assess seasonal changes in moisture condition of living trees may lead to incongruous results because of the influence of sapwood/heartwood percentages when sampling different trees (in the case of destructive sampling).

In the present study if whole-section values are considered, it would appear that the trees on the warm-dry site are drier in winter than in summer and this was true for all the measures of moisture condition, namely saturation percentage (Sat), water content (WC), and the moisture content as percentage of ovendry weight (MC_{ODW}) (Table 5-10). This was caused by the higher sapwood percentage of the trees sampled in summer compared to the trees sampled in winter, and the effect is exaggerated as the difference in sapwood content increases, namely at 16 m (Table 5-10). If saturation values of pure sapwood and heartwood are observed in Table 5-6 then it is clear that the trees were slightly drier in summer than in winter. On the other hand if percent sapwood of the trees sampled is uniform across seasons, as in the high-altitude site (Table 5-10), then assessment of whole-section moisture changes may be more accurate. In any case if destructive sampling is needed then it is possible to correct statistical effects with sapwood or heartwood contents as covariates.

Table 5-10. Changes in whole-section moisture condition with season for two contrasting sites at two different heights; measures of moisture included were water content (WC), saturation percentage (Sat), and the moisture content as percentage of ovendry weight (MC_{ODW})

Height (m)	Site	Season	Sapwood %	Moisture content method		
				WC %	Sat %	MC_{ODW} %
0.2	High-altitude	winter	85.2	55.8	77.9	117
		summer	85.4	55.2	78.0	111
		season diff	ns	ns	ns	ns
	Warm-dry	winter	69.2	48.7	65.6	98
		summer	74.4	51.4	68.6	110
		season diff	ns	ns	ns	*
16	High-altitude	winter	82.2	59.3	79.4	142
		summer	84.0	58.7	79.8	136
		season diff	ns	ns	ns	ns
	Warm-dry	winter	72.0	53.0	68.7	127
		summer	81.4	57.4	75.4	141
		season diff	**	*	*	ns

* $P < 0.05$, ** $P < 0.01$, ns = not significant

5.4 DISCUSSION

5.4.1 Comparing results with previous studies

Cown *et al.* (1991) reported higher absolute heartwood contents and more rapid heartwood formation for sites in the North Island compared to sites in the South Island, New Zealand. Whole-section and/or whole-tree green density and moisture from previous work varied inversely with age and positively with height in the tree as influenced by changes in heartwood content (Hughes and Mackney 1949, Loe and Mackney 1953, Cown and McConchie 1980, 1982) which was in agreement with results obtained in this study. Early work by Hughes and Mackney (1949) indicated no changes in whole-section green density with season which confirmed results obtained here. On the other hand, Cown (1974) reported no differences in heartwood content between moderately and heavily thinned 25-year trees in Central North Island, New Zealand. This differed from the considerable differences in sapwood percentage with thinning regime observed for the warm-dry site in this study.

Differences in saturation with age obtained in this study contradicted Kininmonth (1991), who argued that sapwood of young and mature trees would be equally saturated. In similar fashion, the values obtained in this study for young trees (97.5 % winter and 94.4% summer) differed considerably from Kininmonth (1991) who cited a mean monthly saturation of 90% ± 3% for sapwood of 10-year trees. On the other hand, the 'generic sapwood saturation' (90%) given by Harris and Cown (1991) and Kininmonth (1991) was well in agreement with the values obtained at the bottom of mature trees in the present study.

Average changes up the stem for green density and saturation with both sapwood and heartwood obtained in this study diverged from Cown (1999) and Harris and Cown (1991). The former stated that the green densities of sapwood and heartwood were virtually constant in the tree, and the latter argued no changes in saturation between the base and the top of the tree.

The better results given by saturation percentage over the moisture content as percentage of ovendry weight (MC_{ODW}), and water content as percentage of green volume (WC), confirmed previous work by Chalk and Bigg (1956), and Kininmonth (1991) who advocated the use of this measure for moisture condition of living trees.

Outcomes of this study indicated that using whole-section moisture values may lead to inconsistent trends due to the influence of sapwood/heartwood contents and basic density when sampling different trees; this effect is exacerbated if the MC_{ODW} is used for measuring moisture condition. This inconsistency was confirmed by looking closely at the reports of Hughes and Mackney (1949) in New Zealand and Fielding (1952) in South Australia. In both cases there were some significant differences in whole-tree moisture condition between seasons using MC_{ODW} but moisture trends did not match up with the climate of the region and seasonal differences were not completely obvious.

5.4.2 General patterns of variation in green density

The small changes in sapwood green density were explained by the counteracting effects of wood substance (basic density) and water content in a system relatively close to saturation (88 – 98%) with little air space remaining. For example, mature trees presented 25 – 35% wood substance and 59 - 70% water content, whereas young trees had 23 – 27% wood substance vs. 70 - 75% water content. Recall that wood substance has a density of 1500 kg/m^3 compared to 1000 kg/m^3 for free water and 1018 kg/m^3 for bound water. Generalized patterns are shown in Figure 5-11 below and summarized as follows,

- At breast height, young trees have lower basic density and therefore higher water content, as compared to mature trees which showed higher basic density and lower water content.
- For mature trees, the base of the tree has higher basic density and thus lower water content, as compared to the top of the tree which has lower basic density and therefore higher water content.

- Trees of the high-altitude site showed generally higher basic density and therefore lower water content, as compared to the warm-dry site with lower basic density, thus higher water content.

On the other hand, changes in whole-section green density were considerably greater due to the large differences in sapwood-heartwood sectional percentage among sites and to a lesser extent among thinning regimes (Tables 5-4 and 5-5). The reason lies in the large differences in water content between sapwood and heartwood material for mature trees: 59 - 70% for sapwood, and 14 - 20% for heartwood. So for example, at breast height the whole-section green density of mature trees is much lower than that of young trees because of the presence of heartwood in the former (Figure 5-11). Similarly, the higher whole-section green densities for the high-altitude site were explained by their higher sapwood contents.

5.4.3. Further changes in green density

Results from an independent experiment with an unthinned stand of mature trees in the warm-dry site measured in January 2007 (summer) after a prolonged drought are reported in Appendix 3; results are summarised as follows,

- Sapwood green density decreased considerably due to decreases in saturation associated with water stress. Average breast-height sapwood green densities for large, average, and suppressed mature trees were 1089, 1052, and 887 kg/m^3, respectively.

- Breast-height whole-section green density values for large, average, and suppressed mature trees were: 913, 884, and 762 kg/m^3, respectively.

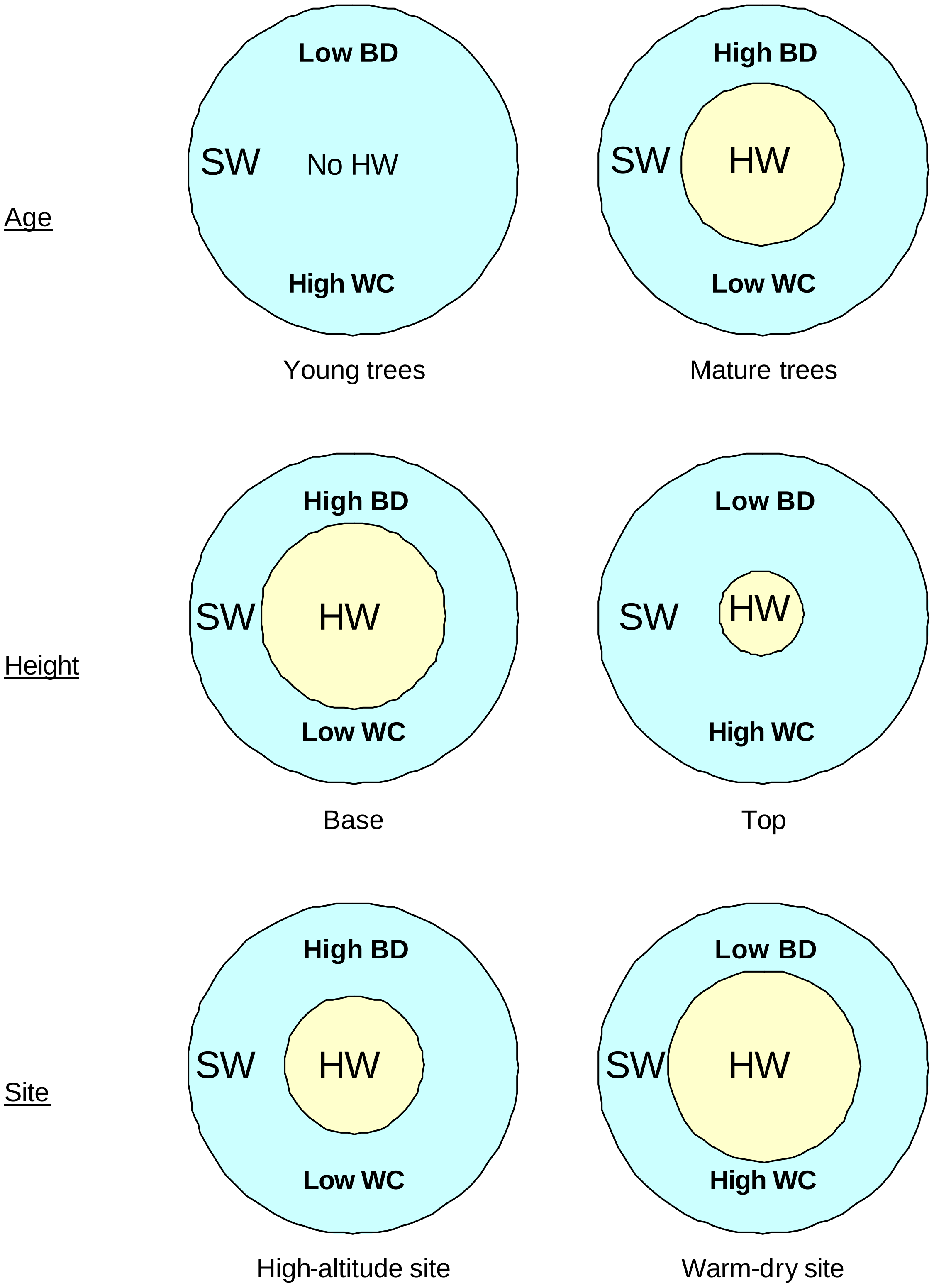


Figure 5-11. Generalized patterns of factors affecting variation in green density: sapwood basic density (BD), water content (WC), and sapwood-heartwood sectional percentage (SW, HW) as influenced by age, height in the stem, and site

5.5 CONCLUSIONS

- Variation in sapwood green density necessary for the calculation of outerwood DMOE was small to moderate as influenced in decreasing order by age, height, site and thinning regime. Average breast-height sapwood green density for young trees was 1100 kg/m^3, whereas for mature trees this ranged from 1097 to 1131 kg/m^3. Average differences in breast-height sapwood green density ranged from 2 to 33 kg/m^3. However, sapwood green density can decrease considerably during extended droughts due to decreases in moisture content caused by water stress.

- Variation in whole-section green density, necessary for calculation of log-DMOE, was considerable due to the differences in sapwood-heartwood content as influenced by age, site, and position in the stem. Average breast-height whole-section green density for mature trees ranged from 952 to 1036 kg/m^3. Average breast-height differences in whole-section green density as influenced by site and thinning regime were as high as 84 kg/m^3, whereas differences between the bottom and the top of the tree ranged from 22 to 64 kg/m^3.

- Percent saturation provided a more unbiased measure of moisture condition when compared with the moisture content expressed as the percentage of ovendry weight (MC_{ODW}), and the volumetric percentage of water (WC). This was due to the influence of sampling and basic density on both MC_{ODW} and WC. Using whole-section values for assessing seasonal changes in moisture condition of living trees will lead to inconsistency on the results because of the influence of sapwood percentage when sampling different trees (in the case of destructive sampling).

- Results in whole-section green density obtained in this study agreed with previous published reports. However, changes in sapwood green density and saturation with age, season and height diverged from the literature reports. This may be due to some biased results in previous reports where moisture content was assessed from whole-section values and using the moisture content as percentage of ovendry weight method.

CHAPTER 6

Influence of moisture content and temperature on acoustic velocity and dynamic MOE of standing trees

6.1 INTRODUCTION

The lack of research on the influence of moisture content and temperature on acoustic velocity and DMOE of green wood was highlighted in Chapter 2. This includes studies in live trees for which there are no published reports. A particular problem of relevance for resource characterisation is the estimation of dynamic stiffness in standing trees at significantly different temperatures and moisture conditions caused by seasonal differences, and/or climate. In this regard, results of Chapters 4 and 5 have provided significant information on the changes in moisture content in live trees of radiata pine as influenced by site and seasonal differences, yet their consequences on the use of acoustic methods for dynamic characterisation remain to be investigated. Another aspect that has not been addressed is the influence of changes in temperature on acoustic velocity of live trees. Both aspects are the main purpose of the present study.

A number of authors have noted the need for correcting the DMOE obtained in wood above the FSP, these include Gerhards (1975), Ross and Pellerin (1991), and Sobue (1993). In this regard, X. Wang and Ross (2002) stated that the fundamental wave equation was developed for idealized elastic materials and has been proved to be adequate for dry wood materials; however, the effectiveness of its application for accurately predicting stiffness at high moisture contents remains to be fully validated. Further, X. Wang and Ross (2002) concluded that research is still needed on methods for the adjustment of DMOE for wood above the FSP to accurately predict the stiffness of green wood using stress wave methods.

Sobue (1993) developed the theory of ‘mobility of free water’ to solve the dilemma of estimating the DMOE for wood above FSP. This explains on one hand, the effects of free water on acoustic propagation; and on the other hand, the correction of density for the calculation of DMOE. The author defined the mobility of free water (k) as the ratio of the weight of free water, which vibrates in the same phase as wood substance, to the weight of total free water. A number of authors have validated the procedures of Sobue (1993) for correcting density above FSP and hence DMOE, including S. Y. Wang and Chuang (2000), S. Y. Wang *et al.* (2002), and S. Y. Wang *et al.* (2003). Procedures of Sobue (1993) and S. Y. Wang and Chuang (2000) were tested with acceptable results for adjusting the DMOE in wood above FSP in the experiment with boards (Chapter 2) where critical values of saturation percentage were used as surrogates for the mobility of free water ratio.

The research questions-objectives of the present investigation were:

1) What is the influence of moisture content and temperature on acoustic velocity and dynamic MOE of standing trees?
2) Do these influences differ between sites?
3) Are there differences in DMOE across seasons (time)?
4) If true, is it possible to make adjustments in DMOE related to changes in moisture content?

6.2 METHODS

The study was carried out in the Hume region of Forests NSW, Australia with radiata pine trees aged 10 years at the beginning of the experiment located in two contrasting sites: a high-altitude sub-alpine climate (Sandy Creek) vs. a warm-dry inland climate (Rosewood Park). The differences in climate between the sites are indicated by the higher air temperatures in spring and summer for the warm-dry site (Table 6-1). Trees were remeasured four times over a period of 17 months covering three climate seasons: winter, spring, and summer (Table 6-1). Note that the actual timings differed between sites normally by no more than a few days with the exception of winter 2005 where measurements were three weeks apart; however, for practical reasons the remeasurements were grouped in four nominal times (Table 6-1).

Table 6-1. Details of the remeasurements conducted over a period of 17 months in two contrasting sites of young trees, including timing, number of plots and trees measured

Site	Nominal time (months)	Actual dates	season	Air Temperature † (°C)	No. plots	No. trees per plot
Sandy Creek (High-altitude)	0	21-22 Jul/05	winter	8.0	5	5
	6	9-10 Feb/06	summer	21.6	5	5
	14	3-4 Oct/06	spring	19.3	5	10
	17	29-30 Dec/06	summer	26.9	3	10
Rosewood Park (Warm-dry)	0	15-17 Aug/05	winter	8.2	5	5
	6	6-8 Feb/06	summer	28.0	5	5
	14	26-27 Sep/06	spring	16.5	5	10
	17	3-5 Jan/07	summer	30.3	5	10

† measured under canopy, average of two readings taken in ca. one hour

Traits considered were acoustic velocity (V), dynamic MOE (DMOE), tree temperature, air temperature, sapwood green density (GD), and sapwood moisture content expressed as saturation percentage; all determined at breast height (1.3 m). Acoustic velocity was measured with the TreeTap, a time-of-flight acoustic tool developed by the University of Canterbury. Acoustic velocity was measured on one side of the tree placing two stop probes 1.5 m apart, whilst the tapping probe was located about 25 cm below the lower stop probe. Preliminary work indicated no statistical differences in acoustic velocity between measuring one side and the average of two sides of the tree for trees aged 10-11 years. Tree temperature was measured using a thermocouple inserted in a hole drilled about 5 cm deep in the sapwood. Once inserted it was necessary to wait for several seconds for the reading to stabilize. Air temperature was also measured with a thermocouple taking two readings per plot corresponding normally to the start and the end of the plot measurements. Sapwood green density and saturation were determined using 12 mm manual cores following procedures previously developed that provide a close approximation to destructive disks and wedges (Section 4.2.1). Staining test for identification of heartwood was done according to procedures described in Section 4.2.2; neither the pith nor any heartwood material was accounted for the determination of green density and saturation. Formulas used are listed as follows:

$$V\ (km/s) = \frac{1.5}{TOF\,(ms)} \times 10^{3} \tag{1}$$

$$DMOE\ (GPa) = V^{2} \times GD \times 10^{-3} \tag{2}$$

$$GD\,(kg/m^{3}) = \frac{GW}{GV} \times 10^{3} \tag{3}$$

$$Saturation\,\% = \frac{Fwater\%}{(Fwater\% + Air\%)} \times 100 \tag{4}$$

where TOF is the transit time between stop probes in μs, GW is green weight in 0.001 g, and GV is green volume in 0.001 cm^3 as measured by water displacement. Fwater% and Air% are the volumetric percentages occupied by free water and air with respect to the green volume of the sample; the derivation of these formulas are given in Section 3.2.1.

Each of the sites included five plots with healthy trees and without malformations. For logistical reasons the first two assessments included five trees per plot whereas the last two assessments included ten trees per plot; similarly, for one of the sites only three plots could be measured in the last assessment (Table 6-1). Additionally, at both sites increment cores were taken only on one side of the tree for the measurements at 0 and 6 months mainly because of limitations on the initial procedures, whereas for the measurements at 14 and 17 months bark-to-bark cores were taken and procedures were improved. These differences in methods may have introduced more experimental error for the first two assessments; however, pre-analysis of the data showed that the standard deviations for green density and saturation were very uniform for all remeasurements. Similarly, pre-analysis for Sandy Creek comparing results between using only the three plots that could be remeasured over the whole period of study and using all the plots gave essentially the same graphical and statistical outcomes. Thus the results presented below included all the plots.

Data analysis consisted in the first place of obtaining plot averages per remeasurement for all the traits studied. Graphical analysis using the plot means revealed large variation in acoustic velocity between plots for both sites which confounded the trends of velocity against saturation and tree temperature. Subsequent analysis was then conducted with the mean values of each of the remeasurements as calculated using the plot means. New results indicated that the noise caused by the differences between plots was effectively reduced by grouping the data by remeasurement.

The strategy of analysis followed the logic of the results obtained in the experiment with boards (Chapter 2). Namely the effects of moisture content and tree temperature on acoustic velocity were first analysed; and then the variation in DMOE was explained in terms of the changes in acoustic velocity and green density. Because of the considerable differences in velocity, saturation percentage, and to a lesser extent in temperature between the two sites, analyses were conducted separately for each of them. Statistical effects of moisture content on acoustic velocity and DMOE were tested by regression analysis. Analysis also included determination of the changes in velocity and DMOE with moisture content. Changes of DMOE over the period of study were also analysed as these are of practical importance for resource assessment. The method developed by Sobue (1993) for adjusting density, and hence DMOE, was tested using values of saturation percentage as surrogates for the mobility of free water ratio k (equation 5).

$$r_{Adj} = r\left[1 - \frac{(1-k)(MC_{ODW} - FSP)}{(100 + MC_{ODW})}\right] \qquad (5)$$

where ?$_{\mathrm{Adj}}$ is the adjusted green density, ? is green density as defined in equation 3 above, FSP is the fibre saturation point (30% for radiata pine), and MC$_{\mathrm{ODW}}$ is the moisture content as percentage of the ovendry weight calculated from green weight (GW) and ovendry weight (ODW) of the samples as follows,

$$MC_{ODW\%} = \frac{GW - ODW}{ODW} \times 100 \qquad (6)$$

6.3 RESULTS AND DISCUSSION

6.3.1 Influence of moisture content and temperature on acoustic velocity

Results revealed a significant inverse effect of moisture content expressed as saturation percentage on acoustic velocity for both sites (Figure 6-1 and Table 6-2). At both sites acoustic velocity increased linearly as saturation decreased although this trend was more regular for the high-altitude site (Figure 6-1). For ease of comparison, the rates of increase of velocity have been calculated in m/sec (velocity is expressed in km/s in the Tables and Figures). The increase in velocity with decreasing moisture content for the high-altitude site was 22 m/s per unit saturation, whereas the increase for the warm-dry site was 10 m/s per unit saturation. These values were in broad agreement with the average decreasing rate of 16 m/s per unit saturation obtained in the experiment with boards for wood between 81.9 and 92.2% saturation and temperatures from 4° to 39°C (Section 2.3.1).

Table 6-2. Mean values of breast-height saturation percentage, tree temperature, acoustic velocity, green density and DMOE as remeasured over a period of 17 months in two contrasting sites of young trees; saturation and green density determined by 12 mm cores

Site	Nominal Time/ Date (months)	Sapwood Saturation (%)	Tree Temperature (°C)	Acoustic Velocity (km/s)	Green density (kg/m^3)	DMOE (GPa)
High-altitude	0 (Jul 05)	92.2	3.5	2.87	1081	9.0
	6 (Feb 06)	89.2	17.0	2.95	1062	9.4
	14 (Oct 06)	84.0	13.6	3.05	1029	9.6
	17 (Dec 06)	80.3	21.8	3.14	1006	10.0
Signif. time †		** / *				
Warm-dry	0 (Aug 05)	87.8	5.1	2.41	1040	6.1
	6 (Feb 06)	84.8	20.9	2.48	1020	6.4
	14 (Sep 06)	75.3	8.5	2.56	957	6.3
	17 (Jan 06)	74.5	22.0	2.55	954	6.2
Signif. time †		* / ns				

† Effects of saturation percentage over time on acoustic velocity / DMOE as determined by regression analysis; * Significant at $P < 0.05$, ** $P < 0.01$, ns = not significant

The differences between sites in the trends of acoustic velocity as influenced by changes in saturation were explained by the different rates at which changes in saturation occurred for each of the sites. Namely in the high-altitude site saturation decreased steadily over the period of study, whereas in the warm-dry site saturation decreased sharply between months 6 and 14 followed by no changes thereafter which suggested that trees reached a critical ‘safety’ level (Figure 6-1). The consistent lower saturation values and different trends for the warm-dry site highlighted the differences in the response of trees to drought with site (this is extensively discussed in Chapter 7). On the other hand, it remained unknown whether the moisture content of the trees in the high-altitude site would continue to decline to a safety level as at the warm-dry site.

Results showed that at both sites any possible effects of temperature on acoustic velocity were overshadowed by changes in moisture content. For example, the highest values of velocity at 13.6° and 21.8°C in the high-altitude site, and at 8.5°C and 22°C in the warm-dry site corresponded to the lowest saturation levels obtained at months 14 and 17, respectively for both sites (Table 6-2). Similarly, the lower velocity values at 3.5°C and 17.0°C in the high-altitude site and at 5.1°C and 20.9°C in the warm-dry site corresponded to the highest saturation levels obtained at months 0 and 6, respectively for both sites (Table 6-2). These unexpected trends of continuous decreases in saturation across seasons were mainly caused by a long drought period which started after month 6 and continued thereafter as indicated by the trends in saturation over the period of study (Table 6-2). This contributed to acoustic velocity increasing gradually with time (Figure 6-1).

6.3.2 Influence of moisture content on DMOE

Results for the high-altitude site revealed a steady increase in DMOE as saturation percentage decreased over time (Table 6-2 and Figure 6-2a). In contrast, results for the warm-dry site showed small changes in DMOE but no definite trend as saturation decreased (Table 6-2 and Figure 6-2b). The ‘direct’ statistical influence of saturation percentage on DMOE was significant for the high-altitude site but not for the warm-dry site (Table 6-2). In the high-altitude site there were increases in DMOE between

0.4 to 1 GPa, whereas in the warm-dry site DMOE changed between 0.1 and 0.3 GPa across the different measurements (Table 6-2).

The differences between sites in the trends of DMOE were explained by the different rates of change in acoustic velocity and green density as influenced by changes in saturation at each of the sites. At the high-altitude site saturation decreased and thus velocity and DMOE increased steadily over the period of study (Figures 6-1a and 6-2a). Further, the increases in velocity at the high-altitude site overrode the corresponding increases in green density (Figure 6-3a). Results at the start and the end of the experiment for the high-altitude site indicated an increase of 19.7% in velocity squared as compared to a decrease of 6.9% in green density giving as a result an increase in DMOE of 11.1% (Table 6-3). In contrast, at the warm-dry site the trend in DMOE was irregular with a sharp increase between months 0 and 6 followed by small decreases thereafter (Figure 6-2b). This trend somehow mirrored that of velocity (Figure 6-1b) but was counteracted by green density after month 6 (Figure 6-3b). Results at the start and the end of the experiment for the warm-dry site indicated an increase of 11.9% in velocity squared as compared to a decrease of 8.3% in green density giving as a result a minute increase in DMOE of 1.6% (Table 6-3). As a comparison, results in Table 6-3 include data from the experiment with boards in Chapter 2 considering temperatures of 4°, 20°, and 39°C and a saturation range similar to the live trees. As saturation increased from 81.6 to 92.3%, velocity squared of boards decreased 11.3% as compared to an increase of 6.6% in green density giving as a result a decrease in DMOE of 5.2% (Table 6-3).

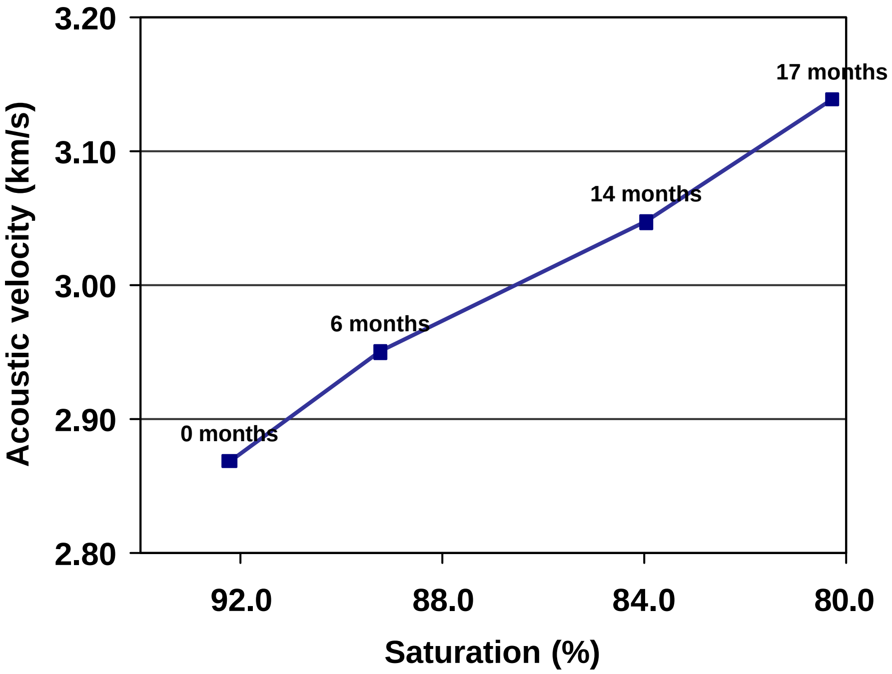
These results suggested that the changes in velocity and green density as a result of changes in moisture content are not proportional and seem to vary between sites and materials (i.e. live trees vs. boards). Additionally, the changes in velocity squared as influenced by large changes in moisture content will not always override changes in green density and there can be counteracting effects between the two parameters. This makes difficult to predict the effect of moisture content on the DMOE of standing trees.

Table 6-3. Mean values and percentage changes in DMOE at the start and the end of the study and selected data from the experiment with boards in Chapter 2, as related to changes in green density and velocity squared

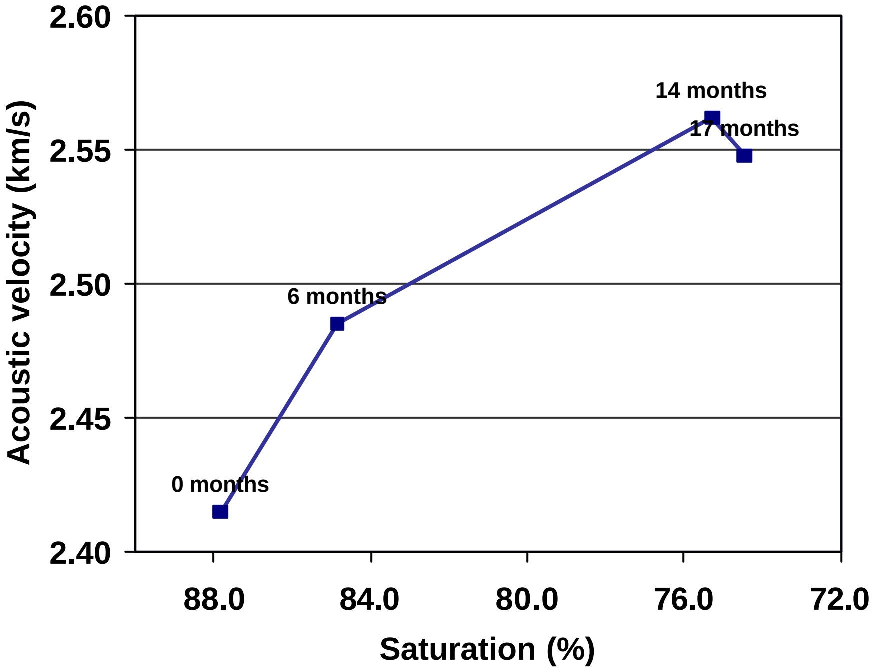
Experiment/site	Sapwood saturation (%)	Green density (kg/m^3)	Acoustic Velocity (km/s)	Acoustic Velocity squared	DMOE (GPa)
Trees high-altitude site					
month 0	92.2	1081	2.87	8.24	9.0
month 17	80.3	1006	3.14	9.86	10.0
Change (%) †	-12.9	-6.9		+19.7	+11.1
Trees warm-dry site					
month 0	87.8	1040	2.41	5.81	6.1
month 17	74.5	954	2.55	6.5	6.2
Change (%) †	-15.1	-8.3		+11.9	+1.6
Boards (Chapter 2) ‡	81.6	1030	2.74	7.51	7.7
	92.3	1098	2.58	6.66	7.3
Change (%)	+13.1	+6.6		-11.3	-5.2

† Change (%) with respect to month 0

‡ Considering temperatures 4°, 20°, and 39°C

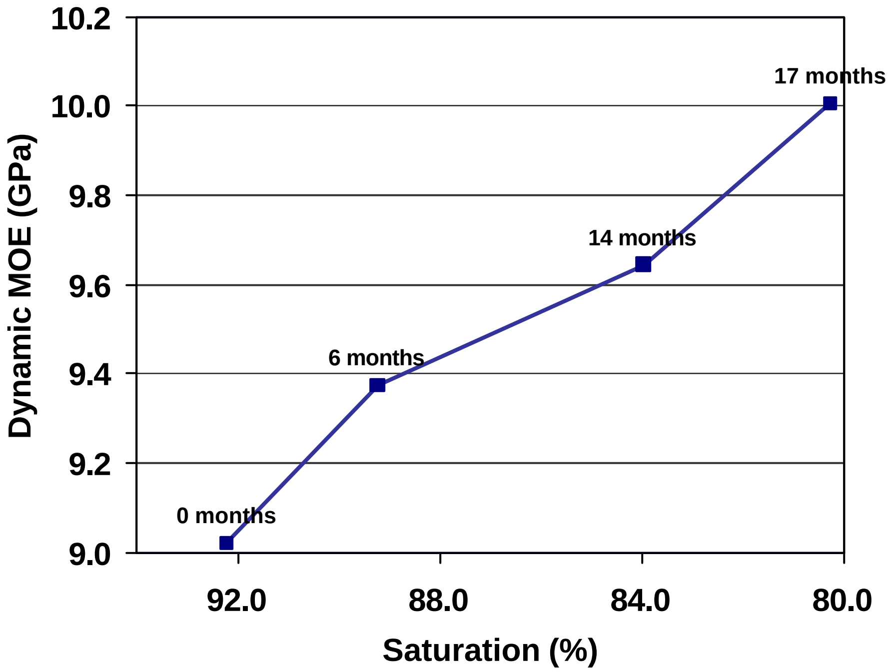


a) High-altitude site

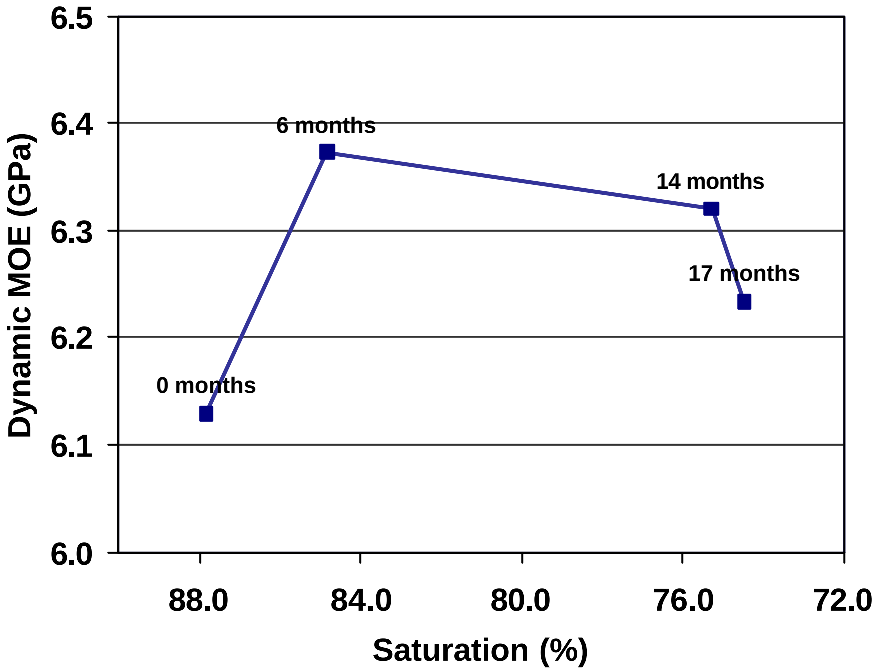


b) Warm-dry site

Figure 6-1. Effects of moisture content expressed as saturation percentage on acoustic velocity at breast height as remeasured over a period of 17 months in two contrasting sites of young trees

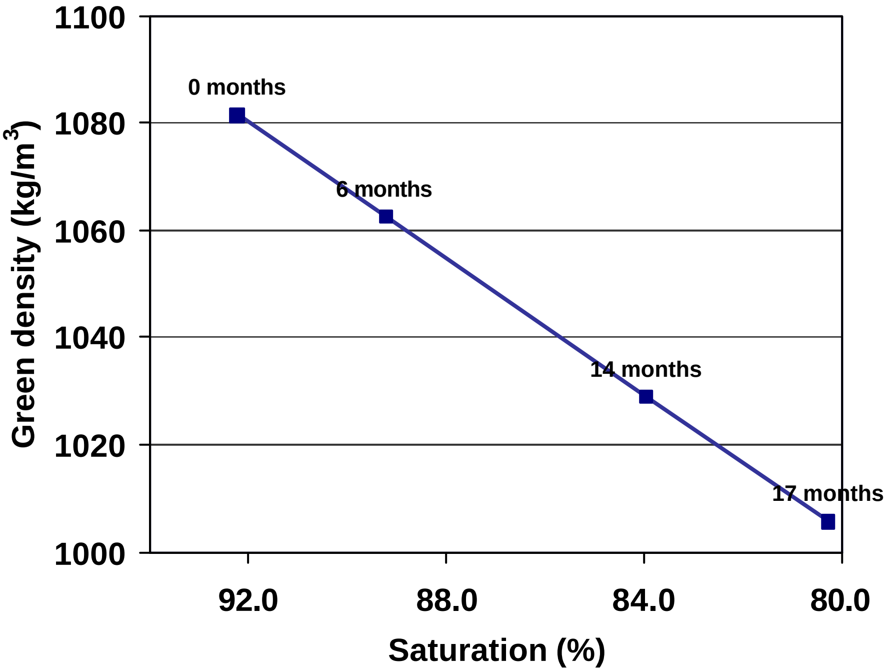


a) High-altitude site

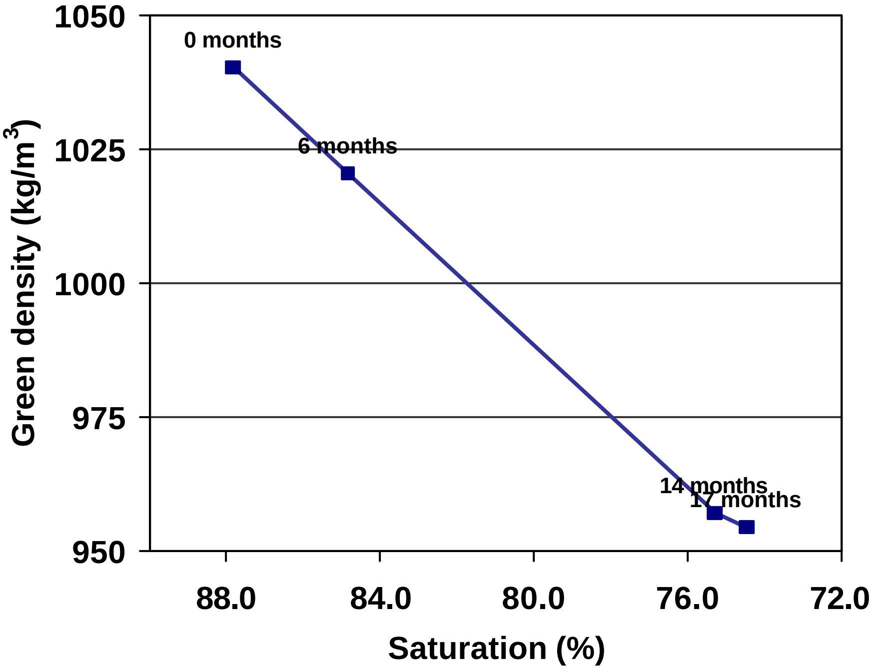


b) Warm-dry site

Figure 6-2. Variation of DMOE with moisture content expressed as saturation percentage at breast height as remeasured over a period of 17 months in two contrasting sites of young trees



a) High-altitude site



b) Warm-dry site

Figure 6-3. Variation of green density with moisture content expressed as saturation percentage at breast height as remeasured over a period of 17 months in two contrasting sites of young trees

6.3.3 Adjustment of DMOE

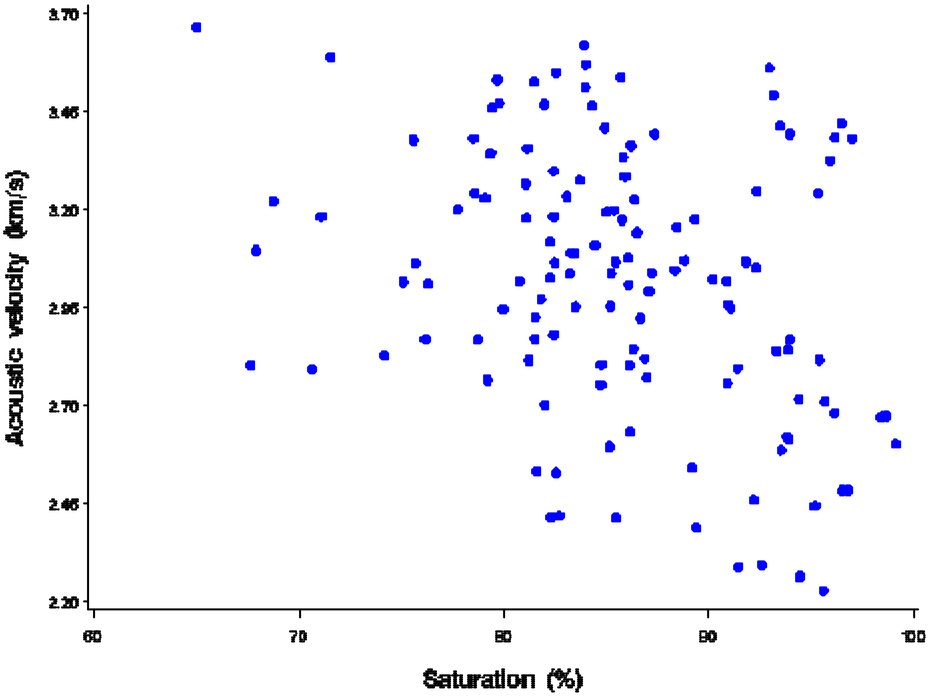
Results in Table 6-3 revealed small to moderate changes in DMOE over the period of study as influenced by changes in moisture content expressed as saturation percentage (Table 6-3). DMOE varied by 0.4 to 1 GPa for the high-altitude site and by 0.1 to 0.3 GPa for the warm-dry site across the different remeasurements.

For the high-altitude site these results are of practical importance for resource evaluation thus corrections of DMOE should be done. The methods developed by Sobue (1993) and S. Y. Wang and Chuang (2000), and tested in the experiment with boards in Chapter 2 using critical values of saturation percentage as surrogates for the mobility of free water ratio, were applied to the present study. The first step consisted of exploring graphically the relationships between acoustic velocity and saturation percentage separately for each of the sites. In the case of the high-altitude site it was observed a rather continuous decreasing trend (Figure 6-4a). In contrast, for the warm-dry site the trend of acoustic velocity with saturation seemed to be V-shaped with a minimum occurring at about 75% saturation (Figure 6-4b). However, if the lower cluster of points is neglected then velocity follows a continue decreasing trend with no obvious changes in slope (Figure 6-4b) essentially similar to that of the high-altitude site.

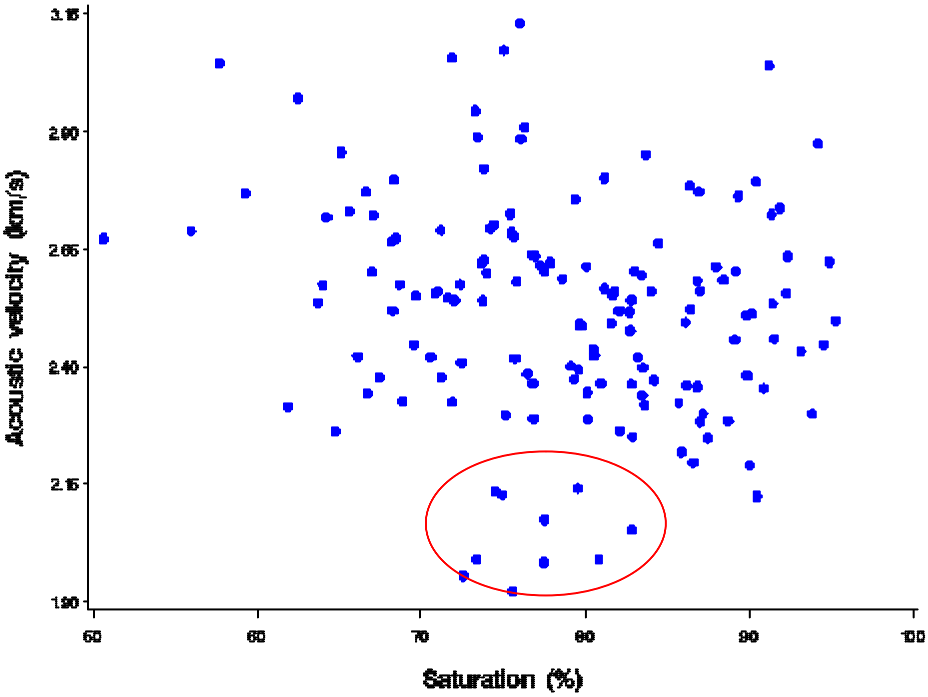
The lack of obvious changes in slope compared to those observed in the experiment with boards at 60% saturation was considered a logical outcome as the saturation values in the present were mostly above that critical point. Moreover, additional noise in the results of the present study (e.g. the warm-dry site) may have been caused by the gradients in moisture in the sapwood for some of the trees, namely the presence of large low-saturation sapwood areas associated with cavitation (Chapter 7). In contrast, it can be assumed that the boards had uniform moisture contents.

Given the lack of critical saturation values to be used as surrogates for the mobility of free water ratio (k) in the equation of Sobue (1993) for correcting green density, different approximations were tested with data from Table 6-3. This included: 1) the saturation averages of wood at ‘low’ and ‘high’ saturation for each of the sites, i.e.

two values per site; 2) overall saturation averages per site; and 3) each of the saturation values. For the high-altitude site the third option gave better results with the drawback that the adjusted DMOEs were reduced in average by 0.8 GPa (Figure 6-5a). For the warm-dry site the second option gave better results but again the adjusted DMOEs were reduced by 0.7 GPa (Figure 6-5b). It was concluded that these results were only a crude approximation and that analytical procedures following the lines of Sobue (1993) are required for the accurate correction of DMOE in green wood.

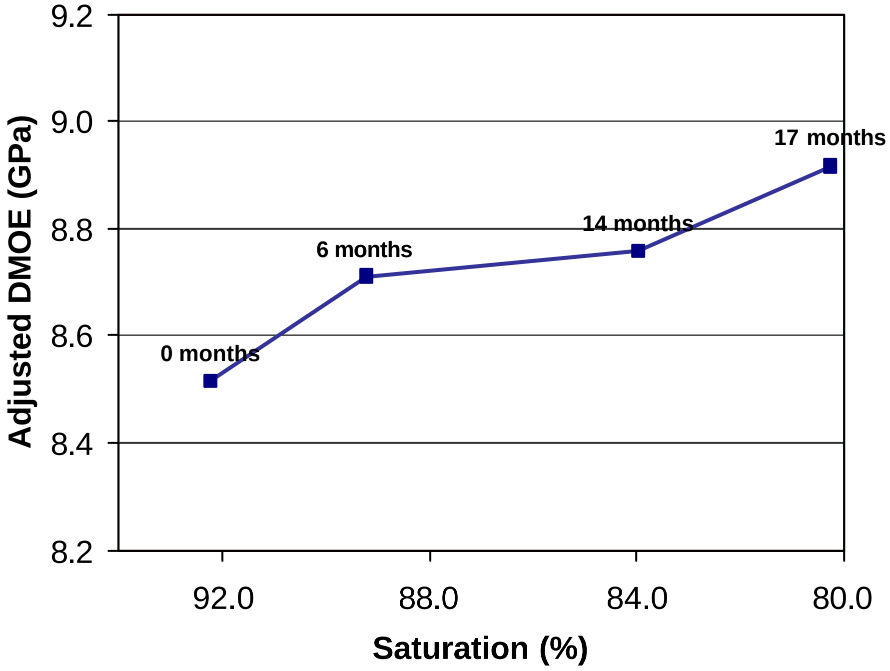


a) High-altitude site

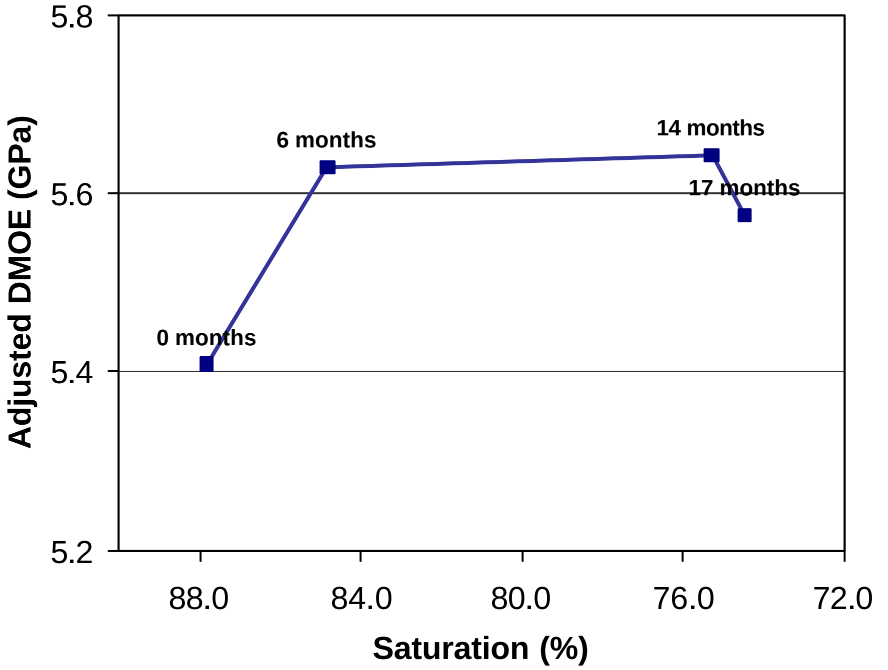


b) Warm-dry site

Figure 6-4. Individual observations of acoustic velocity and saturation percentage at breast height as remeasured over a period of 17 months in two contrasting sites of young trees; these show a rather continuous decrease in velocity with no obvious changes in trends for both sites except by the cluster of points in the warm-dry site (circled)



a) High-altitude site



b) Warm-dry site

Figure 6-5. Adjusted DMOE at breast height as remeasured over a period of 17 months in two contrasting sites of young trees

6.4 CONCLUSIONS

- Moisture content expressed as saturation percentage exerted a significant inverse effect on acoustic velocity although this trend differed between sites. Results were influenced by a long drought during the second half of the experiment, which explained the continuous and large decreases in saturation over the period of study. Another consequence of this phenomenon was that any possible effects of temperature on acoustic velocity were overshadowed by the large changes in saturation.

- There were small to moderate changes in DMOE over the period of study as influenced by changes in saturation percentage. DMOE varied by 0.4 to 1 GPa for the high-altitude site and by 0.1 to 0.3 GPa for the warm-dry site across the different remeasurements.

- Results suggested that the changes in velocity and green density as a result of changes in moisture content are not proportional and seem to vary between sites and materials (i.e. live trees vs. experiment with boards of Chapter 2, Table 6-3). Additionally, changes in velocity squared as influenced by large changes in moisture content did not always override changes in green density and there are counteracting effects between the two parameters. This makes difficult to predict the effect of moisture content on the DMOE of standing trees.

- The different response of trees in contrasting environments to long periods of water stress influences the use of acoustics for dynamic estimation of stiffness as indicated by the considerable differences in trends of DMOE over the period of study. These results are important for sampling strategies and resource evaluation in areas with large seasonal changes in moisture and occurrence of long droughts as the Hume region of Forests NSW, Australia where this study was conducted. For example, broad-acre assessments usually can take several months and sometimes years thus the estimations of stiffness using DMOE may become unreliable. In those situations it would appear that the solution at hand is to correct DMOE for ‘excessive’ differences in moisture content.

- Using saturation percentage values as surrogates for the mobility of free water ratio in the equation of Sobue (1993) for correcting green density and hence DMOE gave only a crude approximation. Thus it was concluded that analytical procedures following the lines of Sobue (1993) would be preferred for a more accurate correction of DMOE in green wood of live trees.

CHAPTER 7

Wood quality and water-stress response on two contrasting sites of the Hume region of Forests NSW

7.1 INTRODUCTION

This chapter addresses two issues (wood quality and water stress) that are rarely analysed together in the literature. They are important for those regions where severe dry seasons and extended droughts are found as in the case of the Hume region of Forests NSW (FNSW), Australia. Further, information on the wood quality of this resource, the response of the trees to water-stress, or even the relationships between the two aspects are still very limited. This research was also prompted by 'unusual' phenomena observed in Chapters 4 - 6 but that were not discussed in those Chapters because they were outside of their scope. Phenomena included young trees with very low moisture condition (saturation) during the summer of 2006 and the presence of large areas of 'dry sapwood' in a site of intermediate climatic conditions of the Hume region. Similarly, mature trees on a dry site showed prominent cavitation signs and considerable variation in saturation also in the summer of 2006 as compared to a wetter site. Differences in saturation with site and further decreases in moisture as a result of an extended drought period were reported in an experiment with young trees in Chapter 6. The present investigation uses material and data from experiments in Chapters 5 and 6 of the thesis. The results obtained offer an insight into the phenomena and suggest further research.

The results of this research are relevant to similar regions in Australia or elsewhere. According to the Bureau of Rural Sciences (2006) 90% of Australian plantations are in areas with 700 – 1500 mm annual rainfall. Due to land availability and costs, new plantations are likely to be established in areas with 600-800 mm rainfall. In the particular case of the Hume region of FNSW, new land on the better sites (high altitude and relatively wetter) has become very limited because of the restrictions of the 1992 National Forest Policy Statement. Consequently, there has been an increase in plantation area on ex-farm land, including lower rainfall sites with high water deficits during the dry season.

7.1.1 Wood quality traits

The present study considered two common measures of wood quality (dynamic MOE and basic density). Information in the literature on the effects of site on wood quality is extensive especially for basic density. There is also a good deal of knowledge on the effects of moisture stress on wood formation of radiata pine which can be used to indirectly assess the impact of water stress on wood quality. According to a summary by Harris (1991), effects of moisture stress on wood formation of radiata pine include alterations to the rate of cambial division, a reduction of cell expansion, and disruption of wood formation under severe water stress. Water stress may also induce thicker cell walls but prolonged stress will reduce both cell diameter and wall thickness.

A number of studies have explored the impacts of site and water availability/deficit on wood density by considering the proportion of earlywood/latewood and/or densitometric analysis. Nicholls *et al.* (1974) recorded that the maximum density occurs in the last-formed latewood of radiata pine in Australia. Nicholls (1971) in an experiment with irrigated radiata pine found that the additional water increased markedly the proportion of thick-walled cells associated with summer and autumn growth. In a subsequent study Nicholls and Waring (1977) compared irrigated versus droughted trees; the results indicated that both treatments produced slight increases in average density: in the first case this was due to an increase in maximum density, and in the second case this was due to an increase in minimum density and in latewood/earlywood ratio. Nicholls and Wright (1976) in a study including sites across Victoria reported that the site with the largest water holding capacity and spring rainfall had the lowest earlywood density. The authors also found a high correlation between maximum latewood density and autumn rainfall. Harris *et al.* (1978) in an experiment with cuttings grown in containers over six years found that periodic moderate moisture stress increased minimum (earlywood) density, mean density and latewood ratio in the outer growth layers.

Craig (as cited in Bamber and Burley, 1983, p. 24) for radiata pine reported that summer and autumn drought reduced the proportion of latewood. In support of this, Nicholls (1971) recorded an increase in the amount of latewood of 9-14% after irrigation. Shepherd (1964) found that large diameter tracheids (earlywood) were produced during periods of optimum growth after heavy rain and small diameter tracheids (latewood) in dry periods. He also reported that the sudden onset of drought during the growing season induced the premature formation of latewood (false rings). However, the influence of moisture stress on wood formation is not completely clear-cut. For example, Nicholls and Waring (1977) showed that, although drought increased the proportion of latewood, the density of latewood, and therefore probably the thickness of the cell walls, was also reduced.

7.1.2 Water-stress response traits

The water-stress traits used in the present study are well supported by functional relationships between tree growth and stem conductance and their response to water deficits (Figure 7-1). Specifically, the two short-term responses considered in this investigation (sapwood saturation and occurrence of cavitation signs) are intrinsically interrelated according to investigations of Edwards and Jarvis (1982), and Tyree and Sperry (1989) (Figure 7-1). Borghetti *et al.* (1993) argued that cavitation and refilling may play a key role in the responses of vegetation to climatic warming and drying. Morris and Benyon (2005) stated that cavitation may be a non-stomatal mechanism for the tree to reduce its conductance and regulate water loss in dry conditions. They also argued that if the affected vessels don't refill, cavitation will cause reductions in sapwood area which in turn may lead to reductions in leaf area. Xylem cavitation is the breakdown of conducting water columns due to pit aspiration. Experiments conducted by Harris (1954a, 1961) concluded that water conduction in radiata pine is related to saturation percentage; he also estimated that at 50% pit aspiration, which is approximately equivalent to 69% saturation, there is a critical sapflow disruption.

Similarly, the three traits considered in the present study as long-term responses to water-stress (sapwood percentage, number of heartwood rings, and dry zones in the inner sapwood) are also fundamentally related to changes in stem conductance. According to the pipe model theory, there is a linear proportion between the amount of foliage and conducting tissue (in the live crown) (Waring *et al.* 1982). Further, the relationship leaf area – sapwood area is affected by sapwood permeability and local climate (Whitehead *et al.* 1984); it changes with species and environment: e.g. *Pinus nigra* 0.15 vs. *Abies lasiocarpa* 0.75 (Waring *et al.* 1982); and varies with site (Whitehead 1978). Moreover, sapwood area has been observed to respond more readily to water limitation than other physiological traits in stands of mature trees (Cinnirella *et al.* 2002). Sapwood percentage and number of heartwood rings are rarely considered as such in forestry texts. Instead of sapwood percentage, the counterpart (heartwood percentage) is normally used and has been traditionally associated to senescence and/or growth rate. Investigations of Harris (1954a, b) and Bamber (1972) pioneered the physiological significance of heartwood and sapwood. Harris (1954a, b) concluded that heartwood formation in radiata pine is related to site and physiological drought. Bamber (1972) argued that heartwood formation is a physiological mechanism for controlling sapwood area rather than a senescence effect. Carrodus (1972) and Bamber (1976) indicated that the width of the sapwood is related to the physiological state of the tree.

Changes in stem conductance in relation to water stress

- **Short term** (daily or shorter)
  - Stomatal closure
  - Xylem cavitation (affects sapwood permeability and water flux)
- **Long term** (Seasonal, yearly or longer)
  - Leaf area reduction
  - Sapwood area reduction

Figure 7-1. Changes in stem conductance as a result of short and long term water stress (according to Morris and Benyon (2005))

Research questions for this study were:

1) Are there differences in wood quality between contrasting sites?
2) If there are site differences, do these differences vary between mature and young trees?
3) Are there site differences in response to water stress and if so, do these differ between mature and young trees?

4) Are there any relationships between wood quality and water stress response traits?

7.2 METHODS

7.2.1 Location and description of sites and stands

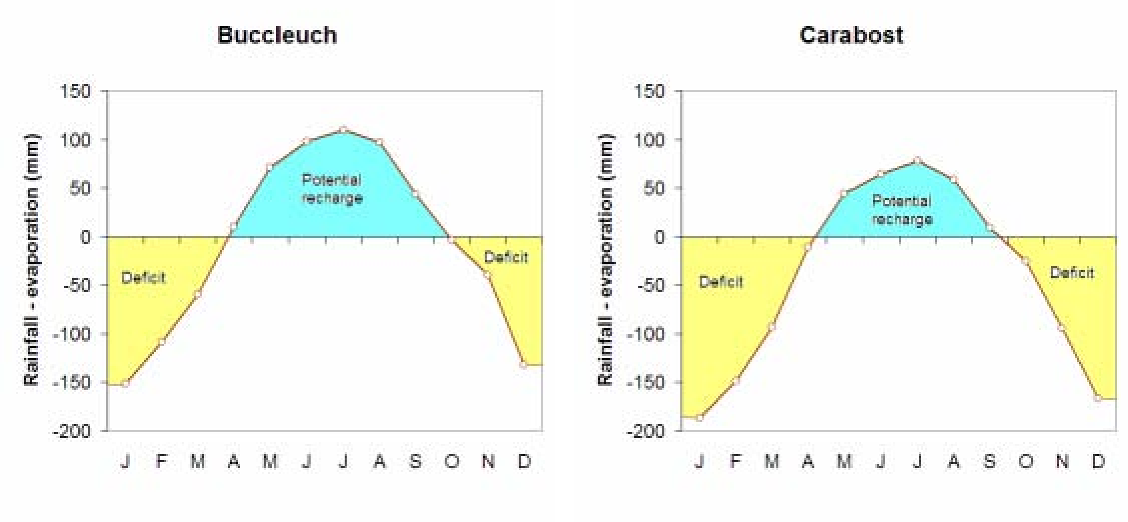


Figure 7-2. Average excess evaporation over rainfall and potential recharge for the two contrasting sites (Buccleuch = high-altitude, Carabost = warm-dry). Data from the ESOCLIM model, run date 28/7/06, Forests NSW Sydney.

The study was carried out in the Hume region of Forests New South Wales (FNSW) and included mature (34-36 years) and young trees (10-11 years) on two contrasting sites in terms of climate: namely a high-altitude sub-alpine (Buccleuch) vs. a warm-dry inland site (Carabost). On average during the driest quarter of the year the warm-dry site receives 25% less rainfall, 9% more evaporation, and almost 3ºC higher temperature (ESOCLIM model). Measurements of needle water potential conducted in the summer of 2006 for the medium-thinned stands (T2) (Chapter 5), showed notably low values at both the high-altitude and warm-dry site (-1.6 and -2.0 MPa, respectively). Yet the needle water-potential values for the warm-dry site were lower ($P<0.001$) which suggested higher transpiration rates and water stress during the hottest part of the year. Excess evaporation over rainfall is much greater throughout the year for the warm-dry site, which also receives considerably less potential recharge (Figure 7-2). Further climatic comparisons between sites are given in Section 7.3.3 below.

Table 7-1. Geology, soil characteristics and previous land use of sites and stands studied

Site	Stand	Parent material	Soil type[†]	Depth (cm) (by horizon)[‡]	Field texture	Previous land use
High-altitude	Mature T2	Granodiorite	Red earth	A 0 – 28 B 28 – 100+	Clay loam	Native forest
	Mature UT, T3	Gabbro/ dolerite	Structured loam/Red earth	A 0 – 28 B 28 – 100+	Clay loam	Native forest
	Young	Granodiorite	Red earth	A1 0 – 13 A2 13 – 23 B 23 – 80+	Sandy clay loam to sandy clay	2nd rotation
Warm-dry	Mature T2	Shales & siltstones	Yellow-brown earth	A 0 – 24 B 24 – 80+	Sandy clay loam to sandy clay	Native forest
	Mature UT, T3	Shales & siltstones	Yellow earth	A 0 – 24 B 24 – 90+	Sandy clay loam to sandy clay	Native forest
	Young ex-pasture	Shales & siltstones	Yellow podzolic	A 0 – 24 B 24 – 80+	Sandy clay loam to light clay	Ex-pasture (improved legume)
	Young ex-forest	Shales & siltstones	Lithosol/ Grey-brown podzolic	A 0 – 14 B 14 – 75+	Fine sandy clay loam to sandy clay	Native forest

Source: Wilkinson C. A. 2006-2007. Harvest plan soils survey. Land Management and Technical services Tumut, Forests NSW

[†] According to Northcote's soils Factual Key

[‡] Root system normally occupied layers A and varying depths of layer B depending on texture

Differences in geology and soils between sites studied were also substantial, namely the soils of the high-altitude site were derived from granodiorite and gabbro materials, whereas the soils of the warm-dry site were derived from shales and siltstone of the Wagga marginal basin (Table 7-1). The soils (horizon B) of the mature stands of the high-altitude site were slightly deeper than those of the warm-dry site, while the soil depths for young stands were fairly similar between sites (Table 7-1). The prior land use for all the mature stands in both sites was ex-native forest, whereas for the young stands this differed among sites (Table 7-1). The fertility of the warm-dry ex-pasture site of young trees was substantially enhanced (Hume region records).

At each of the sites there were paired stands of mature trees representing three thinning regimes: unthinned (UT), two- (T2) and three-thinnings (T3). The criteria for selection of matched thinned stands across sites were that they were thinned at approximately the same age and received the first thinning operation at an early stage (i.e. age 14). This is shown in Table 7-2. In addition to this, the three stands had to be in close proximity and present similar soils within each site. Initial (at planting) and final (at harvesting) stocking levels were similar between paired stands (Table 7-2). The genetic origin of the seedlots of mature trees was basically seed collected from early local unimproved plantings ('climb and select'). The collection areas normally matched the geographic location of the stands (Table 7-2). Diameter at breast height varied positively with thinning status and was considerably higher for the stands of the high-altitude site which confirmed the differences in environment between the two sites (Table 7-2). Tree height showed no definite trends with site or thinning status.

Table 7-2. Characteristics of mature stands

Site	High-altitude			Warm-dry		
State forest (Section)	Buccleuch (Mitchells)			Carabost (Short Cut Rd. and Rosewood Trig Rd.)		
Stand (thinning)	UT	T2	T3	UT	T2	T3
Compartment	624	591	720	163	171	163
Latitude (S)	35°10.7'	35°12.4'	35°10.9'	35°39.7'	35°40.4'	35°39.7'
Longitude (E)	148°34.5'	148°31.7'	148°34.4'	147°45.9'	147°46.5'	147°45.9'
Altitude (m)	890	894	903	464	584	464
Age	36	34.5	36	36.5	35.5	36.5
Initial/Final stocking	1330 / 722	1330 / 220	1330 / 205	1370 / 712	1370 / 280	1370 / 193
Age at thinnings	--	18, 24	14, 23, 30	--	14, 21	14, 27, 30
Seedlot(s)[†]	P101	'Combo'	P105	R	R	R
DBH (mm)	396	489	581	351	418	538
Height (m)	35.1	32.8	32.1	27.6	29.6	36.3
Crown height (m)	18.8	10.0	11.1	11.6	12.5	13.3
Date/season sampled	Nov-05 (spring)	Jan-06 (summer)	Nov-05 (spring)	Dec-05 (spring)	Feb-06 (summer)	Dec-05 (spring)

† P101 = Collection Red Hill SF age classes 1929-1932; P105 = Collection Billapalola SF age class 1950; Combo = mixture several collections; R = routine 'climb/select' seed from the Carabost area

Stands of young trees used in this study were selected from an ongoing wood quality broad-acre assessment in the Hume region of FNSW for stands aged 10 years. The criterion of selection was that they were in close proximity to the mature stands in each of the contrasting sites. One exception was the warm-dry ex-forest site which was located further south of the mature stands and the young ex-pasture planting of the warm-dry site, yet this had similar climatic conditions. Characteristics of young stands are shown in Table 7-3. In all cases none of the stands had received any thinning or major silviculture treatment, except for pruning on some trees at the warm-dry ex-pasture site. Five plots were selected for the high-altitude and warm-dry ex-pasture sites, and three plots for the warm-dry ex-forest site. Some differences were noted in stocking levels between plots for each of the sites; however, after checking initial stocking and management history it was concluded that these differences arose from competition that had occurred recently. A pre-analysis was also conducted and results indicated no association between wood quality traits and stocking, confirming that changes in stocking had occurred recently. Also, the differences in seedlots between sites and within site for the warm-dry ex-pasture site were tested in a pre-analysis and results indicated no relationships between seedlot rating values (GF) and traits measured. It is also known that the GF ratings refer to growth and form performance with respect to unimproved material and has no relation to wood characteristics (RPBC 2002).

Table 7-3. Characteristics of young stands

Site	High-altitude	Warm-dry ex-pasture	Warm-dry ex-forest
State forest	Buccleuch (Sandy Creek Section)	Carabost (Rosewood Park Section)	Seymours†
Compartment(s)	212, 216, 222, 229	452 – 456	110
Latitude (S)	35°14.7 – 15.8’	35°37.9’ – 38.6’	35°55.0’ – 55.3’
Longitude (E)	148°26.2’ – 26.6’	147°48.9’ – 49.6’	147°59.9’ - 148°0.5’
Altitude (m)	756 – 854	622 – 665	560 – 595
Age	11	11	10
Stocking at ages assessed	1060	970	970
Seedlot(s)	GF16 ‡	GF17, GF23	GF19
DBH (mm)	182	231	189
Height (m)	13.5	16.6	11.6
Date/season sampled	Oct-06 (spring)	Sep-06 (spring)	Sep-06 (spring)

† The location of this site was further south of Carabost SF; however both sites have similar climatic conditions

‡ Growth and form genetic rating values

7.2.2 Sampling procedures and traits measured

At each stand of mature trees and each plot of young trees, 10 healthy trees of good form and without severe malformations were selected. In all cases suppressed trees were avoided. With a few exceptions, methods used differed for mature and young trees: procedures for mature trees included destructive sampling at different heights, whereas for young trees these consisted mainly of non-destructive sampling at breast-height. Further descriptions are given in Appendix 1.

The study considered three types of traits: 1) wood quality, 2) long-term, and 3) short-term responses to water-stress. Discussion of the different traits was given in the introduction of this Chapter. Wood quality traits included dynamic MOE (DMOE) and basic density (BD). Long-term response to water-stress traits were sapwood percentage, number of heartwood rings, and the presence of dry sapwood (DSW); the latter was assessed only on young trees. Short-term responses to water-stress traits included sapwood saturation percentage and evidence of cavitation. Diameter at breast height was also considered as an indicator of growth. Measurement procedures are indicated in Appendix 1.

7.2.3 Statistical analysis of wood quality and drought response traits

Statistical effects of site on the different traits for mature trees were determined separately for each of the paired-thinning stands (UT, T2, and T3), whereas analysis of the effects of thinning regime were conducted separately for each paired-site stands (warm-dry vs. high-altitude). In both cases one-way analysis of variance models were used. Analysis was conducted both at breast-height and whole-tree levels. In addition, the percentage differences with respect to the high-altitude site were calculated for each paired stand.

Relationships between long-term water-stress response traits and wood quality and DBH for mature trees were tested by correlation analysis. This was conducted separately for each of the traits (sapwood percentage and number of heartwood rings), for each of the sites, and within sites for each of the sampling heights. Additionally, the association between sapwood percentage and number of heartwood rings for the different stands and sampling heights in the two contrasting sites was also tested by correlation analysis.

For young trees, statistical differences of the two warm-dry sites against the high-altitude site were tested separately by one-way ANOVA models using plot nested within site as the error term. Similarly, percentage differences with respect to the high-altitude site were calculated for each warm-dry stand. As with mature trees, correlation analyses between long-term water-stress response traits and wood quality and DBH for young trees were conducted separately for each of the traits (sapwood percentage, number of heartwood rings, and dry sapwood presence). Analyses were first done using the individual pooled data for each of the sites with poor results, thus a second analysis was done by plot for each site.

7.2.4 Climate information

Climate data available came from three different sources: 1) ESOCLIM model for 'all-time' monthly and annual climatic averages; 2) the Australian Bureau of Meteorology (BOM) for long-term daily information of rainfall and evaporation; 3) automated weather stations of the Hume region of FNSW for the period 2005-2006 for monthly rainfall. The ESOCLIM data was used mainly for general site characterization, whereas the data from the BOM stations was used to aid in the interpretation of results of the wood quality and long-term water-stress traits. The data from the Hume stations was used mainly for the interpretation of results of the short-term water-stress traits. For the data sources (2) and (3) only rainfall and evaporation (where available) were considered, mainly because of the lack of long-term temperature data for one of the sites under study.

There were three BOM climate stations near the areas of study (Table 7-4). Station 1 roughly matched the location and conditions of the high-altitude site, whereas in the case of the warm-dry site, this presented intermediate conditions between stations 2 and 3. Rainfall data for the warm-dry site was obtained as simple averages from stations 2 and 3 provided there was rainfall occurrence at both stations. The annual rainfall for the period 2001-2006 between the average of stations 2 and 3 versus station 5 (Table 7-4) gave good results during a pre-analysis, thus the method was considered as adequate. Evaporation data for the warm-dry site came directly from station 3 as there was no data available from station 2. This was also validated in a pre-analysis in which there was a close agreement in annual evaporation between station 3 and the 'all-time' annual value calculated by the ESOCLIM model for the warm-dry site. Despite the possible drawbacks of the methods used here for gathering long-term climatic information and the occurrence of some gaps in the data, this method was considered to be more realistic than using climate surfaces and other modelling methodologies.

Table 7-4. Location and data available of climatic stations used in the study

Station	Source	Location	Period	Parameter(s)	Site related to
1) Blowering dam	BOM	35º 23.7' 148º 14.8'	1969-2006	Rainfall & Evaporation	High-altitude
2) Tumbarumba	BOM	35º 46.7' 148º 0.7'	1969-2006	Rainfall	Warm-dry
3) Hume reservoir	BOM	36º 6.2' 147º 2'	1969-2006	Rainfall & Evaporation	Warm-dry
4) Bondo	FNSW	Buccleuch SF	2001 - 2006	Rainfall	High-altitude
5) Rosewood	FNSW	Rosewood	2001 - 2006	Rainfall	Warm-dry

The difference between rainfall and pan evaporation was used as an indicator of water surplus/deficit. Although this is not a true measure of water deficit, rainfall constitutes the major input of moisture while pan evaporation is a simple approximation to potential evapotranspiration which is an estimate of the maximum water use of a plantation or crop (Bond 2002, Theiveyanathan and Polglase 2005).

Long-term daily climate data per site was processed as follows: 1) this was first grouped into half-month periods, and rainfall, evaporation, and the difference rainfall-evaporation aggregated. 2) Half-month data was then coded in relation to periods of wood formation according to investigation of Nicholls and Wright (1976) with radiata pine in Australia in which the number the effective growth periods were assessed in terms of favourable water deficits, and similarly to Harris (1991). Wood formation periods are shown in Table 7-5. 3) Half-month data was also coded according to age intervals of mature trees: 0 – 10 years (=1969-1971 to 1979-1981), 10 - 24/26 years (=1979-1981 to 1995), and 24/26 - 34/36 years (=1995 to 2005); the reason of having variable age ranges (i.e. 24/26, 34/36) was due to the differences in age between stands. Note that the age interval 24/26 – 34/36 corresponded roughly to the life of the young trees (10 to 11 years). 4) Finally, climatic averages were obtained by periods of wood formation and age intervals. Note that age intervals were not calendar years but started in June and ended in May assuming all stands were planted in winter.

Table 7-5. Wood formation periods according to Nicholls and Wright (1976) and Harris (1991) used for the influence of climate on wood quality and responses to water-stress

Periods of wood formation	Dates	No. Half-months
Winter	June – 1st half of August	5
Earlywood	2nd half of August – 1st half of December	8
Summer	2nd half of December – 1st half of March	6
Latewood	2nd half of March – May	5

Site differences in DMOE and basic density for both mature and young trees were related to differences in rainfall and water deficits between the two sites during the periods of wood formation (earlywood and latewood) in radiata pine according to the study of Nicholls and Wright (1976) across a range of sites in Victoria, Australia. Nicholls and Wright (1976) also indicated that during summer there is practically no diameter growth for most of the sites because of the extreme water deficits.

7.3 RESULTS

7.3.1 Mature trees

The warm-dry site, compared to the high-altitude site showed an overall inferior wood quality, most evident in the DMOE (Table 7-6). The overall reduction in breast-height outerwood DMOE ranged from -5% to -11%, being worse for the unthinned (UT) and heavily-thinned (T3) stands. Reductions in whole-tree outerwood DMOE mirrored those of breast-height outerwood DMOE. The reduction in whole-tree log-DMOE ranged from -7% to -10% being worse for the heavily-thinned stand (Table 7-6). On the other hand, the thinned stands (T2 and T3) of the warm-dry site showed mostly significant lower breast-height and whole-tree basic density than the high-altitude site but the opposite trend was observed for the unthinned stands (Table 7-6). The overall reductions in basic density for the thinned stands of the warm-dry site ranged from -4% to -9% whereas the increases in basic density for the unthinned stand ranged from 4% to 6% (Table 7-6).

There was an overall and mostly significant decrease in DMOE and basic density with increasing thinning for the warm-dry site (Figure 7-3). In contrast, there were no consistent trends in wood quality with thinning regime for the high-altitude site, i.e. the unthinned stand showed considerably higher DMOE but there were practically no differences in DMOE between the thinned stands. Further, there was no clear relationship between thinning regime and basic density although the heavily-thinned stand showed the lowest basic density especially at breast height (Figure 7-3).

Results revealed marked site differences to long-term water stress. In first place, the trees of the warm-dry site showed considerably and significantly lower sapwood contents across stands: i.e. between 9% and 17% lower breast-height sapwood percentage, and between 7% and 11% lower sapwood volume at 10.5 m than the high-altitude site (Table 7-6). The differences in sapwood content between sites decreased with increasing thinning (Table 7-6 and Figure 7-3). Variability in breast-height sapwood percentage was also considerably greater for most of the warm-dry site stands, especially for the unthinned stand (Figure 7-3).

In second place, the number of heartwood rings at breast height was mostly significantly higher for the stands of the warm-dry site. This effect occurred to a greater extent for the thinned stands where the difference ranged from 2.5 to 3.8 rings and contrasted for a small difference for the heavily-thinned where the difference was of only 1 ring (Table 7-6). Decreases in sapwood percentage were well related to increases in heartwood rings (Table 7-6). This relationship was further tested by correlation analysis and results indicated a moderate to strong negative association between the two traits at breast height (Table 7-8).

Table 7-6. Means of wood quality and water-stress response traits for mature trees across sites (HA = high-altitude, WD = warm-dry) and thinning regimes, and statistical differences with respect to the high-altitude site

Traits	Site	Unthinned(UT) Mean	Unthinned(UT) Diff [1] (%)	2 thinnings (T2) Mean	2 thinnings (T2) Diff [1] %	3 thinnings (T3) Mean	3 thinnings (T3) Diff [1] %	Thinning effects
DBH (mm)	HA	396	(-11)*	489	(-14)**	581	(-7) ns	**
	WD	351		418		538		**
Dynamic MOE (GPa)								
Breast-height outerwood DMOE	HA	22.2	(-11)*	19.6	(-5) ns	19.7	(-11)*	**
	WD	19.9		18.6		17.6		ns
Whole-tree outerwood DMOE†	HA	22.9	(-12)**	19.2	(-4) ns	19.8	(-11)*	**
	WD	20.1		18.5		17.6		*
Whole-tree log-DMOE†	HA	11.7	(-8) ns	10.3	(-7) ns	10.2	(-10)*	**
	WD	10.7		9.6		9.2		**
Whole-section basic density (kg/m^3)								
Breast height	HA	468	(6) *	489	(-9)**	456	(-6)*	*
	WD	495		443		429		**
Whole-tree†	HA	436	(4) ns	447	(-7)**	429	(-4) ns	ns
	WD	455		416		413		**
Long-term water-stress response								
Sapwood (%)								
Breast height (cross-section)	HA	80.1	(-17)**	83.2	(-13)**	82.1	(-9)*	ns
	WD	66.5		72.5		74.4		ns
stem volume to 10.5 m ‡	HA	75.0	(-11)**	80.7	(-10)**	78.8	(-7) ns	*
	WD	66.4		72.4		73.0		ns
Heartwood (No. rings)	HA	7.9	(30) **	7.5	(51) **	10.6	(9) ns	**
(Breast height)	WD	10.3		11.3		11.6		ns
Short-term water-stress response								
Sapwood saturation (%)								
Breast height	HA	90.9	(-1) ns	90.6	(-1) ns	92.3	(-1) ns	ns
	WD	89.9		89.8		91.4		ns
Whole-tree†	HA	92.8	(-2) ns	92.5	(-2) ns	93.0	(0) ns	ns
	WD	91.2		91.1		93.2		ns

[1] Percentage differences with respect to the high-altitude site; ANOVA results * $P < 0.05$, ** $P < 0.01$, ns = not significant

† Weighted-log averages as measured from 1.3 to 21.5 m

‡ As measured from 1.3 to 10.5 m

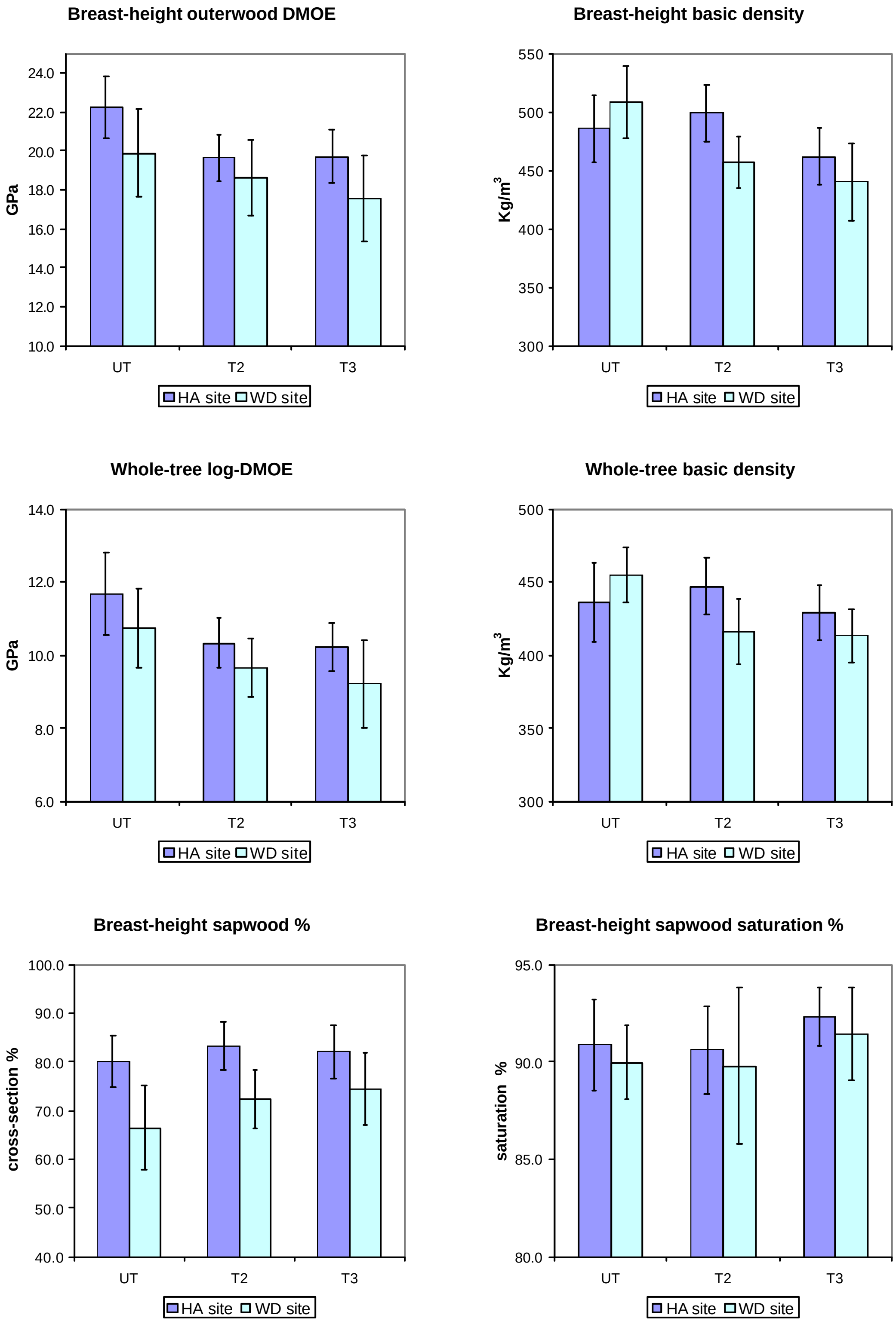


Figure 7-3. Differences in wood quality and selected water-stress response traits with site (HA=high-altitude, WD=warm-dry) across stands (UT=unthinned, T2=two thinnings, T3=three thinnings) for mature trees; sapwood saturation percentage for the T2 stands as measured in the dry season (summer 2006); vertical bars denote ±1 standard deviation

There were site differences to short-term water-stress only for the dry season (summer). Although the differences in percentage saturation with site were small and non-statistically significant, between-tree variation in saturation during the dry season was considerably higher for the medium-thinned stand (T2) of the warm-dry site (Table 7-6 and Figure 7-3). For this stand at breast height, trees ranged from fairly dry (81%) to fairly saturated (94%) as compared to 87-94% for the high-altitude site. This was in agreement with the frequency of cavitation signs which occurred to a greater extent for the warm-dry site as discussed below.

Further, the warm-dry site was considerably more affected by cavitation during the dry season as indicated by the results for the medium-thinned stands (Table 7-7). The percentage of trees from the warm-dry site having cavitation spots of varying sizes ranged from 13 to 90% as compared to 10 to 20% for the high-altitude site (Table 7-7). Also, none of the trees from the high-altitude site showed cavitation bands compared to 10 to 50% from the warm-dry site (Table 7-7). In addition, results indicated an association between the frequency and intensity of cavitation and the position in the stem; namely the occurrence of cavitation spots was more concentrated in the lower part of the stem and decreased up the tree, whereas the cavitation bands occurred mainly within the live crown (Figure 7-4).

Table 7-7. Frequency (% trees) with presence of sapwood cavitation signs for the medium-thinned stands (T2) in the dry season (summer-06) for two contrasting sites

Height (m)	Spots		Bands	
	Warm-dry	High-altitude	Warm-dry	High-altitude
0.2	90	20	0	0
1.3	90	20	0	0
10.5	70	0	10	0
16	80	0	20	0
21.5	40	10	60	0
27	13	10	50	0

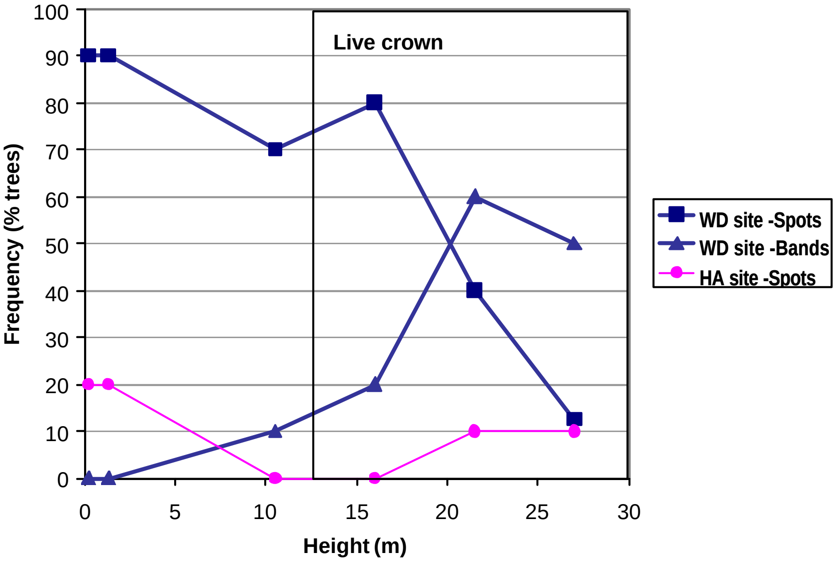


Figure 7-4. Frequency (% trees) of sapwood cavitation signs with height in the tree for the medium-thinned stands measured in the dry season (points represent averages from 10 trees); (WD=warm-dry site, HA=high-altitude site); cavitation signs key: Spots=cavitation spots of varying sizes; Bands=cavitation bands.

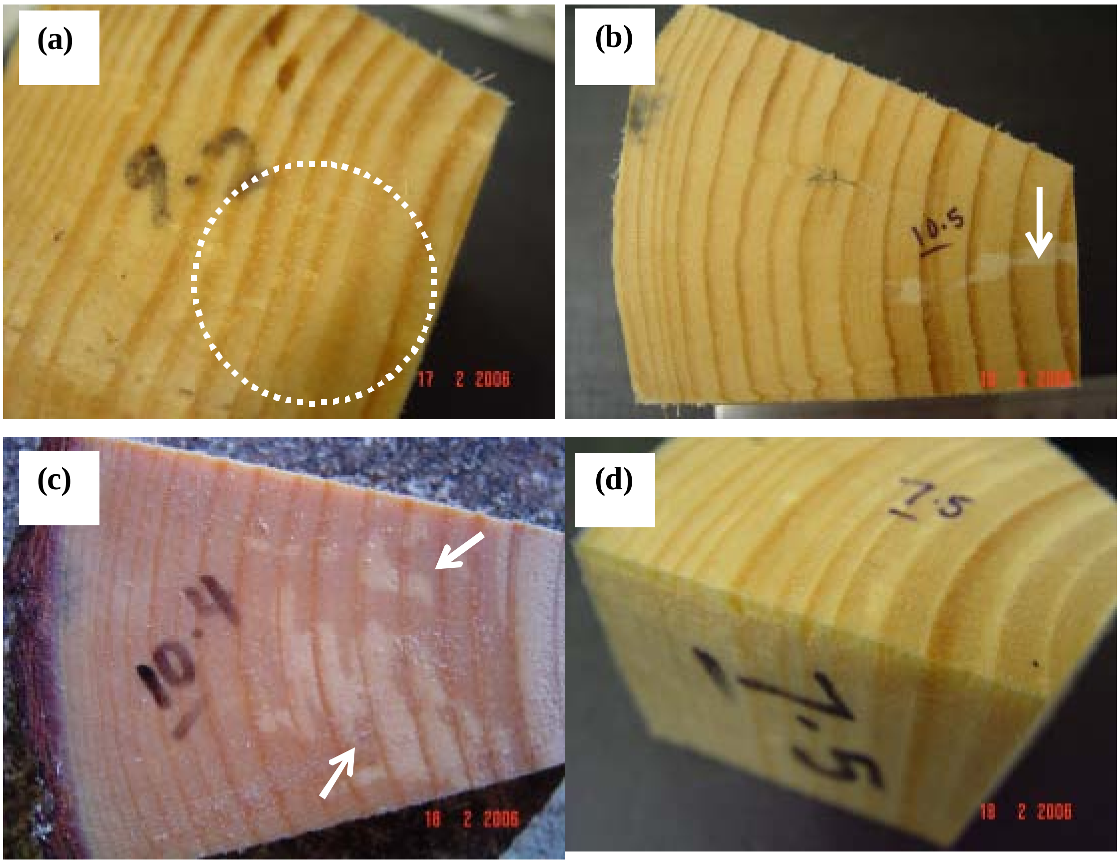


Figure 7-5. Cavitation signs observed in the sapwood samples of mature trees during summer in the warm-dry site; 4a) inset shows small cavitation dots; 4b-c) large cavitation spots, note their relative closeness to the heartwood; 4d) cavitation bands, note the broader bands towards the heartwood and their continuity along the axial direction

Correlation of long-term water-stress traits with wood quality and diameter for mature trees

Results of correlation analyses between long-term water-stress response traits (sapwood percentage and number of heartwood rings) and wood quality (DMOE and basic density), and diameter at breast height (DBH) are shown in Appendix 2. Correlation analyses between short-term water-stress and wood quality or DBH were not conducted as both types of variables involve changes taking place at very different periods of time, i.e. short-term responses of trees to water-stress were assumed to occur over a few days or weeks, changes in outerwood DMOE occur over a few years, and changes in log-DMOE and basic density include the entire life of the trees.

Relevant associations of sapwood percentage with the wood quality traits and DBH only occurred at some points along the stem, and mainly at the upper stem for the warm-dry site. The strength (correlation values) and nature (positive or negative) of the associations did not show definite trends with thinning regime (stand) for any of the sites. Relevant association of the number of heartwood rings with the wood quality traits and DBH only occurred at isolated and sometimes continuous points along the stem for both sites (Appendix 2). Similar to sapwood percentage, there were no definite trends for any of the stands.

The inverse trends shown by sapwood percentage and number of heartwood rings across sites and stands (Table 7-6) was further confirmed by correlation analysis (Table 7-8). The strength of this association differed between stands and at the different points along the stem, which explained the divergence between the two traits with respect to their association with wood quality traits and DBH (Appendix 2). The fairly close association between the two traits suggested that the number of heartwood rings can be an acceptable predictor of the cross sectional percentages of sapwood and/or heartwood.

Table 7-8. Correlation analysis between sapwood percentage and the number of heartwood rings across stands (UT=unthinned, T2=two thinnings, T3=three thinnings) for the two contrasting sites of mature trees (n=10)

Nominal height (m)	Warm-dry site			High-altitude site		
	UT	T2	T3	UT	T2	T3
1.3	-0.59	-0.58	-0.83 **	-0.57	-0.61	-0.56
10.5	-0.44	-0.57	-0.78 **	-0.62	-0.80 **	-0.62
16	-0.19	-0.72 *	-0.88 ***	-0.59	-0.85 **	-0.06
21.5	-0.34	-0.86 **	-0.74 *	--	-0.83 **	--

*Significant at $P < 0.05$, **$P < 0.01$, *** $P < 0.001$

7.3.2 Young trees

The two warm-dry sites produced inferior wood quality with a poorer outerwood DMOE (Figure 7-6). The reductions in breast-height outerwood DMOE for the ex-pasture and ex-forest warm-dry sites were -35% and -36%, respectively, whereas the corresponding reductions in breast-height basic density were -8% and -7%, respectively (Table 7-9). The similar outerwood DMOE and basic density for both the ex-pasture and the ex-forest warm-dry sites suggested that the prior land use had no influence on wood quality.

On the other hand, diameter was considerably and significantly larger for the warm-dry ex-pasture site which was mainly attributed to the high fertility that resulted from the previous land use and perhaps superior genetic material (Tables 7-1 and 7-3). The fact that the high-altitude site had slightly smaller diameter than the warm-dry ex-forest site which was one year younger was partly attributed to differences in genetic material (Table 7-3). Further, this trend also suggested that at this early age of the stands, the environmental differences between the two sites (excluding the effect of prior land use) are not so-limiting for growth. Instead, it would appear that site differences limit growth development at the latter stages of stand development as indicated by the significant differences in diameter at breast height for the mature trees (Table 7-6).

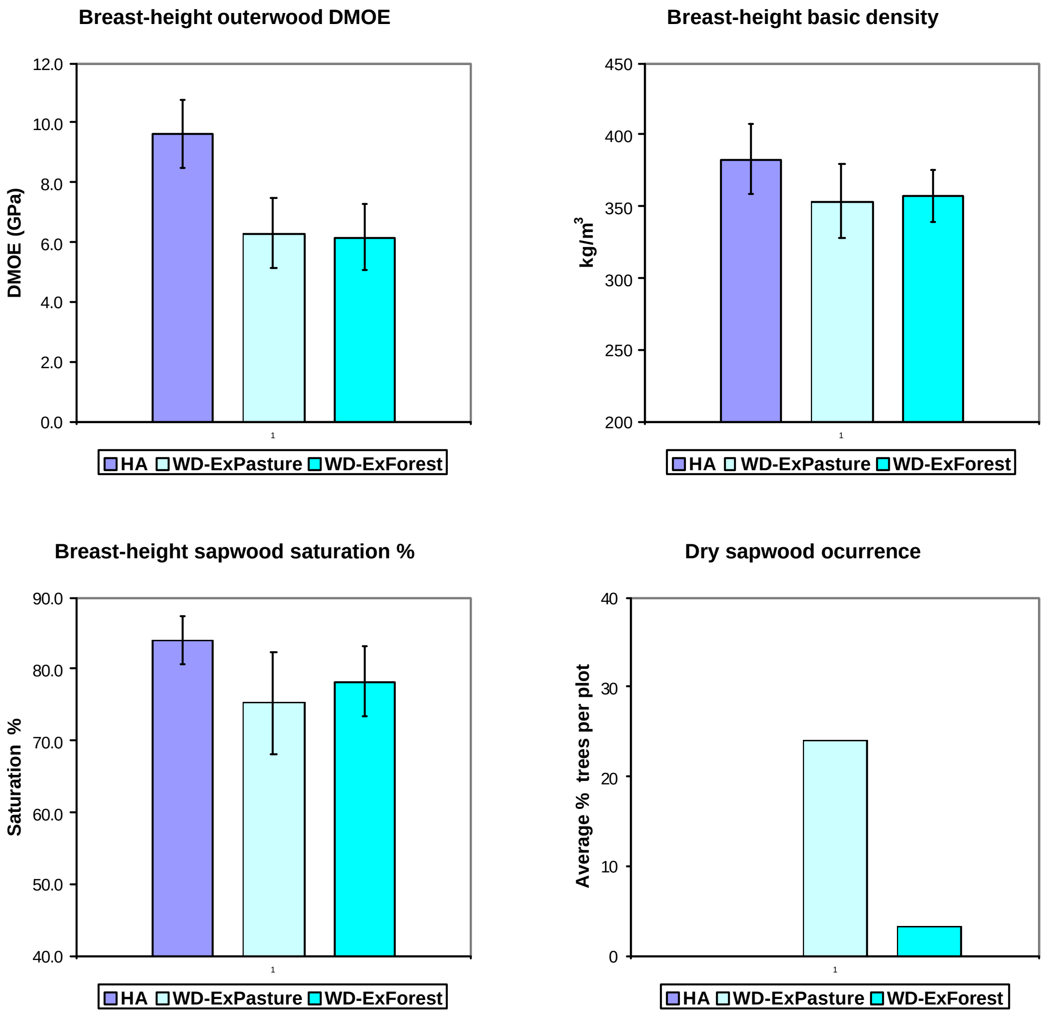


Figure 7-6. Differences in wood quality and selected water-stress response traits with site (HA=high altitude, WD=warm dry) for young trees at breast height (1.3 m); sapwood saturation as measured in spring-06; vertical bars denote ±1 standard deviation

There was an overall incipient response of the young trees to long-term water stress which differed considerably between sites. This is shown by the higher dry sapwood occurrence for the warm-dry ex-pasture site (24% of the trees) as compared to the incipient occurrence for the warm-dry ex-forest site (3%) and the zero occurrence for the high-altitude site (Table 7-9). Moreover, there was a small reduction in sapwood percentage linked to a significant incipient development of heartwood for the warm-dry ex-pasture site (Table 7-9). The inverse relationship between sapwood percentage and number of heartwood rings was not further tested as this is still incipient.

Response of young trees to short-term water stress was considerably higher than that to long-term water stress and was more pronounced for the warm-dry sites (Table

7-9). In first place, the two warm-dry sites showed considerably lower sapwood saturation than the high-altitude site (-10% and -7%, respectively) yet differences were statistically significant only for the ex-pasture site (Table 7-9). Further, both warm-dry sites showed considerable between-tree variability in saturation; i.e. sapwood saturation ranged from 56 to 91% for the ex-pasture site and 66 to 91% for the ex-forest site, as compared to 71 to 93% for the high-altitude site. This means that some trees of the warm-dry sites were relatively 'wet' and some others very 'dry' falling below the critical 69% saturation level advanced by Harris (1954a).

Table 7-9. Means of wood quality and water-stress response traits for young trees at breast height (1.3m) and statistical differences with respect to the high-altitude site

Traits	High-altitude	Warm-dry Ex-Pasture			Warm-dry Ex-Forest		
	Mean	Mean	Diff%†		Mean	Diff%†	
DBH (mm)	182	231	(27)	**	189	(4)	ns
Outerwood DMOE (GPa)	9.7	6.3	(-35)	**	6.2	(-36)	**
Basic density (kg/m^3)	383	354	(-8)	**	358	(-7)	**
Long-term water-stress response							
Sapwood %	99.2	98.6	(-1)	ns	99.3	(0)	ns
No. Heartwood rings	0.7	1.2	--	*	0.7	--	ns
Dry sapwood (% trees per plot)	0	24	--	--	3	--	--
Short-term water-stress response							
Sapwood saturation (%) ‡	84.0	75.3	(-10)	**	78.3	(-7)	ns
Cavitation spots (% trees per plot) ‡	40	32	--	--	33	--	--

† Percentage differences with respect to the high-altitude site
ANOVA results *P < 0.05, ** P < 0.01, ns = not significant
‡ Sapwood saturation and cavitation spots as measured in spring-06

In contrast to the rest of the water-stress response traits, there was a general evidence of cavitation across the different sites (Figure 7-7), with the frequency being higher for the high-altitude site (Table 7-9). Nevertheless, results for the high-altitude site of young trees were highly leveraged by one plot in which 80% of the trees showed cavitation spots compared to 20 to 40% for the rest of the plots of the same site. In comparison, the percentage of trees per plot with presence of cavitation spots ranged between 10 to 40% and 10 to 60% for the warm-dry ex-pasture and ex-forest sites, respectively.

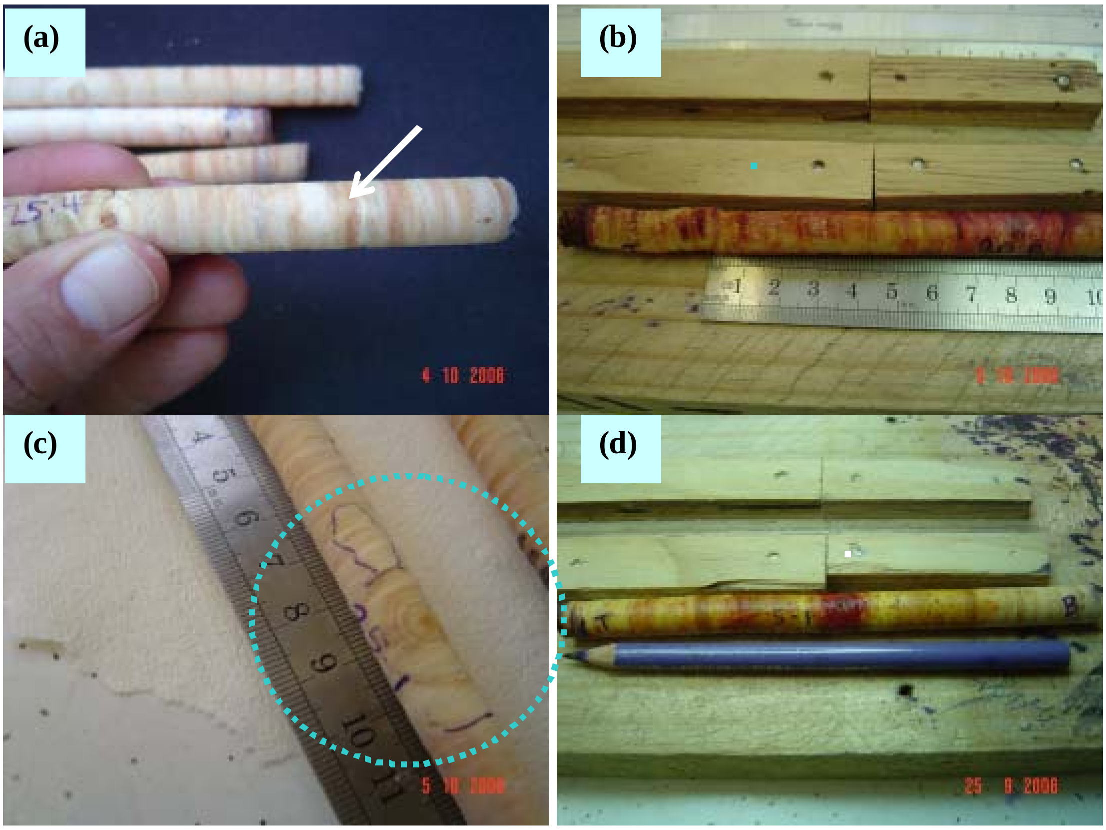


Figure 7-7. 12 mm cores of young trees showing different responses to water-stress: a) large cavitation spot; b) cavitation dots along the sapwood; c) large cavitation spot and presence of dry sapwood area near the pith; d) incipient development of heartwood in red colour after the staining test

Correlation of long-term water-stress traits with wood quality and diameter of young trees

As with mature trees, correlation analysis of water-stress traits versus wood quality and diameter was conducted only for long-term response traits (sapwood percentage, number of heartwood rings, and dry sapwood presence). Initial correlation analysis revealed an overall complete lack of association between traits (not shown). These poor results were further investigated and it was found that they were partly attributed to considerable between-plot differences which confounded any possible trend. Consequently, a new analysis was conducted separately for each of the plots and results are shown in Appendix 2. Correlation analysis by plot revealed that any relevant association between the long-term water-stress traits and wood quality and diameter occurred only at some localized plots across the three sites (Appendix 2). There were no definite trends with site yet the warm-dry ex-pasture and high-altitude sites observed relatively larger responses as compared to the warm-dry ex-forest site which observed very weak relationships (Appendix 2).

7.3.3 Climate differences

The warm-dry site received between 10% and 23% less annual rainfall than the high-altitude site over the different age intervals; however, differences tended to diminish during the last 10 years mainly caused by a decrease in rainfall for the high-altitude site (Table 7-10). According to our definition of water surplus/deficit (rainfall-evaporation) the warm-dry site showed water deficits between 1.2 to 2.5 times higher than that of the high-altitude site (Table 7-10). As for rainfall, the least difference in water deficit was observed during the last 10 years is influenced by the decrease in rainfall for the high-altitude site. On the other hand, the largest site differences in rainfall and water deficit apparently occurred between years 10 - 24/26 as influenced by an increase in rainfall for the high-altitude site (Table 7-10). In contrast to the high-altitude site, the warm-dry site showed relatively little changes in rainfall over the different age intervals (Table 7-10).

Results of rainfall by age intervals and periods of wood formation revealed that the warm-dry site received between 8% and 26% less rainfall during the period of earlywood formation and between 14% and 22% less rainfall for latewood formation than the high-altitude site (Table 7-10). Further, site differences in rainfall for both earlywood and latewood were fairly uniform over the first 24/26 years, followed by a greater site difference for latewood formation during the last 10 years (8% difference for earlywood and 14% for latewood). The increased rainfall at the high-altitude site during latewood formation for the last 10 years is also shown graphically in Figure 7-8. This outcome is of significance to explain site differences in outerwood DMOE of mature and young trees and basic density of the young trees.

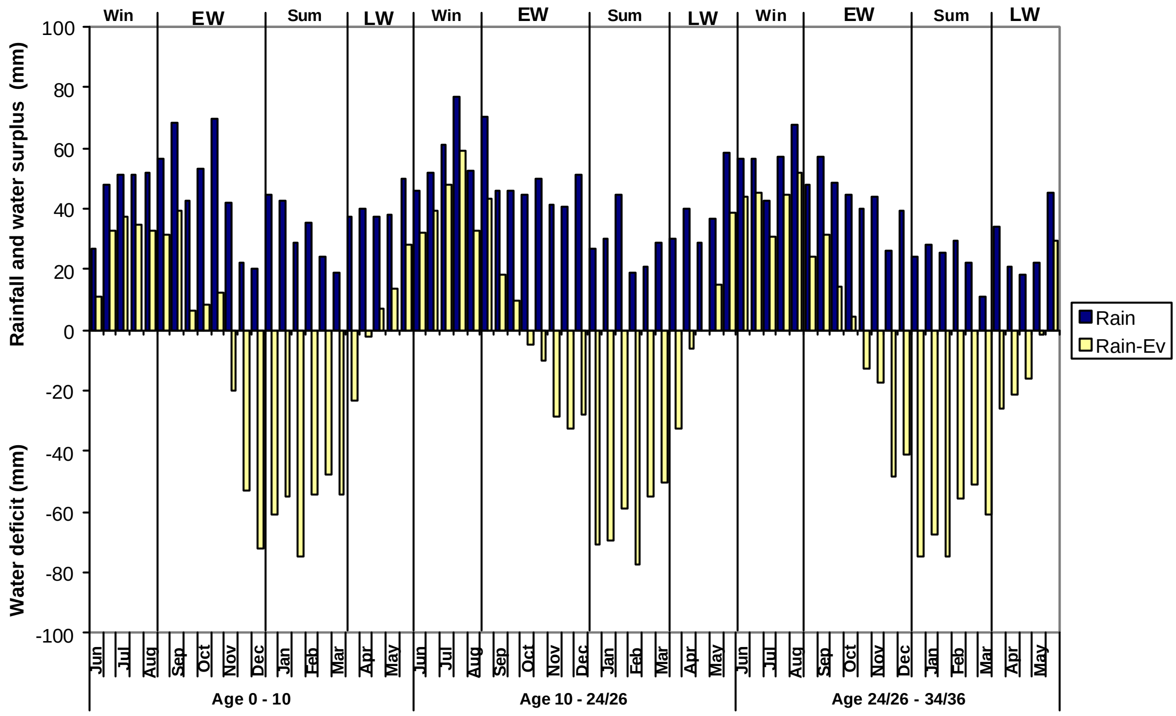
According to expectations, water deficits (rain - evaporation) occurred to a greater extent during summer for both sites and were higher for the warm-dry site (Table 7-10). The warm-dry site had 40%, 35%, and 27% more water deficit for the age intervals 0 - 10, 10 - 24/26, respectively (Table 7-10). On the other hand, and contrary to expectations, differences in water deficits between sites during summer were considerably smaller than those observed during earlywood and latewood periods (1.2 to 7.6-fold differences) (Table 7-10). Water deficits occurring during late spring and summer are of importance for explaining variation in heartwood development and/or decreases of sapwood proportion, and formation of dry sapwood.

Table 7-10. Averages of rainfall (R) and 'water surplus/deficit' = rainfall – evaporation (Ev), by periods of wood formation and age intervals of mature trees for two contrasting sites (HA=high altitude, WD=warm-dry); the age interval 24/26 – 34/36 corresponds roughly to the life span of the young trees

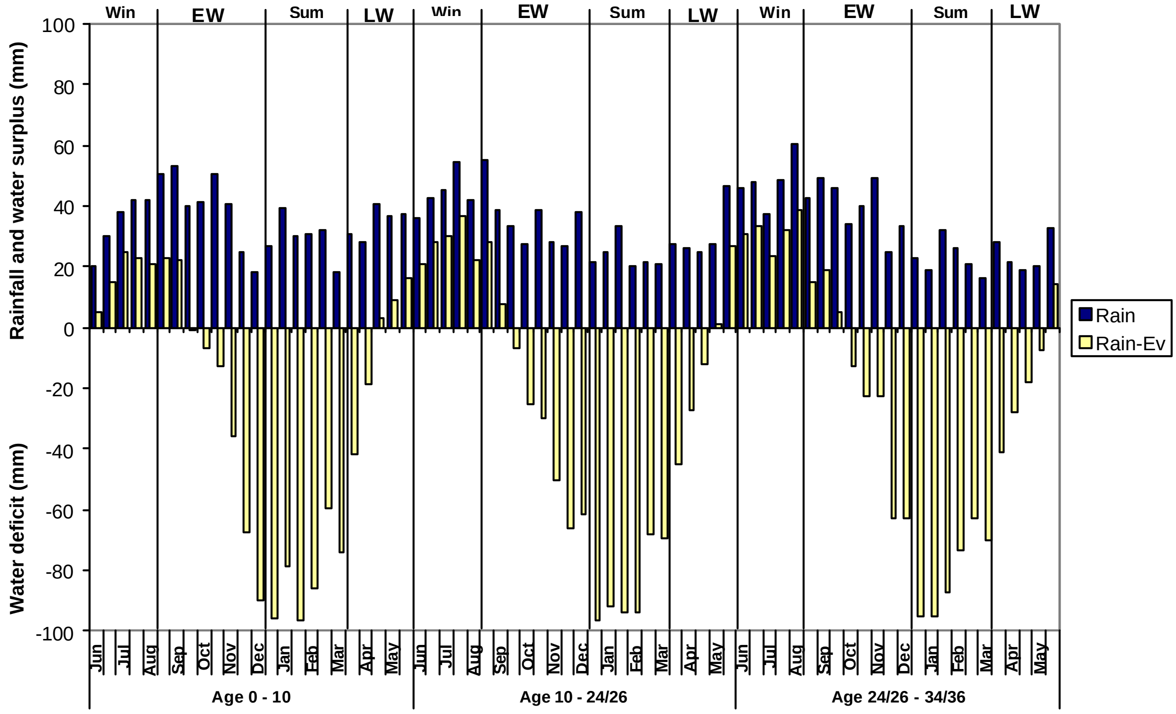
Age (years)/ site	Winter		Earlywood		Summer		Latewood		Annual	
	R (mm)	R-Ev (mm)	R (mm)	R-Ev (mm)	R (mm)	R-Ev (mm)	R (mm)	R-Ev (mm)	R (mm)	R-Ev (mm)
0 – 10 (=1969-1971 to 1979-1981)										
HA	229	148	374	-48	189	-351	203	23	995	-228
WD	172	89	320	-168	179	-490	173	-32	844	-601
Diff(%)[†]	-25	-40	-14	250	-5	40	-15	-239	-15	164
10 – 24/26 (=1979-1981 to 1995)										
HA	289	211	390	-23	170	-383	194	14	1042	-180
WD	223	141	290	-198	140	-516	152	-59	805	-632
Diff(%)[†]	-23	-33	-26	761	-18	35	-22	-521	-23	251
24/26 – 34/36 (=1995 to 2005)										
HA	280	216	347	-45	142	-381	140	-36	909	-246
WD	241	158	320	-146	140	-483	121	-80	821	-551
Diff(%)[†]	-14	-27	-8	224	-1	27	-14	122	-10	124
0 – 34/36 (=1969-1971 to 2005)										
HA	269	195	373	-37	167	-373	180	2	989	-213
WD	214	132	307	-175	150	-499	149	-58	821	-601
Diff(%)[†]	-20	-32	-18	373	-10	34	-17	*	-17	182

[†] Percentage differences with respect to the high-altitude site; differences (%) in R-Ev for the warm-dry site with respect to the high-altitude site should be interpreted as follows:
Winter = less water surplus
Earlywood, summer, and annual = more water deficit
Latewood = either water surplus/deficit
* Value = -3000% not shown as this is an unrealistic amount

Finally, water surplus (rain - evaporation) occurred only during winter for both sites (Table 7-10). The warm-dry site showed less water surplus than the high-altitude site over the different age intervals: -40%, -33%, and -27% for ages 0 - 10, 10 - 24/26, and 24/26 – 34/36, respectively (Table 7-10). Although these results are relevant perhaps to explain site differences in growth during early spring, these may be of lesser significance for wood formation (i.e. earlywood). Namely, the differences in water surplus were small compared to the large site differences in water deficit during earlywood formation.



a) High-altitude site



b) Warm-dry site

Figure 7-8. Half-month average rainfall and 'water surplus/deficit' = rainfall – evaporation (Ev) by age intervals and periods of wood formation (Win=winter, EW=earlywood, Sum=summer, LW=latewood) in two contrasting sites of the Hume region of FNSW; as determined from long-term daily data of BOM stations

Monthly precipitation for the period 2005 – 2006 (Figure 7-9) highlighted the contrasting climatic conditions between two successive years in the region of study and the differences in climate for the two sites under study. In fact, 2005 was an atypical ‘wet’ year with 1128 mm and 931 mm annual rainfall for the high-altitude and warm-dry sites, respectively (as compared to the averages for the last 34/36 years in Table 7-10). In contrast, a long-drought period started early 2006 and continued throughout the year giving as a result one the driest years recorded in the region (470 mm and 324 mm, respectively for the high-altitude and warm-dry sites) which mirrored the trends observed all throughout south east Australia over that year. This was also in agreement with the continuing and considerable decreases in sapwood saturation observed for the experiment with young trees during 2006 in Chapter 6. Implications for short-term water-stress responses are discussed below.

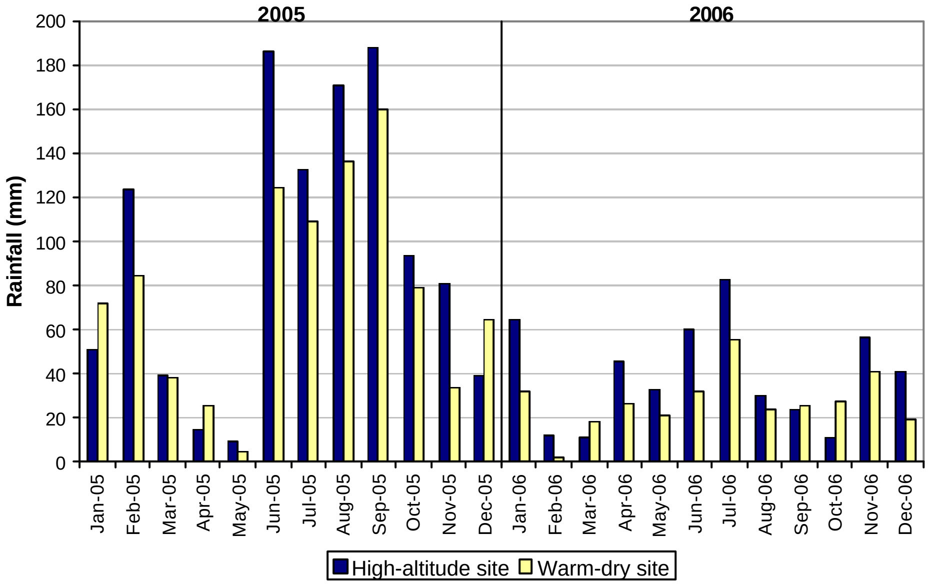


Figure 7-9. Monthly rainfall for the period 2005 – 2006 of the two contrasting sites under study; source: automated weather stations of the Hume region of FNSW (‘Bondo’ and ‘Rosewood’)

7.4 DISCUSSION

Climatic analysis indicated that during summer both sites are in major water deficit thus wood production is probably minimal. This was in agreement with the study of Nicholls and Wright (1976) across contrasting sites in Victoria, Australia, where they concluded that there was practically no diameter growth during summer for most of the sites because of the extreme water deficits. Similarly, in winter both sites are in water surplus and therefore this may have not contributed significantly to differences in wood quality.

Over the past 10 years there has been a greater difference between sites in latewood rainfall than earlywood rainfall. Thus the young trees of the warm-dry site would be expected to produce less latewood leading to lower wood density and stiffness. The same trend would be expected for the wood laid down by the mature trees during that period. Percentage reduction in basic density was similar for the young stands and the thinned stands of mature trees indicating a general site effect. These results agreed with earlier studies with radiata pine in Australia and New Zealand which indicate that the balance of water availability/deficit in spring and autumn influence the ratio earlywood/latewood ratio and hence wood density (Nicholls *et al.* 1974, Nicholls 1971, Nicholls and Waring 1977, Nicholls and Wright 1976, Harris *et al.* 1978, Nicholls 1971, and Shepherd 1964). Similarly, the lower DMOE for the drier site was confirmed with results of Porada *et al.* (2007)[1] with genetic trials of 15-year radiata pine established in similar contrasting areas as our study. On the other hand, results of the present study differed to those obtained by Wimmer *et al.* (2002) who compared high-resolution response of MFA of *Eucalyptus nitens* subject to different water regimes over two years: the trees subjected to severe drought showed the smallest MFA, whereas trees subject to cyclic droughts showed increases in MFA in response to water stress release. Finally, the different trend showed by the unthinned stands of mature trees in the present study was probably obscured by the high competition and therefore minimum amount of wood laid down after canopy closure.

The effect of the rainfall differences differed dramatically between the young and mature trees for outerwood DMOE with large reductions of about 35% in DMOE for young trees (where MFA is intrinsically larger) but much smaller reductions about 11% maximum for mature trees. Results also suggested that stiffness (and hence MFA) is more sensitive to climate stressors than basic density. Unfortunately the present study lacks sufficiently detailed data to make further inferences upon the

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[1] Further information on this study was provided by Henson, M., Tree improvement Manager. Forests NSW, Coffs Harbour NSW, Australia, June 2007, email: MichaelHe@sf.nsw.gov.au

effect of prolonged water stress and release on MFA, including whether these effects differ with mature versus juvenile wood, and what is the period of time at which changes on MFA as a result of water stress start occurring. These questions have not yet been addressed by scientific research; indeed there is a lack of information on the biological process of MFA formation and the influence of environment. In this regard, Walker (2006) highlighted the need for research on how density and MFA are employed by individual trees, species and genera in their particular strategies for survival.

For whole-tree DMOE based on the measurements in logs, there were differences between the sites but these were not significant for the unthinned and medium-thinned stands. In contrast to outerwood DMOE, changes in rainfall and evaporation across the life of the tree will influence both the quantity of wood laid down each year and the quality of that wood. So variability in the weather from year to year may tend to obscure longer term trends.

Water-stress response traits

Site differences in the long-term response water-stress traits mirrored the climatic differences between sites and also indicated that the warm-dry site was indeed a more water-limiting environment. Namely the mature trees of the warm-dry site showed an overall increase in heartwood development and thus a reduction in sapwood percentage. These results validated earlier investigation of Wilkes (1991) which included the two sites considered in our study with stands of similar age[2]. Also in our study, only the young trees of the warm-dry ex-pasture site showed presence of dry sapwood, and also a significant incipient development of heartwood. Results of Hillis and Ditchburne (1974) for 20-year trees in Buccleuch (high-altitude site) gave a much slower rate of heartwood formation: e.g. heartwood percentage varied from 3 to 5.8% and the number of heartwood rings ranged from 1.4 to 2.2. In contrast, in a poorer site (Red Hill) at age 26, their heartwood percentages varied from 15 to 17% and the

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[2] Comparison of Wilkes (1991) vs. the present study for mature trees in the same sites and stand ages

	Heartwood %		No. heartwood rings	
	Buccleuch	Carabost	Buccleuch	Carabost
Wilkes (1991)	16.7 - 20.5	22.7	8.3 - 9.9	11
Present study	16.8 - 19.9	25.6 - 33.5	7.5 - 10.6	10.3 - 11.6

number of heartwood rings ranged from 4.2 to 5.3. According to these results, it was concluded that in response to the water-limiting environment, the warm-dry site tended to develop heartwood and thus to reduce sapwood earlier and at faster rates than the high-altitude site. These results confirmed the physiological meaning of heartwood development indicated by Harris (1954a, b), Bamber (1972, 1976), and Carrodus (1972).

Sapwood area per hectare was calculated to aid in the interpretation of the results as an indicator of the stand water conductance and potential water use (Morris and Benyon 2005). The unthinned stands in both sites showed the larger total sapwood area/ha thus it was hypothesized these may be a threshold for the maximum potential water use. The consistently lower sapwood areas/ha for the different stands of the warm-dry site confirmed the large response of this parameter to water limiting environments and drought as reported by White *et al.* (1998), Cinirella *et al.* (2002), Maherali and DeLucia (2000), Whitehead and Beadle (2004), and Morris and Benyon (2005).

Table 7-11. Breast-height sapwood area calculated for the mature (UT=unthinned, T2=two thinnings, T3=three thinnings) and young trees in the two contrasting sites of the study

Site/Stand	Stocking Stems/ha	DBH (cm)	Sectional Area† (m^2)	% Sapwood†	Sapwood area† (m^2)	Total sapwood† area/ha (m^2)
High-altitude						
UT	722	39.6	0.123	80.1	0.099	71.3
T2	220	48.9	0.188	83.2	0.156	34.4
T3	205	58.1	0.265	82.1	0.218	44.6
Warm-dry						
UT	712	35.1	0.097	66.5	0.064	45.8
T2	280	41.8	0.137	72.5	0.100	27.9
T3	193	53.8	0.227	74.4	0.169	32.7
Young trees						
High-altitude	1060	18.2	0.026	99.2	0.026	27.4
Warm-dry Ex-P‡	970	23.1	0.042	98.6	0.041	40.1
Warm-dry Ex-F‡	970	18.9	0.028	99.3	0.028	27.0

† Sectional area = 22/7 × (DBH/2)×(DBH/2)

Sapwood area = Sectional area × % sapwood

Total sapwood area / ha = Sapwood area × Stems / ha

‡ Ex-P = ex-pasture, Ex-F = ex-forest

The large differences in tree size (diameter) as influenced by thinning regime were matched by differences in sapwood area/ha (Table 7-11) and explained the apparent contradictory effect of having large increases in diameter and fairly small changes in sapwood percentage (Table 7-11). For example, even though the UT and T3 trees on both sites have fairly similar sapwood percentages the actual area of sapwood is much larger in the T3 trees. If the individual area per tree is multiplied by the number of stems per hectare the unthinned stand actually contains a greater amount of sapwood area than the heavily-thinned stand even though each tree in the UT stand has less sapwood in it.

Differences in sapwood saturation between sites of young trees can be explained in terms of sapwood area/ha as a possible indicator of the stand water use. For example, the sapwood area/ha of the young trees of the ex-pasture site (40.1 m^2/ha) is rapidly approaching that of the unthinned mature trees (45.8 m^2/ha) and therefore the trees are competing more intensively for water giving as a result the lowest saturation (Table 7-9). The other warm-dry site (ex-forest) of young trees has reached the same level of sapwood area/ha as the T2 stand of mature trees (27 vs. 27.9 m^2/ha), therefore the trees have almost as low saturation as the ex-pasture site (Table 7-9). On the other hand, although the young trees on the high-altitude site have similar levels of sapwood area/ha as the warm-dry ex-forest site, they still are well below the levels of the mature stands (27.4 vs. 34.4-71.3 m^2/ha) which explained their higher saturation level (Table 7-9).

The onset of heartwood formation in young trees seemed to be related to some site threshold for water use. As shown above, the warm-dry ex-pasture site had the largest sapwood area/ha and possibly the largest water use among the stands of young trees. This may have explained that only the warm-dry ex-pasture site showed significant incipient development of heartwood and thus of sapwood reduction, and this was also the only site showing the presence of dry sapwood (Table 7-9). The large trees of this site would be experiencing an elevated competition for water given the natural moisture limitation in the site.

The increased short-term responses of the warm-dry site to water stress were explained as seasonal mechanisms of the trees to cope with the limiting environment.

For example, transpiration rates were higher for the warm-dry site as indicated by needle water potentials in the dry season of 2006 for the T2 stands. This effect may have been higher for example for the ex-pasture site where the large trees with greater canopies would have had a larger evaporative demand. If this is coupled with the lower moisture available in the warm-dry site then the trees have to compensate by lowering their saturation and disrupting water conduction at some points in order to survive. These mechanisms were in line with the general theory of cavitation as a response of trees to water stress (Tyree and Sperry 1989, Grace 1993). According to Grace (1993) cavitation starts at threshold water potentials of -1.0 to -1.4 MPa, and this increases with tension (negative). In our experiment, the needle water potentials measured in summer 2006 for the medium thinned trees were on average -1.6 and -2.0 MPa for the high-altitude and warm-dry sites, respectively.

The cavitation bands observed in the section of the stem corresponding to the live crown of the medium-thinned stands in the dry site during summer were categorized as another response of the tree to the excessive rates of transpiration. This phenomenon can be seen as a mechanism of the tree for water conservation. Tyree and Sperry (1988, 1989) argued that trees are hydraulically designed to sacrifice vulnerable sections of xylem in order to improve the water balance of the rest of the stem. According to Tyree and Sperry (1989) the tree can survive considerable losses in conductivity because of the stem’s high leaf specific conductivity (LSC). The leaf specific conductivity is defined as the absolute conductivity of the segment divided by the leaf area supplied by the segment. The high LSC of the trunk allows the tree to survive severe but localized damage such as fire or a double saw-cut.

Finally, from a further remeasurement on the same high-altitude and warm-dry ex-pasture sites of young trees of this study reported in Chapter 6, and an independent unthinned stand of mature trees in the warm-dry site (Appendix 3), both measured in January 2007 after a prolonged drought, it was concluded that trees tend to reach ‘safe’ levels of saturation and these vary depending on age, site, and position in the stem. For example, the average sapwood saturation for the young trees of the warm-dry ex-pasture changed from 75.3% on September 2006 to 74.5% on January 2007, suggesting the trees reached a critical level of water content. In contrast, for the high-altitude site, saturation decreased from 84.3% on October 2006 to 80.3% on late

December, indicating the moisture content of these trees would possibly continue decreasing. The differences in saturation levels between sites were attributed to the differences in site limit to water availability as discussed above.

From results in Appendix 3 it seems that the 'safe' saturation level for the large and average mature trees in the warm-dry site lies around 85% and this increases slightly up the stem (Table 7-2 and Figure 7-2, Appendix 3). This trend in saturation with height in the stem was in accordance results obtained in Chapter 5 for mature unthinned trees (Table 5-7). In contrast, the suppressed trees showed a large drop in saturation at the bottom of the stem and much lower saturation values (i.e. 57.7 to 71.7%). This suggested that the suppressed trees are no longer able to compete for water and are drying out from the base upwards. The little water available is being allocated up the stem in order to maintain the canopy functioning so the tree can survive. Further, the large unbalance in saturation levels along the stem for the suppressed trees in comparison with the even distribution for the average and large trees may be a warning sign of vulnerability/death. As mentioned above, trees can withstand considerable losses of xylem conductivity but they also tend to maintain water balance in the stem. Finally, the inverse trends of cavitation spots and cavitation bands with height in the stem (Figure 7-4 and Appendix 3) confirmed results for the medium-thinned trees of the warm-dry site of the present study (Figure 7-5) and suggested the trees have different strategies to sacrifice conducting xylem depending on the position on the stem.

7.5 CONCLUSIONS

- During summer both sites are in major water deficit so wood production is probably minimal. Similarly, in winter both sites are in water surplus. So, the main site effects on wood quality would be related to differences in spring and autumn rainfall.
- Over the past 10 years there has been a bigger difference between the sites for latewood rainfall than earlywood rainfall. So the warm dry site would be expected to produce less latewood leading to lower wood density and stiffness.

Percentage reduction in density is similar for the young stands and the thinned older stands indicating a general site effect.

- However the effect of the rainfall differences differs dramatically between the young and older trees for outerwood stiffness with large reductions of ~35% in DMOE for young trees (where MFA is intrinsically larger) but much smaller reductions of ~11% maximum for the older trees. This difference may be related to a different impact of climate on juvenile versus mature wood.
- Stiffness and hence MFA appears to be more sensitive to climate or climatic stressors than density. Nevertheless, the lower detail of the study and the lack of knowledge on the influence of environment on MFA prevented conclusive inferences.
- There were no definite associations between long-term drought response traits (sapwood percentage and number of heartwood rings) and wood quality (DMOE and basic density).
- It was concluded that in response to the water-limiting environment, the warm-dry site tended to develop heartwood and thus to reduce sapwood earlier and at faster rates than the high-altitude site.
- Sapwood area/ha was consistently lower across the different stands of mature trees for the warm-dry site confirming the large response of this parameter to water limiting environments and drought as reported in the literature.
- Sapwood area/ha was well related to individual sapwood percentage and sapwood saturation in relation to stocking level and site.
- The onset of heartwood formation in young trees seemed to be related to some site threshold for water use as broadly indicated by the sapwood area/ha. This may have explained that the warm-dry ex-pasture site, which had the largest sapwood area/ha and possibly the largest water use among the stands of young trees, was the only site that showed significant incipient development of heartwood and thus of sapwood reduction.
- The increased short-term responses of the warm-dry site to water stress are suggested as seasonal mechanisms of the trees to cope with the limiting environment. The trees have to compensate for the lower available moisture and higher transpiration rates by lowering their saturation and disrupting water conduction in some points (cavitation) in order to survive.

- The cavitation bands observed in the section of the stem corresponding to the live crown during the dry season were interpreted as another response of the tree to the excessive rates of transpiration and as a mechanism of the tree for water conservation. Xylem embolism theory implicates that trees are hydraulically designed to sacrifice vulnerable sections of xylem in order to survive.
- It is suggested that trees tended to reach ‘safe’ levels of saturation as a result of water stress and these varied depending on age, site, and position in the stem.
- The inverse trends of cavitation spots and cavitation bands with height in the stem suggested the trees have different strategies to sacrifice conducting xylem depending on the position on the stem.

CHAPTER 8

CONCLUSIONS

8.1 Variation of acoustic velocity and dynamic MOE in controlled conditions

- The study with sapwood boards of radiata pine with a broad range of moisture contents and temperatures between -72°C and +58°C showed the following trends: 1) acoustic velocity in wood below FSP (dry) is faster than in wood above FSP (wet) because of the negative effect of free water on acoustic propagation; 2) velocity in dry frozen wood is faster than in dry unfrozen wood because the ice stiffens the cell walls; 3) velocity of wet frozen wood is faster than wet unfrozen wood because of the ice in the cell walls, and because free water reduces acoustic velocity as moisture increases; 4) the drop in velocity at 0°C increases with increasing moisture content because of the negative effect of free water on velocity; 5) the gradual decrease of velocity with increasing temperature for both dry and wet wood is due to the general inverse effect of temperature on the stiffness of the cell wall; 6) The higher decreasing rates of velocity per unit moisture and the variation in trends below and above FSP indicated a dominant effect of moisture content over temperature on acoustic propagation.

- Variation in DMOE was explained by the counteracting effects of acoustic velocity and density. This relationship was not straightforward because of the different trends of velocity (mostly curvilinear) and density (linear) with changes in moisture content.

- Above FSP, the varying trends of velocity and density with increasing moisture content gave rise to variation in DMOE which showed two distinct patterns depending on whether temperatures were below or above 0°C. For unfrozen wood there was an average increase of 0.3 GPa in DMOE between wood at low saturation (4.8 and 9.7%, Table 2-4) and wood at the highest saturation (81.9 and 92.2%, Table 2-4). Also for unfrozen wood above FSP, the maximum changes in DMOE across temperatures ranged from 0.5 to 1 GPa (Table 2-4). For frozen wood above FSP, increases in DMOE between wood at low saturation and wood at the highest saturation ranged from 4.5 GPa for wood at -3°C to 6 GPa for wood at -72°C (Table 2-4).

- These results contradicted the theory that mechanical properties should not change above FSP and suggested adjustments to the calculation of DMOE for this range of moisture. Such adjustments should consider that changes in acoustic velocity and density with increasing moisture content are not proportional.

- The large increases in DMOE for frozen wood above the FSP questioned the robustness of DMOE for the estimation of stiffness in frozen green wood. In practice this will limit the use of DMOE for grading logs in regions with freezing winters; use of acoustic velocity alone would be a better option in those situations.

- The formula of Sobue (1993) for correcting densities above FSP and hence DMOE gave good results for unfrozen wood using two critical saturation values (60% and 75%) as surrogates for the ratio of mobility of free water (k). Graphical analysis showed that velocity was strongly affected by the proportion of free water in the lumens up to a critical level of ca. 60% saturation followed by little change thereafter. An adjustment to DMOE for frozen wood above the FSP could not be fully validated because of insufficient information in the literature for changes in static MOE of frozen wood at different moisture contents.

8.2 Dynamic MOE for resource assessment

- Our investigation consisting of four successive remeasurements over 17 months on 10-11 year-old trees of radiata pine on two contrasting sites in terms of climate showed that the decrease in moisture content of trees in contrasting environments due to long periods of water stress influenced dynamic stiffness. Mean DMOEs varied over the period of study by 0.4 to 1 GPa for a high-altitude site and by 0.1

to 0.3 GPa for a warm-dry site. This is important for extended broad-acre assessments or surveys in areas with regular occurrence of long droughts.

- Results indicated that the changes in velocity and green density as a result of changes in moisture content are not proportional and seem to vary between sites and materials (i.e. live trees vs. experiment with boards, Table 6-3). Additionally, changes in velocity squared as influenced by large changes in moisture content did not always override changes in green density and there are counteracting effects between the two parameters. This makes difficult to predict the effect of moisture content on the DMOE of standing trees and green wood in general.

- Using saturation percentage values as surrogates for the mobility of free water ratio in the equation of Sobue (1993) for correcting DMOE of the young trees gave only a crude approximation. Therefore, an investigation on analytical procedures for correction of DMOE in green wood is highly suggested. Such procedures should consider that variations in acoustic velocity and density with changes in moisture content are not proportional.

- Typical variation (under normal climatic conditions) in sapwood green density, necessary for calculation of outerwood DMOE, was small to moderate as influenced in decreasing order by age, height, site and thinning regime. Typical average breast-height sapwood green density for young trees was 1100 kg/m^3, whereas for mature trees this ranged from 1097 to 1131 kg/m^3. Typical average differences in breast-height sapwood green density ranged from 2 to 33 kg/m^3. However, sapwood green density can decrease considerably during extended droughts due to decreases in moisture content caused by water stress. Average breast-height sapwood green densities for large, average, and suppressed mature trees in an unthinned stand in the warm-dry site were 1089, 1052, and 887 kg/m^3, respectively. Corresponding values for young trees in the warm-dry and high-altitude sites were 954 and 1006 kg/m^3.

- It remained to be investigated whether the typical variation in sapwood green density has some implications for resource characterization using DMOE, i.e. whether the changes in acoustic velocity and green density as a result of small changes in moisture content would introduce any bias on the estimation of DMOE.

- Typical variation in whole-section green density of radiata pine, necessary for calculation of log-DMOE, was considerable due to the differences in sapwood-heartwood content as influenced by age, site, and position in the stem. Typical average breast-height whole-section green density for matures trees ranged from 952 to 1036 kg/m^3. Typical average breast-height differences in whole-section green density as influenced by site and thinning regime were as high as 84 kg/m^3, whereas differences between the bottom and the top of the tree ranged from 22 to 64 kg/m^3. During an extended drought, breast-height whole-section green density values for large, average, and suppressed mature trees in an unthinned stand in the warm-dry site were: 913, 884, and 762 kg/m^3, respectively (i.e. a range of 151 kg/m^3).

- The large differences along the stem and among stands in whole-section green density may bias DMOE measurements in logs for resource assessment. This effect was not investigated in this thesis. It is especially important to study the counteracting effects between the two parameters, including the extent to which green density overrides the effect of acoustic velocity and *vice versa* for determination of DMOE in logs.

- An alternative for grading logs and standing trees would be to use acoustic velocity alone (*V*). According to the experiment with boards, this parameter measured the true Young's modulus (*E*) of wood and accounted for the influence of both moisture content and temperature on *E*. Nevertheless, this recommendation needs to be validated because of the large effect of moisture content on acoustic propagation. A comparison between velocity and DMOE for resource assessment under different scenarios is recommended.

$$V = \sqrt{\frac{E}{r}}$$

8.3 Methods for measuring green density and moisture content

- Disks or wedge-shaped samples, 50 – 100 mm thick, were shown to provide accurate destructive determinations of green density and moisture content of live trees. Both fine-dropsaw and chainsaw as cross-cutting methods gave good results with close-to-saturation material collected in the wet season.

- A novel protocol for non-destructive assessment of green density and moisture content was validated for both young and mature trees of radiata pine. Procedures included manual borers with a custom-made handle to collect high-quality bark-to-bark cores even in mature trees over 50 cm in diameter. The inherent loss of moisture from the core during the boring process was overcome successfully by soaking the cores in water for 24 hours. Acceptable prediction of green density and saturation as measured by destructive disks or wedges was obtained with the manual 12 mm cores for both breast-height and whole-tree values. Additional traits predicted with good results were the sapwood sectional percentage and the number of heartwood rings.

- Percent saturation provided an unbiased measure of moisture condition in live trees for seasonal effects and water stress when compared with the moisture content as percentage of ovendry weight, and the water content as volumetric percentage due to the influence of basic density and sampling on the last two measures.

8.4 Wood quality and mechanisms of drought and water-stress response

- A study in two climate contrasting sites (high-altitude vs. warm-dry) in the Hume region of Forests NSW, Australia including young (10-11 years) and mature trees (34 – 36 years) of radiata pine showed distinctive short and long-term responses to coping with the water-limiting environment. In response to long-term water deficits the warm-dry site tended to develop heartwood and thus to reduce sapwood earlier and at faster rates than the high-altitude site. The onset of heartwood formation seemed to be related to some site threshold for water use as broadly indicated by the sapwood area/ha. The latter was consistently lower for the warm-dry site across the different stands suggesting different long-term physiological responses to water stress between the contrasting sites.

- The increased short-term responses of the warm-dry site to water stress were suggested as seasonal mechanisms of the trees to cope with the limiting environment. The trees compensated for the lower available moisture and higher transpiration rates by lowering their sapwood saturation and disrupting water conduction at some points (cavitation). Sapwood area/ha, as a broad indicator of the stand water conductance and potential water use, regulated individual sapwood percentage and sapwood saturation in relation to stocking level. The cavitation bands in the section of the stem corresponding to the live crown during the dry season were interpreted as another response of the tree to the excessive rates of transpiration and a mechanism of the tree for water conservation. The inverse trends of cavitation spots and cavitation bands with height in the stem suggested the trees have different strategies to sacrifice conducting xylem depending on the position on the stem. Finally, it is suggested that trees tended to fall to critical 'safe' levels of saturation as a result of water stress and these varied depending on age, site, and position in the stem.

- Significant decreases in DMOE and basic density were observed for the warm-dry site and were attributed to lower proportions of latewood due to lower rainfall for that site during the period of latewood formation. These showed no obvious association with any of the long-term water-stress traits (sapwood percentage and number of heartwood rings).

8.5 Practical implications and recommendations for further research

- The large increases in DMOE for frozen wood above the FSP will limit the use of DMOE for grading logs in regions with freezing winters

- Results from the experiment remeasuring young trees and the upper range of moisture content and temperatures above 0°C from the experiment with boards showed small to moderate variation in DMOE which calls for further investigation on analytical procedures for adjustment of DMOE.
- It remains to be investigated whether the typical variation (under normal climate conditions) in sapwood green density observed in our experiments has some implications for the use of DMOE.
- On the other hand, it is anticipated that the large differences along the stem and among stands in whole-section green density may bias DMOE measurements in logs for resource assessment. This also needs to be investigated.
- A comparison between acoustic velocity alone and DMOE for resource assessment under different scenarios is recommended.

- The investigation on wood quality and water stress response on two contrasting sites in a region of Australia provided the following practical outcomes:
  - Results can be relevant for sustainability of radiata pine plantations in water-limiting environments.
  - The water-stress traits studied can be useful and cost-effective for measuring short and long-term response of trees in limiting environments; other applications may include detection of unsustainable sites and breeding for dry environments.
  - Radiata pine has indeed a natural capability to provide commercial yields even in water limiting environments.
  - Further research is recommended to identify the mechanisms that allow the species to achieve this.

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Appendix 1

Further description of traits and destructive and non-destructive measurement procedures for mature and young trees of Chapter 7

1) Wood quality and long-term water-stress traits of mature trees	
Breast-height outerwood DMOE	Breast-height (1.3 m) outerwood DMOE was determined from standing-tree acoustic velocity measured with TreeTap and sapwood green density. Acoustic velocity was measured on two opposite sides of the tree (upside and downside of the slope).
Destructive sampling of mature trees	Mature trees were felled and log-sectioned after the standing-tree measurements. The lower 1.3 m section of the tree was discarded and from that point upwards the stem was sectioned into logs; nominal lengths were 3.7 m for the first log and 5.5 m for the subsequent logs. At least four logs were obtained from each tree. Disks about 70 mm thick for determination of green density, saturation percentage, and water-stress response were cut at least from four locations: the bottom end of the first log, and the top ends of the second, third, and fourth logs. Nominal heights of the disks were approximately 1.3, 10.5, 16, and 21.5 m. Actual log lengths were recorded for calculation of log-volume and log-DMOE. Handling, storage, machining of disks into wedge-shaped samples and processing for determination of green density, saturation percentage, and basic density was conducted according to the procedures developed in Chapters 3 and 4. Green density, saturation percentage and basic density were calculated separately for sapwood and heartwood. Whole-section values were the weighted averages of the sapwood and heartwood sections by their respective cross-sectional percentages. The detection of the boundary sapwood/heartwood on the wedges was determined by the contrast between the corresponding wet/dry appearances of the two materials. This method was validated against the staining test described in Chapter 4 using a few samples.

Whole-tree outerwood DMOE and log-DMOE	Whole-tree outerwood DMOE and log-DMOE were log-weighted averages as measured from 1.3 to 21.5 m. Whole-tree outerwood DMOE was determined from measurements of TreeTap acoustic velocity and sapwood green density for each of the logs. TreeTap was measured near the bottom end of the log using similar procedures as the standing-tree measurement but in this case only on one side of the log. Log- DMOE was also measured in each of the logs by resonance velocity using a Director HM200 acoustic tool and weighted averages of whole-section green density from the two ends of the log. Note that for calculating whole-tree DMOE values, green densities at 5 m had to be interpolated from measurements at 1.3 and 10.5 m as disks were not taken at that height.
Basic density	Breast-height basic density was determined from the disk taken at 1.3 m whereas whole-tree basic density was the log-weighted average as measured from 1.3 to 21.5 m. Whole-section basic density was reported in the results for effects of site and thinning regime both at breast height and whole tree of mature trees. The reason was that using whole-section values allowed valid comparisons between stands and sites as pure sapwood and heartwood values are affected by the differences in sapwood proportion among stands and sites and thus comparison would be biased. Nevertheless, sapwood basic density was included in the correlation analysis between sapwood percentage and wood quality traits. Note that for calculating whole-tree basic density, values at 5 m had to be interpolated from measurements at 1.3 and 10.5 m as disks were not taken at that height.
Sapwood percentage and number of heartwood rings	Cross-sectional percentages of sapwood and heartwood were determined by measuring the pith-to-cambium and heartwood radii of the wedges in green condition. The number of heartwood rings was also recorded in green condition. Breast-height sapwood percentage corresponded to that measured at 1.3 m whereas whole-tree sapwood percentage corresponded to the log-weighted average from 1.3 to 10.5 m. The reason for calculating whole-tree sapwood up to this height was that above this point there was considerable lower variation in sapwood sectional percentage among stands.

2) Short-term water-stress traits for both mature and young trees	
Sapwood saturation	For mature trees, breast-height sapwood saturation was that measured at 1.3 m, whereas whole-tree values where the log-weighted averages as measured from 1.3 to 21.5 m. For young trees, breast-height sapwood saturation was measured non-destructively with 12 mm cores as explained below.
Cavitation signs	Cavitation signs were defined in this study as prominent dry marks of different sizes and shapes occurring in the sapwood (Figures 7-5 and 7-7). This phenomenon was first observed with the samples of mature trees in summer-06 and therefore was assessed only for the medium-thinned stands (T2) of both sites. In the case of the young trees, this phenomenon was well established at the time of the assessment for this study (spring-06) but was first observed in summer-06 with destructive disks of young trees from another experiment. There were mainly three types of cavitation signs: **dots, spots, and bands** -in frequency order-. In first place, the **dots** were small points (visible to the naked eye) which occurred anywhere across the sapwood section and seemed to be more conspicuous at the latewood and transition early-latewood (Figure 7-5a); these were present practically in all the samples and trees. In second place, the **cavitation spots** varied in shape and size from a few millimetres to several centimetres; these occurred at any place across the sapwood section but were most frequent near the heartwood, indeed in some cases they seemed to have 'originated' at the sapwood-heartwood boundary (Figures 7-5b-c). The cavitation spots appeared on both cross-sectional faces of the samples in most cases indicating axial continuity along the xylem. They also appeared at all the different sampling heights, namely bottom, middle and top of the tree. In third place, the **cavitation bands** occurred along the earlywood-latewood boundaries of groups of growth rings. These varied from thin lines to broad bands that covered most of the earlywood section. The bands were located across the sapwood section but the broader bands appeared towards the heartwood. In all cases the dry bands had continuity in the axial direction (Figure 7-5d)

	suggesting complete cavitation of large xylem areas. Cavitation signs reported for mature trees included spots and bands, whereas cavitation signs reported for young trees included only spots as the cavitation bands were difficult to detect visually with the increment cores. The cavitation dots were not included in the analysis.
3) Wood quality and long-term water-stress response traits of young trees	
Breast-height outerwood DMOE	Similar procedures as the mature trees with the exception that acoustic velocity was only measured at one side of the tree
Breast-height basic density, saturation percentage, sapwood sectional percentage and number of heartwood rings	For young trees, green and basic densities, and drought response traits were all measured non-destructively at breast height using 12 mm cambium-to-cambium manual cores. Procedures included a method previously developed for determination of green density and saturation percentage with 12 mm cores that provides a close approximation to destructive disks and wedges (Chapter 4). Staining test for identification of heartwood was done also according to procedures described in Section 4.2.2 of Chapter 4. After the staining test, heartwood and pith-to-cambium radii were measured in order to obtain cross-sectional percentages of sapwood and heartwood in similar way to the wedges of mature trees. At this stage the number of heartwood rings was also recorded. Unlike the mature trees, green density, basic density and saturation percentage were determined only for sapwood material. Whole-section values were not relevant mainly because of the small or sometimes inexistent heartwood. Breast-height green density, basic density, saturation percentage, sapwood sectional percentage and number of heartwood rings were determined from the averages of the two sides of the increment cores (i.e. ‘entry’ and ‘exit’ sides) as suggested by results of Chapter 4.
Dry sapwood (DSW)	Dry sapwood (DSW) was defined as the occurrence of relative large pale-coloured areas of sapwood towards the pith with very low saturation and presumably high cavitation. This can also be characterised as the occurrence of cavitation bands affecting both earlywood and latewood of several growth rings. Note that both definitions were

	formulated according to observations with destructive disks of young trees from another experiment in summer 2006 in which this phenomenon was first observed. In the present experiment this phenomenon was not observed in the stands of mature trees considered for drought response traits (summer-06, T2). In the case of young trees the occurrence of DSW was difficult to assess visually using the increment cores so another method was devised as follows. The presence of DSW was done with the 12 mm cores in green condition after the staining test for detection and removal of any heartwood material. The test consisted of placing the sapwood sections in vertical position into a glass cylinder containing 70% isopropyl alcohol. The sapwood sections were immersed leaving the outerwood section at the bottom and the close-to-pith section on the top. The isopropyl alcohol has a density of ca. 870 kg/m^3 which would correspond to a piece of green wood having an average saturation of 56 - 64% according to regression equations. These values were a practical approximation to the saturation threshold (69%) for critical pit aspiration and sapflow disruption indicated by Harris (1954a). Any section of the core with density lower than the isopropyl alcohol would tend to float indicating presence of 'dry sapwood'.

Appendix 2

Correlation analyses between long-term water-stress response traits (sapwood percentage and number of heartwood rings) versus wood quality (DMOE and basic density), and diameter at breast height (DBH)

1) Mature trees

Table 1. Correlation analysis between sapwood percentage and wood quality traits and diameter at breast height (DBH) for the two contrasting sites of mature trees (n = 9-10)

Stand	Nominal height (m)	DBH	Outerwood DMOE	Log-DMOE	Sapwood basic density	Whole-sec basic density
Warm-dry site						
UT	1.3	0.18	0.10	0.40	0.15	0.07
	10.5	0.43	-0.18	0.27	-0.31	-0.25
	16	0.59	0.02	0.22	**-0.75** *	**-0.74** *
	21.5	-0.03	-0.17	-0.22	-0.38	-0.08
T2	1.3	-0.10	0.01	0.08	0.22	0.23
	10.5	-0.13	-0.28	0.15	0.14	0.21
	16	-0.41	-0.44	-0.38	-0.28	-0.18
	21.5	-0.57	**-0.64** *	-0.49	-0.27	0.09
T3	1.3	0.13	0	-0.18	0.02	0.15
	10.5	0.24	-0.53	-0.25	-0.30	-0.07
	16	0.37	-0.35	-0.33	**-0.65** *	-0.53
	21.5	0.57	-0.24	-0.47	-0.38	-0.30
High-altitude site						
UT	1.3	0.46	-0.02	-0.12	0.14	0.33
	10.5	0.30	-0.22	0.04	-0.22	-0.01
	16	0.43	-0.26	-0.27	-0.56	-0.40
	21.5	0.34	-0.17	-0.22	--	--
T2	1.3	-0.63	0.60	0.25	0.15	0.19
	10.5	-0.43	0.57	0.09	-0.31	-0.12
	16	-0.45	-0.22	-0.06	-0.25	-0.16
	21.5	-0.22	-0.50	-0.25	-0.24	-0.37
T3	1.3	-0.21	0.46	**0.69** *	0.30	0.29
	10.5	-0.06	-0.04	**0.71** *	-0.18	0.04
	16	-0.23	0.29	0.49	0.27	0.36
	21.5	-0.57	0.42	0.43	--	--

*Significant at $P<0.05$, **$P<0.01$

Table 2. Correlation analysis of the number of heartwood rings with wood quality traits and diameter at breast height (DBH) for the two contrasting sites of mature trees (n = 9-10)

Stand	Nominal height (m)	DBH	Outerwood DMOE	Entire-sec DMOE	Sapwood basic density	Whole-sec basic density
Warm-dry site						
UT	1.3	0.28	-0.37	--	-0.35	-0.43
	10.5	0.16	-0.35	--	-0.24	-0.27
	16	**-0.65** *	-0.05	--	0.05	-0.08
	21.5	-0.21	0.27	--	0.51	0.52
T2	1.3	0.61	0.34	--	-0.06	-0.23
	10.5	**0.68** *	**0.78** **	--	0.41	0.34
	16	**0.85** **	0.21	--	0.20	0.11
	21.5	**0.75** *	**0.78** **	--	0.55	0.19
T3	1.3	-0.47	0.35	--	0.37	0.26
	10.5	-0.31	0.38	--	0.56	0.40
	16	-0.03	0.03	--	0.49	0.45
	21.5	-0.09	0.14	--	0.62	0.62
High-altitude site						
UT	1.3	-0.38	-0.12	--	0.17	0.06
	10.5	-0.06	0.01	--	0	-0.06
	16	0.17	0.15	--	0.10	0.01
	21.5	--	--	--	--	--
T2	1.3	0.60	-0.55	--	-0.29	-0.45
	10.5	0.60	-0.48	--	0.06	-0.04
	16	0.41	0.27	--	0.57	0.48
	21.5	0.30	0.23	--	0.40	0.41
T3	1.3	**0.65** *	-0.39	--	**-0.66** *	-0.63
	10.5	0.47	-0.14	--	-0.38	-0.52
	16	**0.73** *	-0.34	--	0.08	0.08
	21.5	--	--	--	--	--

*Significant at $P<0.05$, **$P<0.01$

2) Young trees

Table 3. Correlation analysis by plot between long-term water-stress response traits and diameter at breast height (DBH), outerwood DMOE (ODMOE), and sapwood basic density (BD) for the three contrasting sites of young trees; results are at breast height (1.3 m) as measured by 12 mm cores; n=10 (trees per plot)

Site	Plot	Sapwood %			No. heartwood rings			Dry sapwood		
		DBH	ODMOE	BD	DBH	ODMOE	BD	DBH	ODMOE	BD
Warm-dry ex-pasture	2	0.17	-0.07	0.32	-0.15	-0.04	-0.37	0.05	**0.65** *	-0.08
	7	-0.16	0.22	0.41	0.31	-0.15	-0.40	-0.37	-0.55	-0.02
	12	0.10	-0.10	-0.12	0.04	0.18	0.22	0.61	-0.20	-0.46
	16	-0.54	-0.36	0.01	0.62	0.43	-0.18	**-0.83** **	-0.44	0.54
	19	0.27	0	0.48	0.12	0.06	**-0.72** *	--	--	--
Warm-dry ex-forest	5	0.07	-0.49	0.13	0.14	0.47	0.11	0.05	-0.30	0.25
	9	0.02	0.27	0.02	-0.02	-0.25	0.15	--	--	--
	21	-0.17	-0.29	-0.15	0.20	0.28	-0.10	--	--	--
High-altitude	4	0.18	-0.01	0.02	0.23	-0.01	0.16	--	--	--
	7	**-0.64** *	0	0.17	**0.65** *	-0.05	-0.22	--	--	--
	15	0.62	**-0.69** *	0.48	**-0.66** *	0.37	-0.41	--	--	--
	20	0.03	0.41	0.31	0.12	-0.32	-0.32	--	--	--
	25	0.04	-0.04	-0.02	0.29	-0.24	-0.35	--	--	--

*Significant at P<0.05, **P<0.01

Appendix 3

Further influence of extended drought on green density and water-stress response traits for mature trees

This experiment was conducted in January 2007 during an extended drought period that started early 2006 (Figure 9, Chapter 7). Material for this experiment came from a 36-year old unthinned stand located in a warm-dry inland climate site. The same stand was used for prediction of green density, saturation, sapwood percentage and number of heartwood rings for mature trees using increment cores in Chapter 4. The present study included 29 mature trees covering all the range of diameter sizes; these were grouped into three classes: large, average, and suppressed. The latter were purposely selected as being not only the smallest trees of the stand but also as being completely overtopped, yet alive and in healthy condition. Mean diameters and heights for the different tree sizes are shown in Table 1. Trees were felled and sampled destructively at three different heights for green density, basic density and the water-stress response traits. Procedures are described in Section 4.2.2.

Table 1. Characteristics of the unthinned, 36-year trees used in the study

Tree size	No. of trees	DBH mm (Std dev)	Height m (Std dev)
Large	10	454 (37)	30.9 (2.4)
Average	10	367 (26)	26.8 (2.7)
Suppressed	9	243 (32)	24.0 (4.4)

The suppressed trees showed considerably lower sapwood and whole-section green density values than the other two tree sizes (Table 2 and Figures 1, 3). Sapwood green density of the suppressed trees was between 97 and 202 kg/m^3 lower than the large trees, and between 85 and 165 kg/m^3 lower than the average trees. Similarly, whole-section green density of the suppressed trees was between 52 and 151 kg/m^3 lower than the large trees, and between 61 and 122 kg/m^3 lower than the average trees. On the other hand, differences in both sapwood and whole-section green density between large and average trees were rather small yet the large trees showed slightly higher values (Table 2 and Figures 1, 3).

Changes in sapwood green density with height were small for both large and average trees; in contrast, changes with height for suppressed trees were considerably large (Table 2 and Figure 1). For the suppressed trees there was an increase of 55 kg/m^3 between 6.8 and 12.3 m height, yet differences were non-significant statistically due to the large between-tree variation along the stem (Figure 1). In the same way, changes in whole-section green density with height were small for large trees, but in contrast these were considerable for average and suppressed trees (Table 2 and Figure 3). There were increases in whole-section green density of 54 and 95 kg/m^3 between 6.8 and 12.3 m height for average and suppressed trees, respectively.

There was a positive and highly significant relationship between tree size and sapwood moisture condition as indicated by the differences in saturation between tree classes (Table 2 and Figure 2b). In first place the sapwood of large trees was fairly wet; next the average trees were slightly drier, and finally the suppressed trees were surprisingly dry. Indeed the sapwood saturation averages of the suppressed trees at breast height and at 6.8 m height were below the critical level of 69% pointed out by Harris (1954a). Furthermore, looking at the between-tree variation of the suppressed trees at the lower 6.8 m, some of the trees were well below the critical point (Figure 2a). On the other hand, differences in moisture condition for heartwood across tree sizes were minimal. In fact the saturation levels in all cases were just above the fibre saturation point as indicated by the heartwood saturation values close to zero (Table 2).

Suppressed trees also showed considerable changes in sapwood moisture condition with height, yet differences were non-statistically significant because of the large between-tree variation in saturation along the stem (Table 2 and Figure 2a). Saturation of suppressed trees increased moderately between breast height and 6.8 m, followed by a large increase at 12.3 m. On the contrary, large and average trees showed virtually no change in sapwood saturation with height.

Table 2. Mean values and ANOVA results for sapwood and heartwood green density, cross-sectional proportion, basic density, and saturation percentage, and whole-section green density of mature unthinned trees aggregated in tree sizes

Tree size	Height (m)	Sapwood				Heartwood			Whole section
		Green density (kg/m^3)	% Cross section	Basic density (kg/m^3)[†]	Saturation (%)	Green density (kg/m^3)	Basic density (kg/m^3)[†]	Saturation (%)	Green density (kg/m^3)
Large	1.3	1089	66.2	463	87.8	564	415	4.2	913
	6.8	1065	68.3	428	86.5	512	375	4.0	892
	12.3	1063	73.1	417	87.1	515	373	4.6	915
	Signif[‡]	ns	ns	***	ns	*	**	ns	ns
Average	1.3	1052	67.9	448	82.2	527	386	4.0	884
	6.8	1048	66.2	423	83.9	519	379	4.1	870
	12.3	1051	76.5	411	85.5	506	368	4.2	924
	Signif[‡]	ns	ns	**	ns	ns	ns	ns	ns
Suppress	1.3	887	65.1	417	57.7	529	382	5.1	762
	6.8	911	66.7	406	63.0	490	347	5.9	768
	12.3	966	75.9	411	71.7	544	365	10.8	863
	Signif[‡]	ns	*	ns	ns	*	*	*	**
ANOVA	1.3	***	ns	**	***	ns	*	ns	***
Tree size	6.8	***	ns	ns	***	ns	**	ns	***
	12.3	***	ns	ns	***	ns	ns	*	*

[†] Unextracted basic density; [‡] ANOVA results for differences with height
* P <= 0.05, ** P <= 0.01, ***P <= 0.001, ns = not significant

Changes in sapwood green density were mainly related to changes in saturation as indicated by variation patterns across tree sizes (Figures 1 and 2). Differences in sapwood green density indeed mirrored differences in saturation; in contrast, influence of wood substance (basic density) on sapwood green density was virtually non-existent (Figures 1 and 2). The opposite situation was observed for heartwood green density, which varied mainly as a result of differences in basic density given the lack of variation in heartwood saturation (Table 2). Finally, according to patterns of variation across stands, changes in whole-section green density responded mainly to changes in sapwood green density and at some extent to changes in sapwood sectional percentage (Figures 1 and 3). The latter explained the substantial increase observed at 12.3 m (Figure 3).

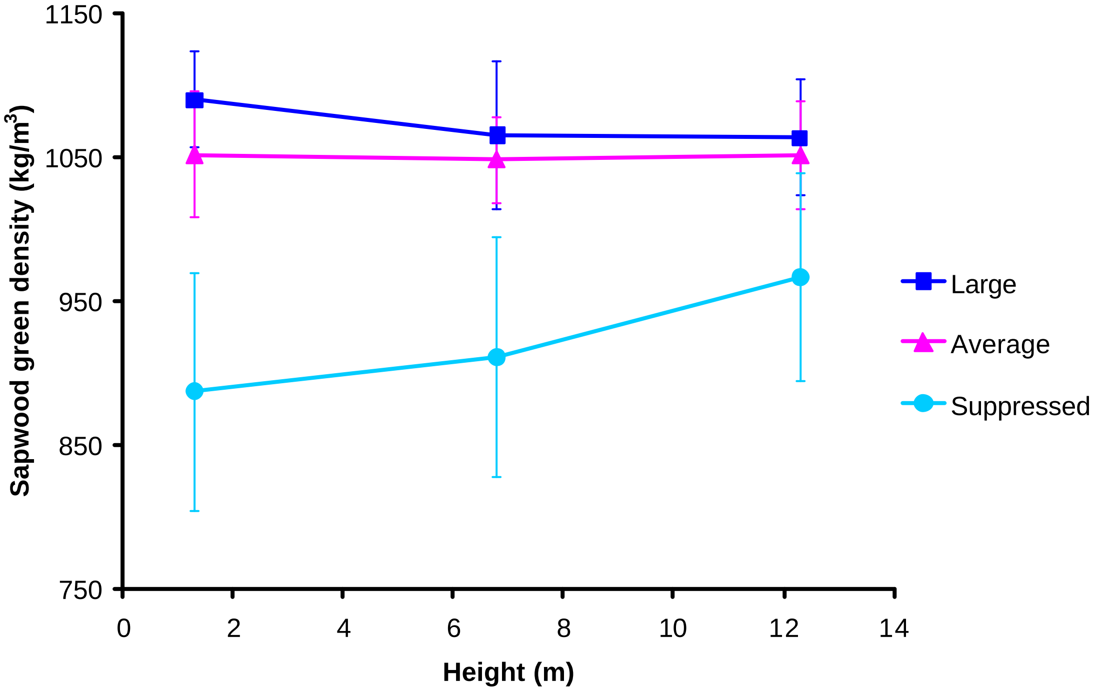

Figure 1. Variation in sapwood green density with height for three different tree sizes of mature unthinned trees (vertical bars = ±1 standard deviation)

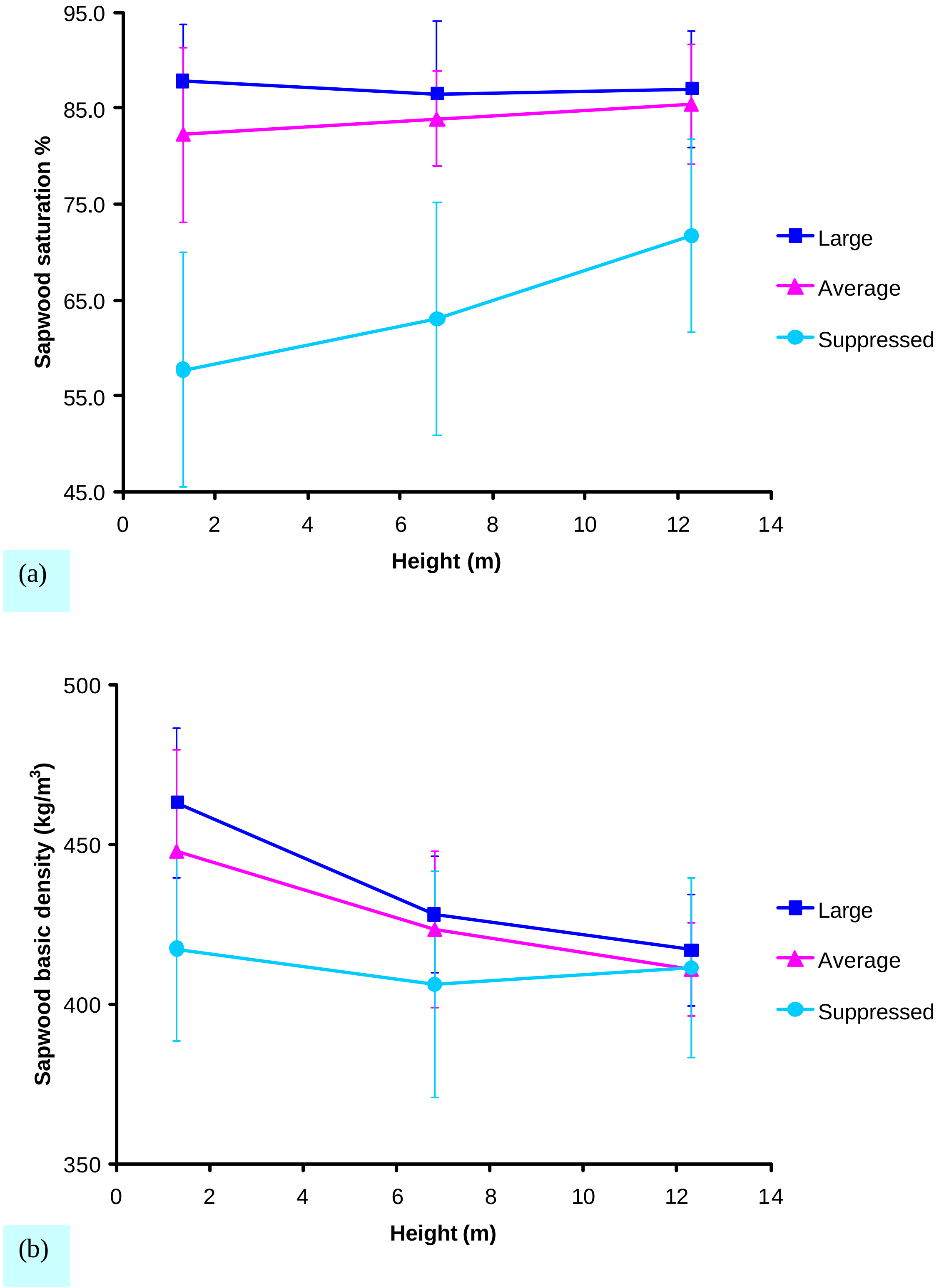

Figure 2. Variation in a) sapwood saturation, and b) sapwood basic density with height for three different tree sizes of mature unthinned trees (vertical bars = ±1 standard deviation)

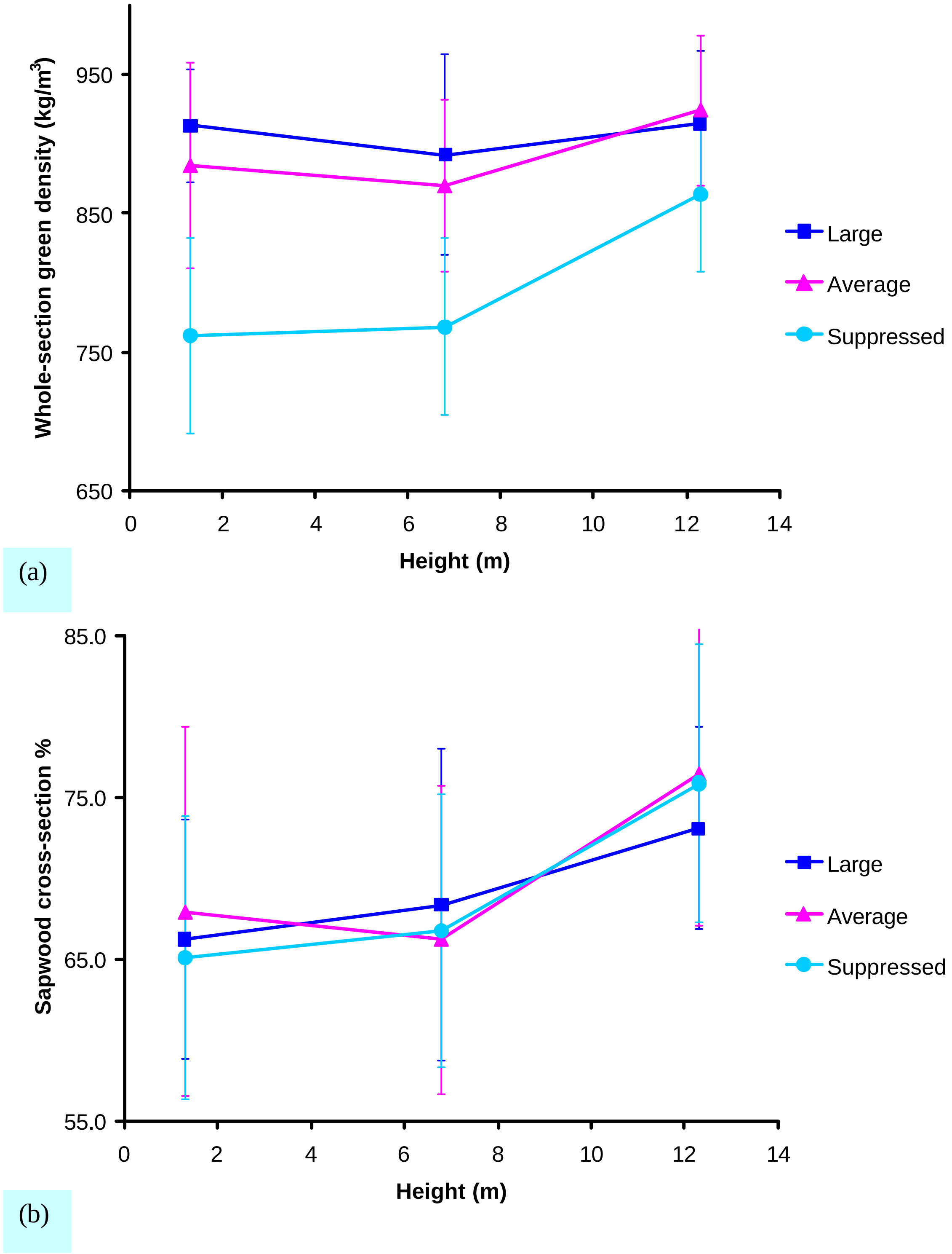

Figure 3. Variation in a) whole-section green density, and b) sapwood sectional percentage with height for three different tree sizes of mature unthinned trees (vertical bars = ±1 standard deviation)

Results revealed that dry sapwood occurred only for the suppressed trees at a rather low extent; furthermore, its presence was confined only to the lower 6.8 m of the stem (Table 3). Additionally, even thought all the suppressed trees have lost a considerably amount of moisture as indicated by the low saturation at the lower 6.8 m, they were still being able to survive. The increased saturation and absence of dry sapwood at 12.3 m suggested that the water-use strategy of suppressed trees in this water-limiting site was to store a greater amount of water in the upper part of the stem.

Cavitation in the conducting xylem occurred at a considerable larger extent than the presence of dry sapwood (Table 3). Differences in presence of cavitation bands between tree sizes ranged between small to moderate; larger trees tend to show a lower frequency of cavitation spots at the lower 6.8 m section of the stem; in contrast, there were no differences at 12.3 m. On the other hand, there was a consistent negative association between tree size and frequency of cavitation bands; additionally, presence of cavitation bands excluding result at 6.8 m was considerably higher for the suppressed trees. The presence of cavitation spots and bands showed opposite trends with height; namely the presence of cavitation spots tends to occur more commonly near the base of the tree, whereas the development of extensive cavitation bands across the sapwood tends to occur towards the top of the tree, in the living crown area. This effect was observed with medium-thinned trees growing in the same site during the dry season of 2006 (Chapter 6 Figure 4).

Table 3. Means values for No. of heartwood rings, and percentage of trees with presence of dry sapwood, cavitation spots, and cavitation bands, at three heights in the tree and across tree sizes

Tree size	Height (m)	No. Heartwood rings	Dry sapwood (% trees)	Cavitation spots (% trees)	Cavitation bands (% trees)
Large	1.3	11.9	0	40	0
	6.8	10.8	0	20	30
	12.3	8.1	0	20	30
Average	1.3	10.5	0	60	10
	6.8	8.9	0	30	50
	12.3	7.3	0	20	40
Suppressed	1.3	7.5	30	50	50
	6.8	5.9	20	40	50
	12.3	4.7	0	20	50

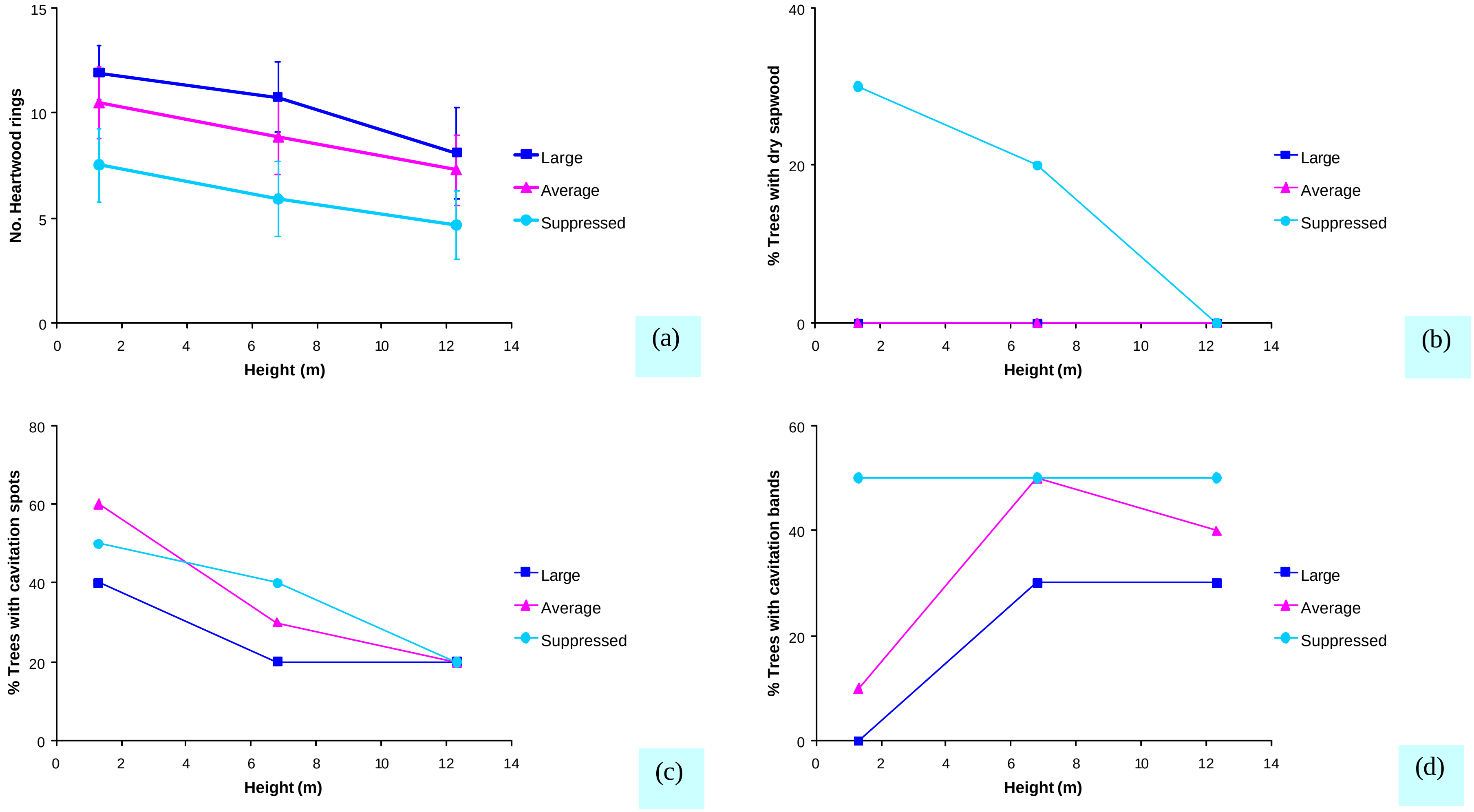

Figure 4. Variation with height in the tree and across tree sizes for (a) No. of heartwood rings, (b) Percentage of trees with presence of dry sapwood, (c) Percentage of trees with presence of cavitation spots, and (d) Percentage of trees with presence of cavitation bands