The effect of site and cambial age on selected anatomical properties of mid-rotation *Pinus radiata*

By

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Thesis presented in partial fulfilment of the requirements for the degree Master of Science in Forestry (Wood Product Science) at the Faculty of AgriSciences, Stellenbosch University

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March, 2012

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Abstract

The aim of this project was to determine the site effect- especially water availability - and the effect of cambial age on selected anatomical properties of *Pinus radiata,* in order to be able to predict possible changes in wood quality due to an expected change in climate. A second objective was to correlate ring and fibre properties, in order to determine, if ring properties could be used as a proxy to describe wood quality. The samples consisted of 12 trees, sampled at an age of 1 to 16 from six selected sites in the Western Cape, which ranged from water stressed to moist. Apart from the water availability all other external factors, such as elevation etc. were kept as equal as possible.

Anatomical wood properties such as fibre length and fibre diameter, lumen diameter, cell wall thickness, ring width and earlywood/latewood ratio were determined and their change with cambial age and water availability was evaluated. Fibre length, fibre diameter and cell wall thickness increased with increasing cambial age, and ring width and earlywood/latewood ratio decreased with increasing cambial age. No significant correlations were found between any of the ring or fibre properties and water availability. Most of the fibre properties were significantly correlated with ring width and earlywood/latewood ratio when age was not considered as covariate, but showed no correlation when the age effect was excluded.

Opsomming

Die doel van die projek was om die perseel se effek te bepaal, veral water beskikbaarheid, ten opsigte van die effek van kambium ouderdom en geselekteerde anatomiese eienskappe van *Pinus radiata*, om sodoende die moontike verandering in hout kwaliteit as gevolg van verwagte klimaatsverandering te voorspel. ‘n Tweede doelwit was om die ring en vesel eienskappe te korreleer en ook te bepaal of ring eienskappe gebruik kan word om hout kwaliteit te beskryf. Die monsters het bestaan uit bome van ses geselekteerde persele in die Wes Kaap en het gevarieer van ‘n water tekort na klam. Behalwe vir water beskikbaarheid is al die ander eksterne faktore, soos hoogte ens., konstant gehou waar moontlik.

Anatomiese hout eienskappe soos vesel lengte en deursnee, sel deursnee, selwand dikte, ring wydte en E/L verhouding was bepaal asook die verandering met kambium ouderdom en water beskikbaarheid. Vesel lengte , vesel deursnee en selwand dikte het toegeneem met toename in kambium ouderdom, en ring wydte en E/L verhouding het afgeneem met toename in kambium ouderdom. Toename in water beskikbaarheid het gelei to afname in vesel lengte en selwand dikte, waar vesel deursnee, sel deursnee, E/L verhouding en ring wydte toegeneem het. Meeste van die vesel eienskappe het betekenisvol gekorrelleer met ring wydte en E/L verhouding wanneer ouderdom nie as ko-variant gebruik is nie.

ACKNOWLEDGEMENTS

A special word of thanks to the following people and organization:

-Martina Meincken and Thomas Seifert for supervising my studies;

-Rural capacity building project (RCBP) for sponsoring my studies;

-To all forestry and wood science staff and students;

- My parents for their love and support during my studies;

- Philip Fischer for the data collection and his continued help in this project;

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

CWT-EW: Cell wall thickness of earlywood

CWT-LW: Cell wall thickness of latewood

DBH: Diameter at breast height (1.3 m)

ETa: Actual Evapotranspiration

ETp: Potential evapotranspiration

ETa/ETp: Supply/demand ratio

Ew/Lw: Earlywood/Latewood ratio

FD-EW: Fibre diameter of earlywood

FD-LW: Fibre diameter of latewood

FL-EW: Fibre length of earlywood

GPa: Giga Pascal

Ha: Hectare

LD-EW: Lumen diameter of earlywood

LD-LW: Lumen diameter of latewood

MAP: Mean annual precipitation

MAT: Mean annual temperature

MFA: Microfibril angle

MOE: Modulus of elasticity

MOR: Modulus of rupture

MTO: Mountain to Ocean Forestry

RW: Ring width

1. INTRODUCTION

Pinus radiata is also known as the Monterey, Insignis or Radiata pine and is native to California. It is the most widely planted pine species in the world and valued for its rapid growth and good lumber and pulp qualities. In Australia, New Zealand, and Spain it is the leading introduced tree species and in Argentina, Chile, Uruguay, Kenya, and South Africa it is a major plantation species. As pinewood is the primary raw material for the sawmilling, particleboard and plywood industries (Pinto 1998), so knowledge of its properties is a prerequisite for its proper utilization. Pine Wood properties are affected by various factors, such as site quality (soil quality, temperature, light, and water availability), silvicultural practices, geographic location (Guilley *et al*. 2003), and stand density, which are some of the external factors that affect wood and fibre properties and thus wood quality. Watt *et al.* (2008), for example, found variations in fibre length for different site qualities. This concurs with Lindström's (1997) report that site quality strongly affects fibre development. Watt *et al.* (2009) found that various *P. radiata* stand structural variables (tree height, root collar diameter, stem slenderness, green crown width and relative green crown height) showed significant variation between sites. Stem slenderness (tree height/ground-line tree diameter) showed a negative relationship with site fertility. Soil nitrogen has a strong influence on the tree nitrogen content, which means that trees on fertile soils have a lower density than trees growing on unfertile soil under similar climatic conditions (Beets *et al.* 2001). Wright (1988) studied the density and within sample variation for two pine species *(P. oocarpa and P. patula ssp. tecunumanii)* from different provenances at six sites (in six countries) and found significant differences between sites. The modulus of elasticity (MOE) was significantly influenced by site quality and Watt *et al.* (2009) found a threefold increase (1.58 to 5.26 GPa) in MOE in six year old *P. radiata* across 30 sites in New Zealand. They concluded that sites with low temperature, high soil fertility, and low competition for light tend to produce low stem slenderness and low MOE wood. Oppositely, sites with high temperature, low fertility and high competition for light produced trees with high stem slenderness and high MOE.

The availability of soil water also affects the growth rate and formation of wood, over long time periods and within a season. For example, the relationship between summer rainfall and wood density in *P. radiata* was examined in a study of juvenile wood from a range of sites in Victoria (Australia) by Nicholls and Brown (1976). They found that average density was less in the region with the highest summer rainfall and they attributed this to a lower proportion of latewood and an increased growth rate. Wright (1970) compared the outer wood of 16 year old *P. radiata* trees and found that wood of lower density was produced on better sites. He established a correlation coefficient of -0.77 between basic density and mean annual volume increment. Wright considered this effect to be due to the higher moisture availability on the better sites. Larson (1964) recorded that drought encourages the formation of narrow-diameter thin-walled tracheids and therefore less dense wood. Polge and Keller (1968) also indicated that in *Pinus sylvestris* irrigation increased the amount of earlywood at the expense of latewood. Downes *et al.* (2002) mentioned that on sites experiencing drought in spring but good growth conditions in summer or autumn more latewood than earlywood was produced, therefore reversing the relationship between growth rate and density into a positive correlation.

Similar to site, age has strong effect on the various wood properties of *Pinus radiata* tree, for instance wood property variation in six *Pinus radiata* (D.Don) trees grown in the Jonkershoek state forest were studied by Malan (1989). The sources of variation, their relative contribution to the total and random variation, and the general pattern of variation were investigated for total ring width, latewood width, latewood percentage, basic density and fibre length. The results indicated that all wood properties showed significant variation with the ring number. Ring width decreased linearly with increasing ring number, while latewood width increased rapidly in the first 11 rings followed by a rapid decrease further outwards. Tracheid length, latewood percentage and basic density also showed an increase with increasing ring number. Bowyer *et al*. (2003) and Walker (1993) reported that cell wall thickness, fibre diameter, proportion of late wood and fibre length increased with age while ring width decreased with age.

Zobel and Sprague (1998) indicated that there is usually an inherent increase in latewood proportion with cambial age. With increasing age and stand closure, crowns of trees gradually recede upwards, resulting in tree rings with a higher proportion of latewood. Lindström's (1997) research on Norway spruce *(Picea abies)* showed that age has strong effect on the different fibre properties: tracheid length and diameter increased with age, and latewood percentage increased with decreasing growth ring width.

The expected worldwide climate change will also affect South Africa. Various simulation programs predict a significant warming and the mean annual temperature (MAT) are expected to rise between 1 and 3°C (van Jaarsveld and Chown 2001). With regards to the precipitation, the forecasts are not that clear. Most simulations predict a decrease of the mean annual precipitation (MAP) for most of the country and mostly in winter, but others predict a slight increase in MAP (Turpie *et al.* 2002).

For the Western Cape the expected climate will be warmer and drier and indeed, over the last three decades a warming was already recorded (Midgley *et al.* 2005). The simulations predict a drying from west to east, which will be caused by a weakening of winter rainfalls. The summer rainfalls will possibly increase slightly (Midgley *et al.* 2005). Generally the winter rainfall season will be shorter (DEA and DP 2007).

The increase in MAT will be most significant in spring and summer months and this effect will be more pronounced in the inland areas (Midgley *et al.* 2005, DEA and DP 2007). The wind velocity is expected to rise in all seasons and this will be most notable in coastal regions (DEA and DP 2007).

The aim of this project was to predict the effects that this climate change can be expected to have on the properties of *P. radiata*, especially with regards to the water availability.

1.1 Objectives

The main aim of this project was to determine the site effect- especially water availability, and cambial age on selected anatomical properties of *Pinus radiata* in the Western Cape, South Africa, in order to be able to predict possible changes in wood quality that can be expected with the predicted climate change. The fibre length, fibre diameter and the cell wall thickness, as well as the ring width and earlywood/latewood ratio of trees from six different sites were determined.

A second aim was to correlate macroscopic ring and microscopic fibre properties, in order to determine if the more accessible ring properties could be used to describe wood quality.

The project tried to answer the following questions:

- How are tree ring and fibre properties affected by the site specific water availability?
- How are tree ring and fibre properties affected by cambial age?
- How are ring properties and fibre properties correlated with each other?

2. Background

2.1 Wood

Generally wood is separated into two types: hardwoods and softwoods (gymnosperms), which are mostly evergreen conifers. *Pinus radiata* belongs to the gymnosperms. Gymnosperms have a comparatively simple cell structure and are more uniform in appearance than hardwoods. Winandy and Rowell (2005) defined wood as a series of cemented tubular fibres or cells with the main function of transporting water and nutrients, store nutrients and give support to the growing biomass of the tree in the prevailing conditions (Dejardin *et al*. 2010, Biermann 1996). The formation of new wood takes place in three growth related developmental stages: (1) cell division from the vascular cambium, (2) cell expansion (elongation and radial enlargement), (3) secondary cell wall deposition, the next two stages transform functional cells into dead inactive tissue and comprise of (4) cell death and (5) heart wood formation (Dejardin *et al*. 2010, Plomion *et al*. 2001).

Chemical, anatomical and physical variations in the cell structure result in variations in wood properties within and between trees (Dinwoodie 1971). These wood properties also depend on genetic variation, growth conditions and environment (Biermann 1996). Within tree differences are mostly between juvenile, heart and sapwood, variation within annual rings and between reaction and normal wood (Diwoondie 1971). Thus it is important to take into account possible effects and interactions of these variables if anatomical properties are analysed.

2.1.1 The macroscopic structure of pine wood

During radial growth new wood is produced in a thin zone of cells just beneath the bark (Bowyer *et al*. 2003, Walker 1993), known as the vascular cambium. The cambium is essential for the continued growth of the tree. As the crown of the tree gets larger with more leaves and branches, the sapwood area must be increased and the stem must increase in diameter to support this extra load. More wood is added by the cambium to the trunk and the stem thickens. The cyclic production of new wood cells each spring and summer, and the subsequent cessation of cambial division in climates with a dormant period, result in the familiar pattern of growth rings.

In temperate climates typically one growth ring is produced each year, but in tropical areas the trees grow a new ring with each rainy period so that there may be two or more apparent annual rings in a single growing season (Bowyer *et al*. 2003). *False rings* typically occur when the normal growing season is interrupted by drought, frost or defoliation, resulting in a ring of apparent latewood. When the conditions improve, trees can once again produce earlywood and complete the annual growth normally with another latewood production in autumn (Bowyer *et al.* 2003). Growth rings are generally more distinct on sites with clear distinction between growth periods and dormant periods. In the early growing season the vascular cambium produces earlywood: tracheid or fibres with large lumen diameters and thin cell walls (Walker 1993). The main function of these cells is the conduction of water rather than biomechanical support. Towards the end of the growing season the cambium produces latewood: these are fibres or tracheids with smaller lumen diameter and thicker cell walls, with the primary function of mechanical support. In the case of *P. radiata* the transition from earlywood to latewood is gradual (Bamber and Burley 1983). Species and growth conditions also affect the appearance of growth rings. For example, wood with short growth periods from dry areas, produces thinner rings than wood growing in good growth conditions (Winandy 1994). Winandy also reported that the width of growth rings is affected by the availability of sunlight. Trees growing under shade produce thinner growth rings than trees growing in open areas.

2.1.2 The microscopic structure of softwood

P. radiata, as a conifer, consists primarily of longitudinally elongated, pointed cells called tracheids (Figure 1). Their length varies with position in the stem. Generally, in mature wood the tracheid length ranges from 2 to 5 mm and the diameter from 15 to 60 µm, which means they are about 100 times longer than wide (Walker 1993, Winandy 1994). The tangential diameter of the tracheids remains fairly uniform throughout the year rings. The radial diameter is larger in earlywood than in latewood where the cells appear flattened (Walker 1993). The tracheids overlap on their wedge-shaped ends. This cell arrangement gives softwoods their high strength along the grain, as well as allowing for maximum side wall cell contact for the movement of water. Edlin (1965) indicated that *P. radiata* earlywood and latewood tracheids differ with respect to length, radial diameter, and cell wall thickness. He observed that earlywood tracheids are usually shorter than latewood tracheids**.** Nicholls and Dadswell (1965) found that the tracheid length across a growth ring in *P. radiata* ranges from 2.6 mm in the first formed earlywood to about 3.2 mm in the latewood. The radial diameter of the first formed earlywood tracheids was about 0.045 mm and that of the last formed tracheids in the latewood about 0.013 mm, whereas the tangential dimensions were similar around 0.04 mm. Because of genetic variations, climate and growth differences and other external influences, wood fibres can exhibit very diverse properties. This idea was supported by Miller (1999) who examined different fibre properties and showed that, the fibre length varied within a tree and between species, due to the above mentioned variables. Shorter fibres are produced in the early growing period (spring) where vegetative growth accelerating conditions (temperature and sunlight) are conductive (Dejardin *et al.* 2010).

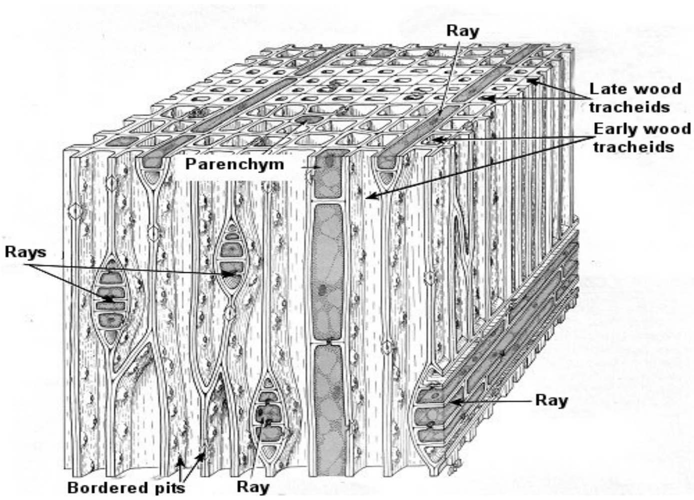


Figure 1: Softwood cell structure (Rost *et al*. 1979)

2.2 Relationship between wood properties and mechanical strength

The two properties mostly used to describe the mechanical properties of wood are the modulus of elasticity (MOE) and modulus of rupture (MOR). These properties greatly affect the performance and strength of wood, especially for structural applications. The MOE describes the elastic/bending behaviour of wood and is considered more important than the MOR, which measures strength, as an indicator for wood quality (Waghorn *et al*. 2007, Watt *et al*. 2009). MOE showed an increase with increasing growth ring number (Lasserre *et al*. 2009), which indicates the influence of tree age on this MOE. The authors also reported that MOE was significantly correlated to MFA, fibre length, cell wall thickness and ring width, but they found no correlation to the wood density in *Cupressus lustanica* and *P. radiata*. Similarly, Roth *et al*. (2007) observed that harvested logs with a lower proportion of juvenile wood exhibited a low MOE. Mature wood has fibres with thick cell walls, lower MFAs and higher density (Dejardin *et al.* 2010). The strength of wood is linearly related to the density (Tsoumis 1991).

Differences in density derive from anatomical differences, such as cell types (fibres, vessels, parenchyma cells) and their quantitative distribution, cell wall thickness and lumen diameter (Tsoumis 1991, Bowyer *et al*. 2003, Walker 1993). The faster a tree is growing the larger the earlywood bands per annual ring will be and thus the density will be lower (Tsoumis 1991). In some species the lowest density coincides with the zone of juvenile wood, which has few latewood cells and a high proportion of thin walled cells. In trees that have grown fast over a short rotation period, the juvenile core occupies a large proportion of the stem and such trees tend to have a low density. The influence of ring width on density is different in softwood and hardwoods. In softwoods, the statistical correlation between ring width and density is low, but density tends to decrease with increasing ring width (Tsoumis 1991), whereas in ring porous hardwoods density increases up to a certain level, with increasing ring width and in diffuse-porous hardwoods ring width is not clearly correlated with density (Tsoumis 1991, Bowyer *et al.* 2003). Koga and Zhang (2002) reported on the relationship between wood density and annual growth rate components in balsam fir (*Abies balsamea*) and found that wood density was not significantly correlated with ring width in either juvenile or mature wood. Generally in softwoods the density decreases with height in the tree and increases with distance from the pith (Bowyer *et al.* 2003). Density is directly related to the percentage of latewood in a growth ring. Generally a large difference in density exists between earlywood and latewood, for example in southern pine the specific gravity of the earlywood is less than one half that of latewood (0.28 versus 0.7) and for this reason wider latewood zones are indicative for higher density. Experiments performed on Norway spruce by Lindström (1996) indicated that the density depended on the latewood percentage and early wood radial tracheid diameter.

2.3 The effect of silivicultural practice on wood properties

Bowyer *et al.* (2003) defined silviculture as the practice of tending and cultivating forest trees. In forest plantations, different silvicultural practices, including fertilization, thinning, spacing and pruning are applied in order to maximize the amount of harvestable wood. Several studies (Wimmer 2002, Bowyer *et al.* 2003, Lundgren 2004, Saren 2006, Cao *et al*. 2008, Jyske 2008, Lindström 1997) indicated that accelerated growth rates of trees due to various silvicultural practices resulted in lower quality wood products, because fast growth encourages trees to produce a high proportion of juvenile wood. At the same time, as the growth rate is increased the proportion of latewood becomes lower compared to the earlywood proportion (Miller 1999).

2.3.1 Effect of stand density on wood properties

The amount of space in which a tree grows is an extremely important determinant of growth rate and thus of wood properties. The spacing between trees and the extent of surrounding vegetation define the degree of competition for such critical growth elements as nutrients, water, and sunlight. Wider spacing between trees decreases the competition for nutrients, moisture and light and increases their growth rate. The growth rate, however, has a great influence on wood properties. Tsoumis (1991) reported that trees grown with wide spacing produce wider growth rings, which indirectly decreases the density, because wider rings contain more earlywood. On the other hand, as the stand density increases, competition for light occurs causing crown recession and delayed crown development, which could cause a growth rate reduction (Lindström 1997) and a lower production of juvenile wood. Zhu *et al.* (2006) reported that as the population density increases, the ring widths of the trees decrease.

The MOE is also highly affected by the initial spacing in the plantation (Bowyer *et al.* 2003). Wider spacing encourages early diameter growth with large crowns, which favours the formation of large diameter knots (Lasserre *et al.* 2005, Waghorn *et al.* 2007, Watt *et al.* 2009). Knots interrupt the fibre grain and reduce its flexibility and therefore the MOE. Waghorn *et al.* (2007) reported that the MOE increased linearly with the stand density in *P. radiata*. Their results showed an increase of MOE from

5.4 GPa to 7.2 GPa as the stand density increased from 209 stems ha^{-1} to 835 stems ha^{-1}. They also found that the increase in MOE slowed when more trees were added (7.5 GPa for 2551 stems ha^{-1}).

2.3.2 Effect of fertilization on wood properties

Additional nutrients and optimum soil moisture through supplementary irrigation accelerate the growth rate of trees (Bowyer *et al.* 2003, Guilley *et al.* 2003). In most cases the application of nutrients and water is directly focused on harvesting a larger volume of biomass with reduced rotation periods (Bowyer *et al.* 2003, Wimmer *et al.* 2002). Bowyer *et al.* (2003) pointed out that if wood properties are studied, the application of fertilizer and irrigation might have both negative and positive impacts. In a density study of nitrogen fertilised *P. radiata,* Beets *et al.* (2001) found that earlywood and latewood densities were significantly affected throughout the tree. They noted a significant reduction in latewood formation compared to unfertilized *P. radiata*, especially at a younger age, below 15 years. Bowyer *et al.* (2003) reported that growth accelerating treatments, such as fertilization and irrigation, affect the average fibre length differently in softwoods and hardwoods. They reported a reduction in fibre length in softwoods but an increase in fibre length in hardwoods. Watt *et al.* (2008), on the other hand, reported that fertilization had an insignificant influence on MOE in *P. radiata*. In a density study of phosphate fertilized *P. radiata* in Australia by Rudman and McKinnell (1970) indicated that the density dropped after fertilization; in these studies decreases of nearly 20% were recorded in plantations treated with phosphatic fertilizers. Experiments performed in New Zealand by Cown (1977) on *P. radiata* showed that fertilizers reduce the wood density by 10% when compared to unfertilized site. Cown indicated that this reduction is due to a decrease in the proportion of latewood in the ring. Bisset *et al*. (1951) also found that tracheid length was about 33% shorter in *P. radiata* fertilized with phosphates. Posey (1964) presented a comprehensive study on the effect of fertilization on wood properties of 12 and 16 years *Pinus taeda* growing in Northern Carolina. He found that fertilizer application increased ring width, decreased specific gravity, latewood percentage, tracheid length and cell wall thickness.

2.3.3 Effect of growth period and rate on wood properties

The microfibril angle (MFA) is affected by the duration of the growth period and growth rate. Longer growth periods and higher growth rates result in higher MFA values (Wimmer *et al*. 2002). Saren (2006) reported that the increased growth may cause intrusive growth where the tips of cells may curl more than in slow growing trees, resulting in a larger MFA. A higher MFA was observed during the early growth period than during the later period (Wimmer *et al*. 2002, Saren 2006).

The faster growth rate due to the use of improved genetic material and adjustment of silvicultural practices to the prevailing environmental conditions was found to result in the reduction of rotation length but at the same time it increased the proportion of juvenile wood and decreased the quality of wood (Watt *et al.* 2009). These findings were supported by Saren (2006) who found that fast growing trees produce shorter cells with thinner cell walls that tend to be round in their cross-sections. Jyske (2008) reported that wood density, fibre length and cell wall thickness decreased on average by 2-7%, 0-9% and 1-17%, respectively in Norway spruce due to fast growth rate.

Rotation age also affects the average fibre length in a tree (Bowyer *et al.* 2003). In shorter rotation cycles more juvenile wood is formed compared to the mature wood, which contains shorter fibres. Wimmer *et al.* (2002) stated that trees should grow to larger diameters to reduce the proportion of juvenile wood; otherwise the average fibre length would be too small. Kojima *et al.* (2008) agreed with these findings that fast growing trees contain large proportions of juvenile wood with unstable properties. Moore *et al.* (2009) reported a negative relationship between growth rate and MOE of *Picea sitchensis.* As the growth rate increased the latewood proportion decreased and with it the density and MOE. Table 1 shows the expected effect of various external factors on wood and fibre properties.

Table 1: Effect of an increase of external factors on fibre and wood properties

Wood/Fibre Properties	Moisture/ irrigation	Fertilization/ Soil Fertility	Thinning	Initial Stand density	Pruning	Temperature	Wind	Altitude	Tree age
Fibre length	Shorter[1]	Shorter[2]	Shorter[3]	Longer	-	Longer[4]	-	Shorter[5]	Longer[6]
Fibre diameter	Wider[7]	Wider[8]	Wider[9]	Smaller	-	Smaller[10]		Wider	wider[11]
Cell-wall thickness	Thinner[12]	Thinner[13]	Thinner	Thicker	-	Thicker	-	Thinner	Thicker [14]
Lumen diameter	Larger[15]	Larger[16]	Larger[17]	-	-	Smaller[16]	-	-	Lower[19]
Earlywood ratio	Higher[20]	Higher[21]	Higher[22]	Lower	Lower[23]	Lower	-	Higher	Lower[24]
Latewood ratio	Lower[25]	Lesser [26]	Lower[27]	Higher	Higher[28]	Higher	-	Lower	Higher[29]
Ring width	Wider[30]	Wider[31]	Wider[32]	Narrow[33]	-	Narrow[34]	-	-	Narrow[35]
Tree structure									
Juvenile wood ratio	Higher[36]	Higher[37]	Highe[38]	Lower[39]	Lower[40]	Lower	-	-	Lower[41]
Mature wood ratio	Lower[42]	Lower[43]	Lower[44]	Higher	Higher [45]	Higher	-	-	Higher[46]
Mechanical properties									
Wood density	Lower[47]	Lower[48]	Lower[49]	Higher[50]	Higher[51]	Higher[52]	Higher[53]	-	Higher[54]
MOE	Lower[55]	Lower[56]	Lower	Higher[57]	-	Higher[58]	-	Lower[59]	Higher[60]
MOR	Lower[61]	Lower[62]	-	-	-	-	-	-	-
Reaction wood	Higher	Higher	Higher[63]	-	-	-	Higher[64]	-	-

1.Posy (1965), 2.Bisset *et al*. (1951) and Bowyer *et al*. (2003), 3.Cao *et al*. (2008) and Bowyer *et al*. (2003), 4.Lindström (1997) and Jyske (2008), 5.Via *et al*. (2004), 6.Bowyer *et al*. (2003), Malan (1989), Lindström (1997), 7.Cao *et al*. (2008), 8.Cao *et al*. (2008), 9.Bowyer *et al*. (2003), 10.Rudman and Mckinnell (1970), 11.Lindström (1997), Bowyer *et al*. (2003), 12.Saren 2006 and Jyske 2008), 13.Posy (1964), 14.Bowyer *et al*. (2003), Walker (1993), 15.Nicholls and Brown (1976), 16.Posy (1964), 17.Bowyer *et al*. (2003), 18.Thomas *et al*. (2004), 19. Bowyer *et al*. (2003), Walker (1993), Tsoumis (1991), 20.Polge and Keller (1968), 21.Cown (1977), 22.Bowyer *et al*. (2003), 23.Bowyer *et al*. (2003), 24. Bowyer *et al*. (2003), Walker (1993), Tsoumis (1991), 25.Miller (1999) and Nicholls and Brown (1976), 26.Cown (1997) and Beets *et al*. (2001), 27.Larson (1973), 28.Bowyer *et al*. (2003), 29.Malan (1989), Zobel and Sprague (1998), 30.Wimmer *et al*. (2002), 31.Posy (1964), 32.Bowyer *et al*. (2003), 33.Lindström (1997) and Zhu *et al* (2006), 34. Zhu *et al* (2006), 35.Bowyer *et al.* (2003), Malan (1989), 36.Wimmer *et al*. 2002, 37.Saren (2006) and Cao *et al*. (2008), 38.Bowyer *et al*. (2003), 39.Lindstrom (1997), 40.Zobel (1992), 41.Bowyer *et al*. (2003), Walker (1993), Tsoumis (1991) 42.Miller (1999), 43.Cao *et al*. (2008), 44.Bowyer.*et al* (2003), 45.Smith (1965), 46.Bowyer et al.(2003), Walker (1993), Tsoumis (1991), 47.Mäkinen *et al*. (2002), 48.Posy (1965), 49.Lindström (1997) and Cao *et al.* (2008), 50.Tsoumis (1991), 51.Smith (1965), 52.Thomas *et al.* (2004), 53.Dunham and Cameron (2000), 54. Bowyer *et al.* (2003), 55.Kao and Walter (1975), 56.Kao and Walter (1975), 57.Waghorn *et al*. (2007), 58.Watt *et al*. (2009), 59.Moore *et al*. (2009), 60.Lassere *et al*. (2009), 61.Tsoumis (1991), 62.Kao and Walter (1975), 63.Bowyer *et al*. (2003), 64.Bowyer *et al*. (2003).

3. Materials and Methods

The content of this thesis was part of a bigger research project on the effect of climate change on tree growth and wood quality. The sample trees for the fibre characterisation where therefore selected as a sub-sample from a previously used, bigger sample (Fischer 2011) in order to make use of the extensive water balance modelling results obtained there.

3.1 Site selection and description

Plantations from the Boland (Grabouw plantation) and Tsitsikamma (Kruisfontein and Blueliliesbush plantation) area were selected for this trial to ensure that a wide range of water availabilities was covered, while all other site properties were tried to be kept as constant as possible (Fischer 2011). Furthermore, only sites with available weather data were chosen. Compartment information for each site was supplied by Mountain to Ocean Forestry (MTO) and only compartments with trees aged between 12 and 16 years were selected. After site selection, field inspections – looking e.g. at the slope of the stand, stand uniformity and soil type - were carried out to determine the suitability of each stand. Areas with a uniform distribution of trees were identified and then inspected on foot. To ensure that the available soil water would not be affected by sub-soil drainage or that soil water could be replenished by the lateral movement of water within the soil, the trial plots were placed in topographical positions that were water-shedding rather than water-accumulating. Also, where stands were in close proximity to mountain foothills, stands with a deep soil profile were avoided, because it would have been more difficult to determine the soil water movement into the plot area by a visual inspection of the soil profile.

Plots of 25 x 25 trees were selected in suitable areas and the diameter of each tree was measured and recorded. The tree spacing was 2.7 m X 2.7 m at the Grabouw (G36), Blueliliesbush (D3 and D10) and Kruisfontein (G19) plantation sites, whereas Grabouw (E18) and Kruisfontein (F14c) had a spacing of 3 m x 3 m and 3.5 m x 3.5 m, respectively.

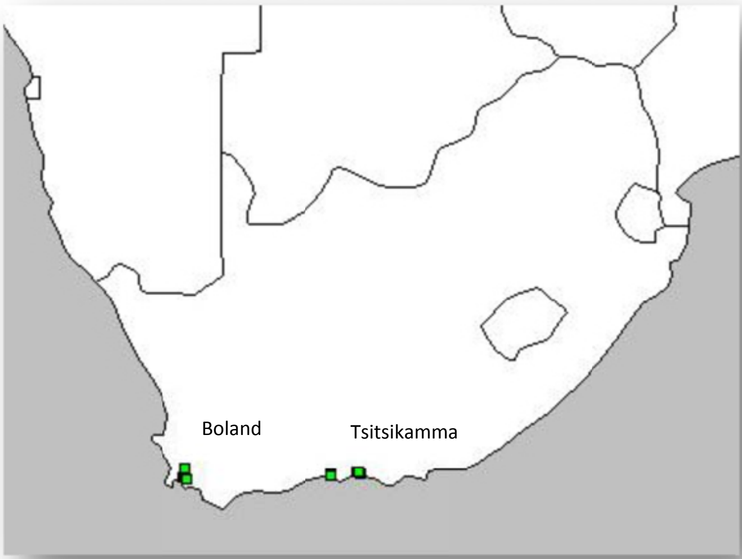


Figure 2: Plantation locations

The stand characteristics of the sites and the soil profile of the selected stand for this study are given in Table 2 and Appendix B and the location of the sites is shown in Figure 2. Six sites were selected according to their ETa values and they were chosen so that the widest possible range of ETa values was covered.

Table 2: Stand characteristics of the selected trial sites

Compartment.	Plantation	Altitude [m]	Age [y]	PTPH	CTPH	Age of first thinning [y]	Pruning age [y]	MAP [mm]	MAT [°C]	6 months ETa/ETp	12 months ETa/ETp	Soil profile water	Latitude	Longitude
G36	Grabouw	394	18	1372	413	10	8	954	11.9	0.17	0.27	115	34.074	19.074
D3d	Blueliliesbush	228	15	1372	473	8	10	1060	12.7	0.70	0.73	99	33.974	23.869
E18	Grabouw	350	14	816	727	13	7	1188	9.1	0.32	0.39	75	34.129	19.015
F14c	Kruisfontein	247	13	1111	540	12	11	791	13.3	0.51	0.56	313	34.034	23.129
G19d	Kruisfontein	156	13	1372	567	10	11	791	13.3	0.45	0.52	312	34.050	23.109
D10	Blueliliesbush	343	10	1372	648	8	7	1060	12.7	0.6	0.64	52	33.959	23.894

PTPH: Planted trees per hectare, CTPH: Counted trees per hectare, MAP: mean annual precipitation, MAT: mean annual temperature, ETa: actual evapotranspiration, ETp: potential evapotranspiration, soil profile water: the maximum available soil water if the profile is at field capacity.

3.1.1 Estimation of evapotranspiration, soil water content and water supply/demand ratio

Actual evapotranspiration (ETa) is the quantity of water that is actually removed from a surface due to the processes of evaporation, and transpiration (Pidwirny 2006), which is dependent on water availability, temperature, humidity and wind. The ETa increases with temperature, as long as there is water to evaporate and for plants to transpire (Pidwirny 2006). The potential evapotranspiration (ETp) describes the environmental demand for evapotranspiration. For that the evapotranspiration rate of a short green crop is used that is completely shading the ground, of uniform height and with adequate water in the soil profile or the amount of water that would be evaporated under an optimal set of conditions, among which is an unlimited supply of water (Pidwirny 2006). The factors that affect the ETp value include the plant's growth stage or level of maturity, percentage of soil cover, solar radiation, humidity, temperature and wind. ETp is higher in the summer, on less cloudy days, and closer to the equator. ETp is also higher on windy days because the evaporated moisture can be quickly moved away, allowing more water to evaporate. The supply/demand ratio (ETa/ETp) is the ratio of actual (ETa) to potential (ETp) evapotranspiration. A lower value of ETa/ETp indicates that the stand is under stress (Fischer 2011).

For this study the ETa/ETp ratio was used to characterise the water availability as an index of water supply to demand. The ETa/ETp ratio was determined for all stands in this study by Fisher (2011) based on the hydrological model (HyMo), which was developed by Rötzer *et al.* (2004). This model calculates a full water balance for a stand of plants based on daily temperature, precipitation, radiation or sunshine duration, wind speed and humidity and additional site information, such as latitude, longitude, altitude, soil depth, soil texture and stand characteristics (see Appendix B). The daily change of the soil water content was calculated by estimating the actual evapotranspiration, the interception and the runoff (Equation 1):

$$\Delta\Psi = rr - e\,t_a - \mathrm{int} - ro - cr + irr \qquad \text{(Eq.1)}$$

With

$\Delta\Psi$: change in soil water content in mm/d *rr* : Precipitation in mm/d

et_a : actual evapotranspiration in mm/d

ro : total runoff in mm/d

int : rainfall interception by canopy in mm/d

cr : capillary rise in mm/d

irr : irrigation in mm/d

The supply/demand ratio (ETa/ETp ratio) was determined after estimating the daily actual and potential evaporation with the HyMo model and from the daily actual and potential evapotranspiration the monthly and yearly average ETa/ETp was calculated from those values.

3.2 Sample selection

The genetic tree material of the sample tree originates from genetically improved seeds from California fields were imported in 1930 and planted in South Africa. The seeds were open pollinated, which might have led to the production of new variations, because of breading is uncontrolled and the pollen source is unknown. The trees from the MTO plantations were, however, all of the same genetic stock.

From each of the 6 sites, six trees were felled and disks with a thickness of ± 25mm were cut at diameter at breast height (dbh), (Fischer 2011). As indicated above, a subsample from these was used in this study by selecting the dbh disks of two trees per site. Disks with visible reaction wood were excluded and regions close to knots were avoided for the fibre sampling. The disks were sanded with a disk sander to improve the visibility of the annual growth rings and to determine the width of growth rings (Figure 3).

Figure 3: a) sanding of disks, b) sanded disk

3.3 Determination of ring width and early/latewood ratio

The year ring width was determined with a custom built Eklund machine and measured were the earlywood width, latewood width and earlywood/latewood ratio (Ew/Lw ratio) for each ring (Seifert, unpublished). The Ew/Lw ratio was determined based on the colour of the wood on an visual base.

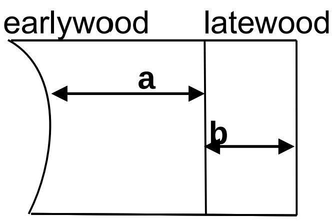


Figure 4: Measurement of early and late wood width

The earlywood to latewood ratio is given by:

$$\text{Ratio} = a/b \qquad \text{(Eq. 2)}$$

3.4 Sample preparation for fibre analysis

Each disk was cut in half with a band saw, leaving the pith intact on one half for possible further ring analysis. A thin strip was then cut from the pith to bark (Figure 5) and from this strip, very small blocks of early and latewood were separated and clearly labelled (site, tree, year, Ew/Lw). The blocks were separated according to their colour and by carefully distinguishing the translation from earlywood to latewood. The latewood of *P. radiata* is visibly darker than the early wood. Disks that contained compression wood were cut on the tension side, because on this side the rings are wider.

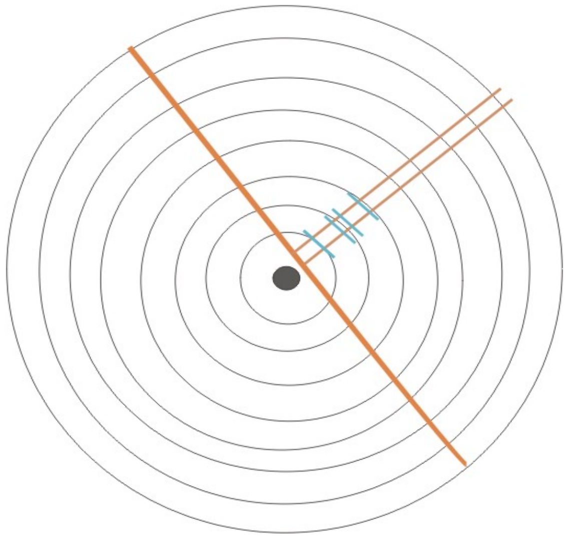


Figure 5: Sample preparation for fibre analysis

3.5 Determination of fibre length

The fibre length was determined in all earlywood sections after maceration. Maceration is the technique used to separate fibres by dissolving the middle lamella. Match-size stick sized sections of earlywood were macerated in Jeffrey's solution (10g chromic acid dissolved it in 190 ml distilled water, to which 15 ml nitric acid was added) at room temperature for 24 hours. The fibres were crushed with a glass rod before they were cleaned and stored in distilled water (Figure 6a, b).

a)  b) 

c) 

Figure 6: a) fibres in Jeffrey's solution, b) washed fibres in distilled water, c) fibres prepared for analysis on a microscop slide.

For microscope analysis a few drops of the fibre suspension were spread on a microscope slide (Figure 6c) and the water was allowed to evaporate. Two slides were prepared per sample and from each slide three images were acquired with a Leica EZ 4D stereo microscope (Figure 7). The images were 16x magnified and the length of about 100 intact fibres (or as many as possible) were determined with the Leica image software and the average fibre length per year ring was determined.

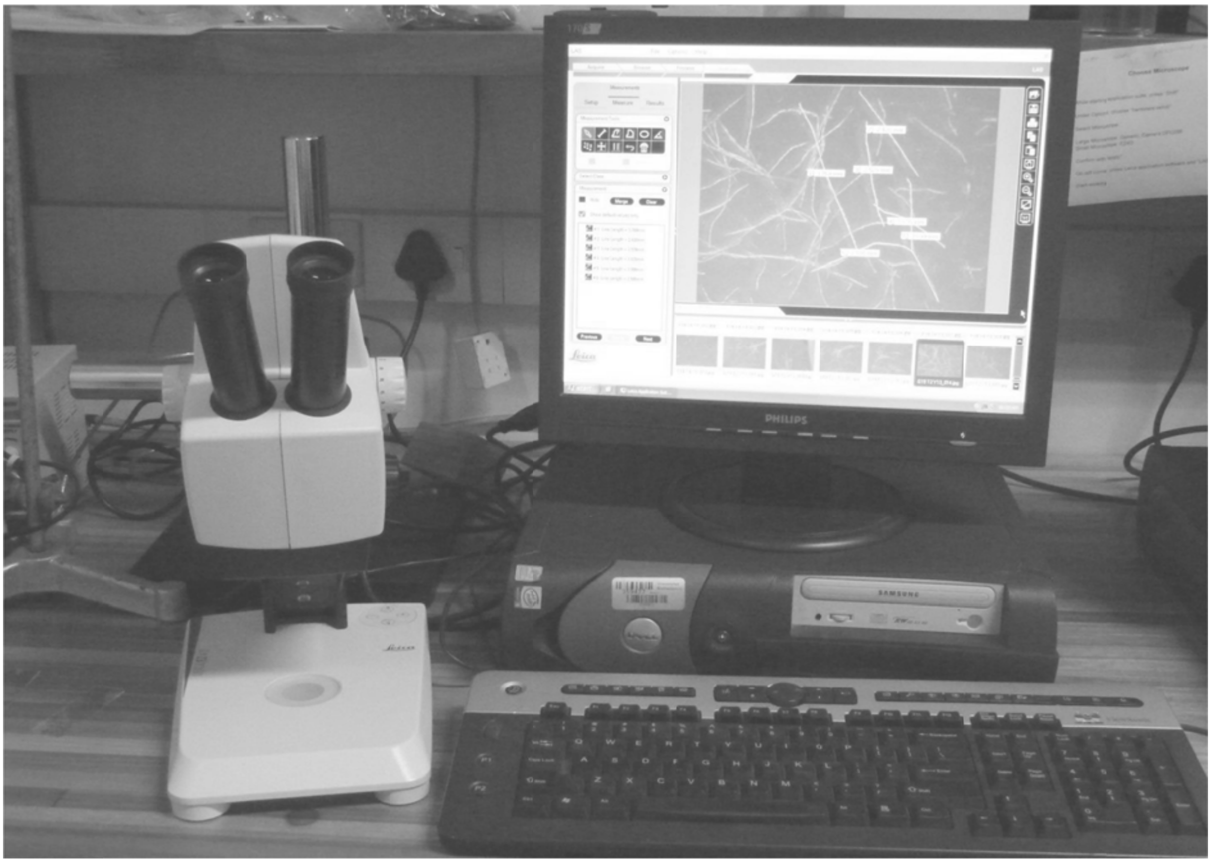


Figure 7: Measurement of fibre length.

3.6 Determination of cell wall thickness, cell and lumen diameter

Cell wall thickness, cell and lumen diameter were measured on about 20 µm thick cross-sections cut from each earlywood and latewood section. Before cutting the sections, the wood was softened in warm water below 100 °C for one hour and sections were cut with a Leitz sliding microtome. The first 5 sections were discarded to avoid deformed cells in the samples, and then the following three sections were kept for analysis. Before image analysis, the samples were conditioned for about two weeks at 20 °C and 65 % relative humidity in a conditioning room.

One image was acquired of each of the three sections with a Leica DM transmission microscope (Figure 8). The images were 400x magnified and the cell wall thickness, lumen and cell diameter of 100 cells (or as many as possible) per sample were measured to determine the average values per tree ring.

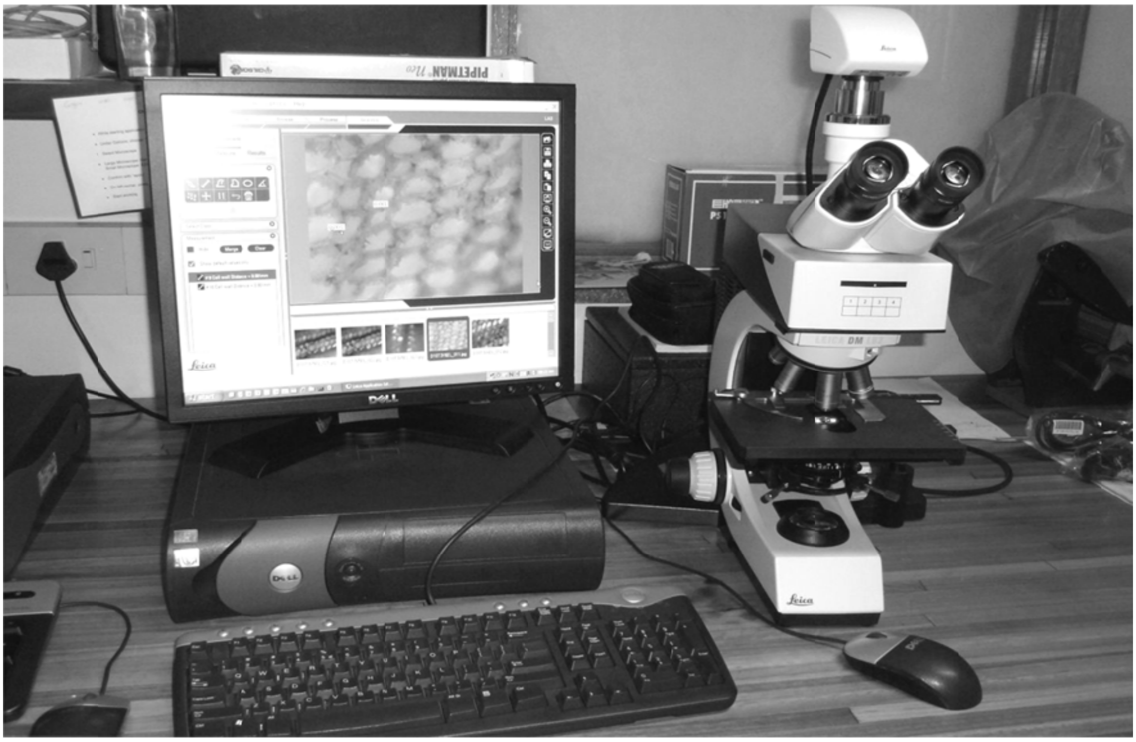


Figure 8: Measurement of cell wall thickness, cell and lumen diameter.

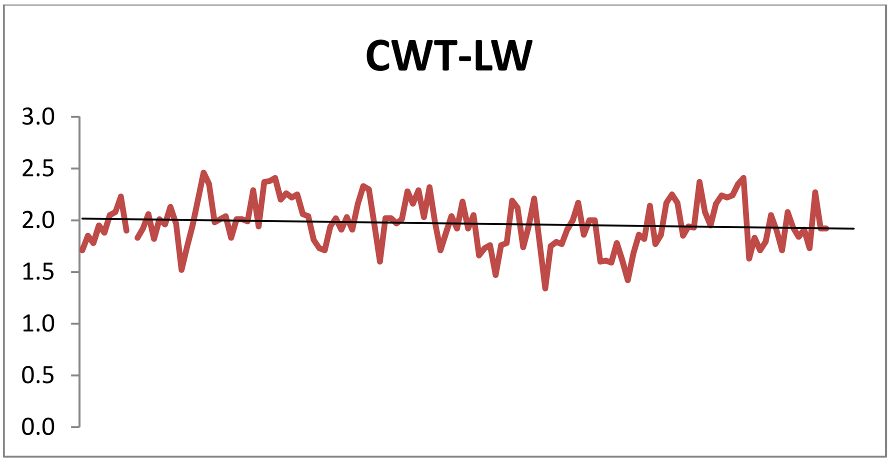
3.7 Statistical Analysis

The measured ring and fibre data were captured in an Excel spreadsheet and averages and standard deviations of each property determined. Subsequently, all fiber and ring properties were "detrended" to eliminate the age factor. The age effect is removed by a regression (See Figure 9a and b). The regression equations for the detrending of each variable were selected based on the principles of best fit across all trees and the principle of parsimony (less parameters is better) and are displayed in Table 3.

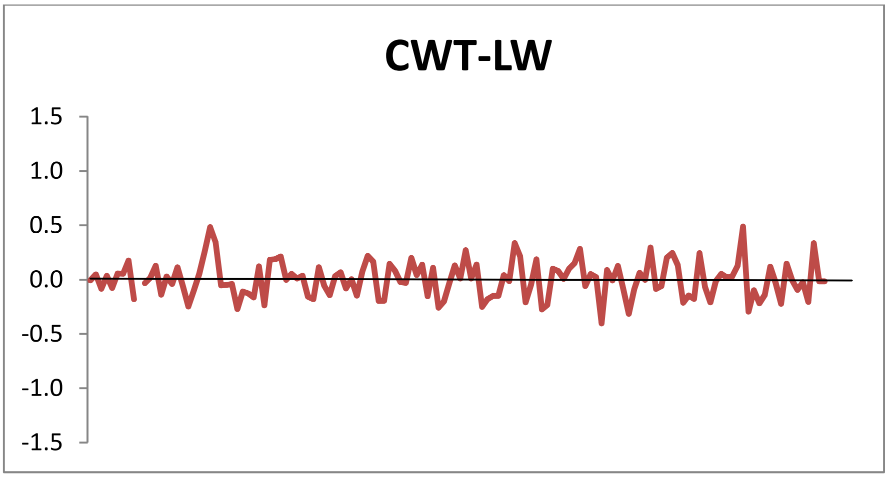
The detrending resulted in annual deviations from the average wood property. Those values were then regressed against the ETa/ETp deviations, which were calculated based on the average annual value determined over all 5-10 years (Fisher 2011).

Table 3: Selected functions for detrending of tree ring and fibre properties.

Wood property	Equation for detrending
Ring width	$Y = x^4 . a_4 + x^3 . a_3 + x^2 . a_2 + x. a_1 + a_0$
Earlywood/latewood ratio	$Y = x^2 . b_2 + x. b_1 + b_0$
Fibre length	$Y = x^4 . c_4 + x^3 . c_3 + x^2 . c_2 + x. c_1 + c_0$
Fibre diameter	$Y = x. d_0$
Lumen diameter	$Y = x^2 . e_2 + x. e_1 + e_0$
Cell wall thickness	$Y = x^2 . f_2 + x. f_1 + f_0$



a)



b)

Figure 9: a) averaged cell wall thickness of latewood, b) detrended cell wall thickness of latewood.

Thus the deviations of the wood properties from the trend contain the effect of all other factors than age. This yielded effectively a centering of the data on both axes, where negative values indicate smaller values of wood properties or ETa/ETp respectively than the average and positive values indicate bigger than average values. Figure 10 shows possible outcomes of this correlation:

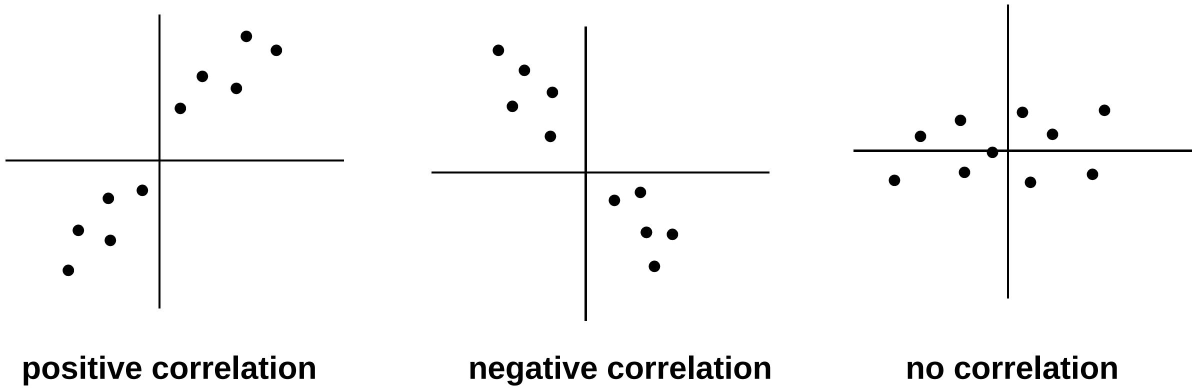


Figure 10: Possible correlation types between wood properties and ETa/ETp

The data was then imported in to statistical analysis program (SPSS 19) for a linear regression.

$$Y = a + b.x \qquad \text{(Eq.3)}$$

For the correlation of macroscopic ring properties with microscopic fibre properties Pearson's correlation and partial correlations were calculated. In partial correlation the age is used as a control variable (covariate) in order to eliminate its influence on the correlations of other variables.

4. Results and Discussion

4.1 General description of ring width and fibre properties

A general description of the tree ring and fibre properties, based on minimum, maximum average and standard deviation is provided in Table 4.

Table 4: The minimum, maximum and the mean of all ring width and fibre properties

Wood property	N	Minimum	Maximum	Mean	Standard deviation
Ring width (mm)	136	2.22	29.49	8.81	4.45
Earlywood/Latewood ratio	136	0.19	13.31	2.57	2.34
Fibre length (mm)	137	0.69	2.65	1.45	0.43
Fibre diameter of earlywood (µm)	135	1.74	3.00	2.46	0.28
Fibre diameter of latewood (µm)	135	1.34	2.46	1.97	0.23
Lumen diameter of earlywood (µm)	135	1.14	2.55	1.87	0.25
Lumen diameter of latewood (µm)	135	0.85	1.78	1.18	0.17
Cell wall thickness of earlywood (µm)	135	0.40	1.27	.84	0.18
Cell wall thickness of latewood (µm)	135	0.42	1.67	1.04	0.24

4.2 Fibre and ring properties as a function of cambial age

This chapter presents fibre and ring properties as a function of the cambial age. The values presented were obtained from dbh discs of two trees of each site. According to literature (see Chapter 2) fibre diameter (FD), cell wall thickness (CWT), and fibre length (FL) are expected to increase with increasing tree age, whereas lumen diameter (LD), earlywood/latewood ratio (Ew/Lw) and ring width (RW) are expected to decrease with increasing age.

The mean annual ETa/ETp ratio is plotted additionally in order to identify outliers caused by a typical weather conditions. The ETa/ETp ratio is also used to characterise the average water availability of the different sites, as it integrates the underlying water balance via modelled precipitation, soil water holding capacity and temperature/ air water deficit. The weather data is presented in Appendix A.

Trends are marked in all graphs with a dashed line. These trend lines are, however, not fitted regression lies but are introduced to increase the visibility. The regression curves are shown in Appendix C.

4.2.1 Site D3

This site is located in Bluelilliesbush / Tsitsikamma and is with a five year average ETa/ETp value of 0.7 the site with the highest average water availability in this study.

Figure 11 illustrates how fibre and ring properties changed with cambial age. The fibre length did not increase with age, as expected - it showed rather scattered values in tree 1 and remained more or less constant in tree 2. The fibre diameter increased, as expected, until an age of about seven years, after which a slight decline can be observed. This could have been caused by lower MAP in the years 2005 (year8), 2008 (year11) and 2009 (year12), and higher MAT in the years 2005 (year8), and 2009 (year12), when the Tsitsikamma region experienced a severe drought. Cell wall thickness increased with age, as expected. The lumen diameter increased in the first six years, after which it decreased slightly, as expected. Since no weather data is available for the early growth years, this pattern cannot be explained with environmental factors.

The ring width shows large fluctuations but a general reduction with cambial age. At 8 years age the ring width shows a sudden peak, after which it decreased further. This peak value could have been caused by a high ETa/ETp value in this year. The Ew/Lw ratio decreased with increasing age, as expected.

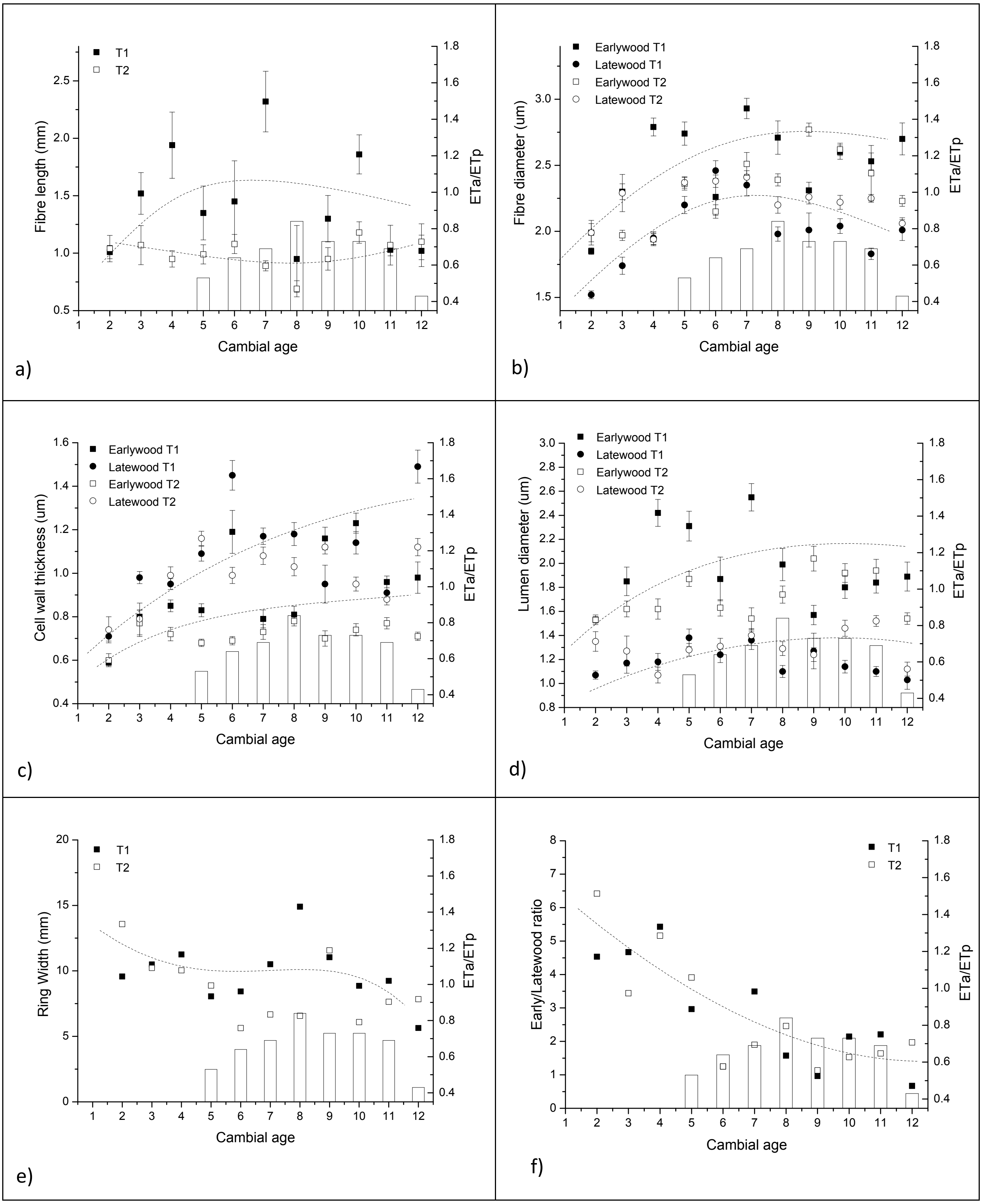


Figure 11: Yearly ETa/ETp values and a) fibre length, b) fibre diameter, c) cell wall thickness, d) lumen diameter, e) ring width and f) earlywood/latewood ratio of the two trees obtained from site D3. Dashed lines are for easier visibility.

4.2.2 Site D10

This site is located in Bluelilliesbush / Tsitsikamma and is with a five year average ETa/ETp value of 0.6 the site with the second highest water availability in this study.

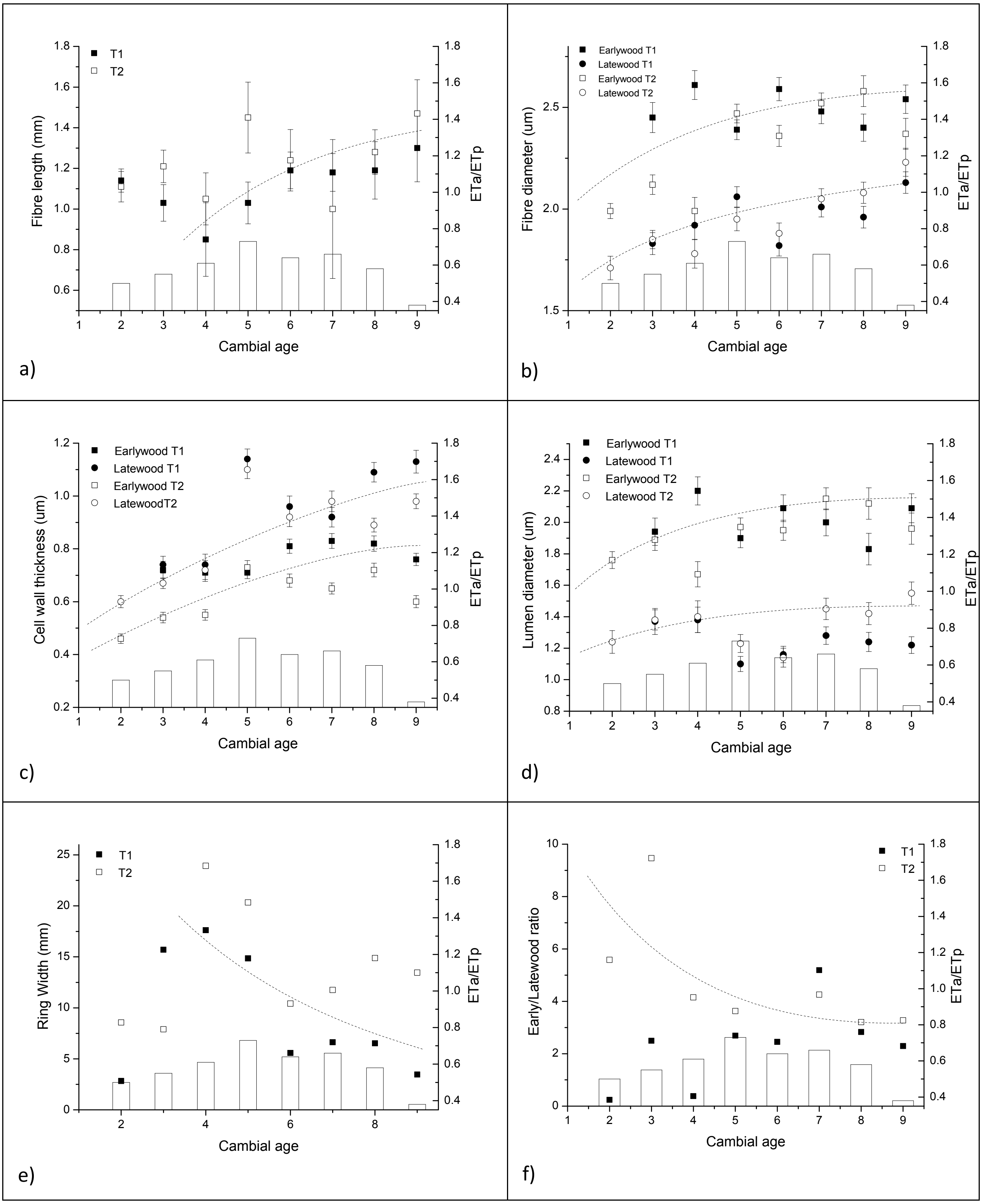


Figure 12: Yearly ETa/ETp values and a) fibre length, b) fibre diameter, c) cell wall thickness, d) lumen diameter, e) ring width and f) earlywood/latewood ratio of the two trees obtained from site D10. Dashed lines are for easier visibility.

The fibre length shows an initial decrease in both trees and increases after about four years of age. The fibre diameter and cell wall thickness increase, as expected with age. The lumen diameter also increases in the early years, after which it remains constant.

The ring width decreases after four years and the Ew/Lw ratio shows very scattered values with a rather unclear trend of decreasing values.

The unusual behavior in the early years could possibly be explained by an average MAP and low MAT in year two (2002) and an increased MAP in the years three (2003) and year four (2004).

4.2.3 Site E18

This site is located in Grabouw / Boland and is with a five year average ETa/ETp value of 0.32 the second driest site of this study.

Figure 13 shows that fibre length increased with increasing age, as expected, although tree 1 shows a decrease in the last three years, which correlates with lower ETa/ETp values in those years. The fibre diameter and cell wall thickness increased with increasing age in both samples. The lumen diameter increased in the earlywood of both samples until an age of 6 years, after which it remained more or less constant. This trend could not be observed in the latewood, where the lumen diameter hardly changed. Ring width and Ew/Lw ratio decreased with increasing tree age after 4 years.

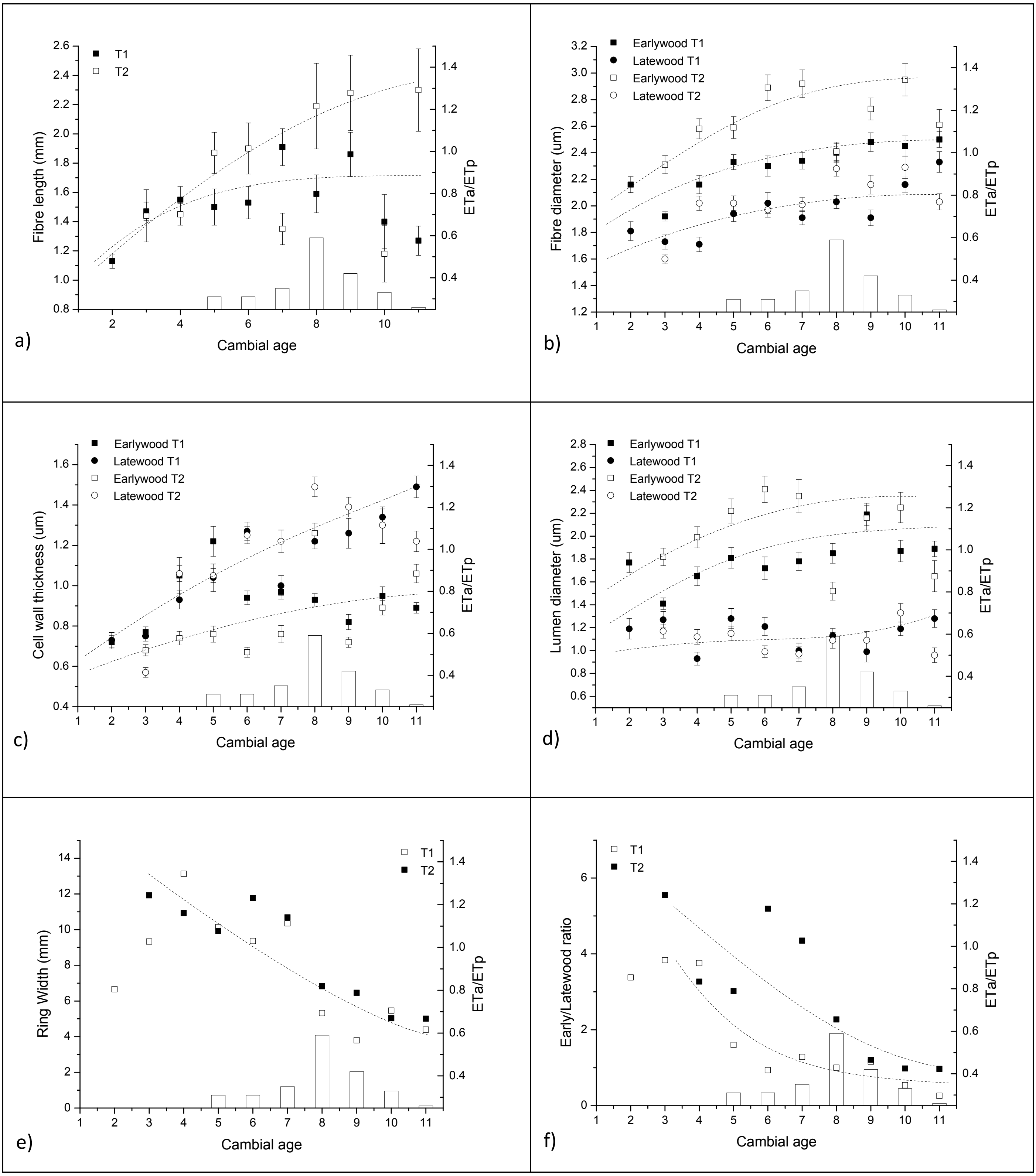
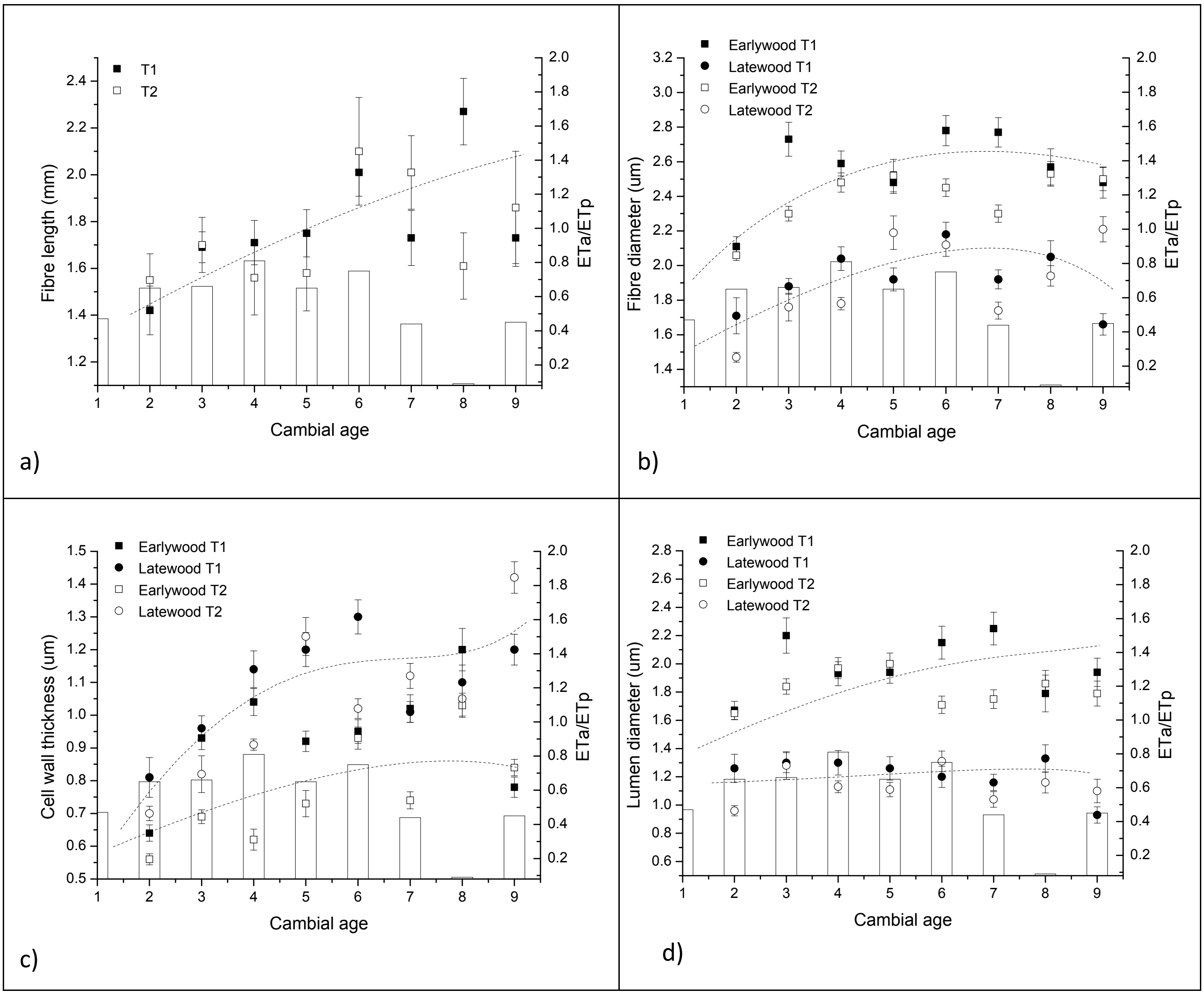


Figure 13: Yearly ETa/ETp values and a) fibre length, b) fibre diameter, c) cell wall thickness, d) lumen diameter, e) ring width and f) earlywood/latewood ratio of the two trees obtained from site E18. Dashed lines are for easier visibility.

4.2.4 Site F14

This site is located in Kruisfontein / Tsitsikamma and is with a five year average ETa/ETp value of 0.51 the third wettest site of this study.

Figure 14 shows that the fibre length increased with increasing age, as expected. The fibre diameter increased with increasing age in both early and latewood until an age of 6 years, after which it decreased again. Cell wall thickness also increased with age in both earlywood and latewood. The lumen diameter increased in the earlywood and remained constant in the latewood. The ring width and Ew/Lw ratio decreased with increasing age. However, an initial increase and subsequent fluctuation of ring width could be observed in both trees.



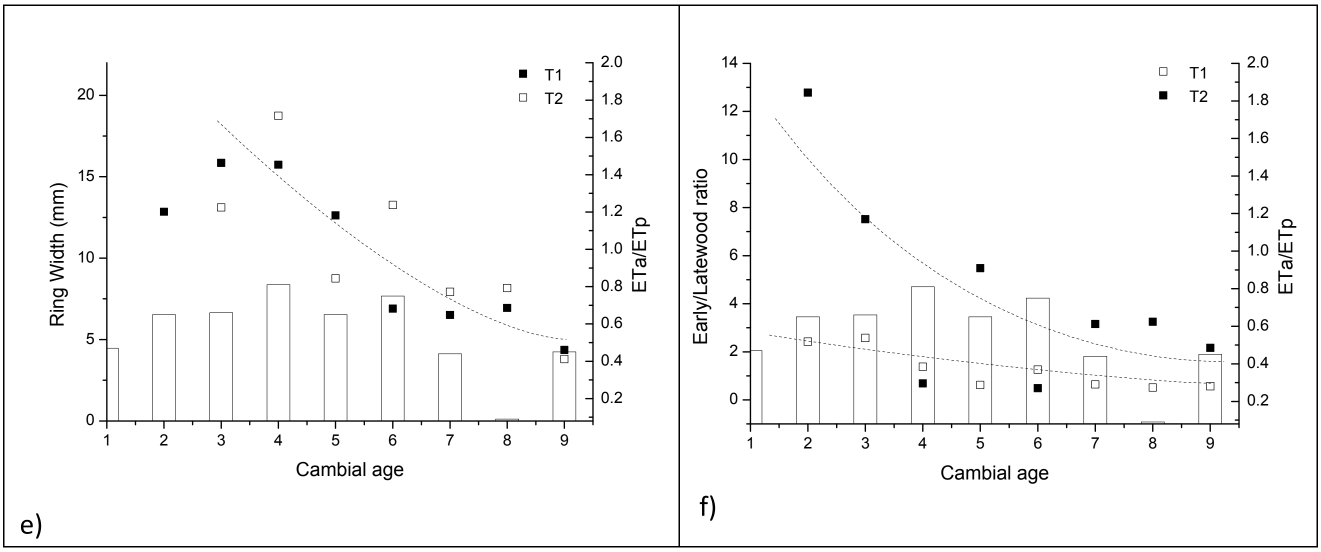


Figure 14: Yearly ETa/ETp values and a) fibre length, b) fibre diameter, c) cell wall thickness, d) lumen diameter, e) ring width and f) earlywood/latewood ratio of the two trees obtained from site F14. Dashed lines are for easier visibility.

4.2.5 Site G19

This site is located in Kruisfontein / Tsitsikamma and is with a five year average ETa/ETp value of 0.45 the third driest site of this study.

Figure 15 shows that the fibre length increased after about 5 years of age. The fibre diameter, as well as the cell wall thickness increased, as expected, with increasing age in both trees. The lumen diameter increased in the earlywood cells and decreased in the latewood until about 6 years of age, after which it increased again. 2002 (year 2) had an average MAP and higher MAT, which could explain the low initial lumen diameter. 2003 and 2004 were wetter years, which could explain the increase in lumen diameter. The ring width and Ew/Lw ratio fluctuated visibly but showed a general decrease with age.

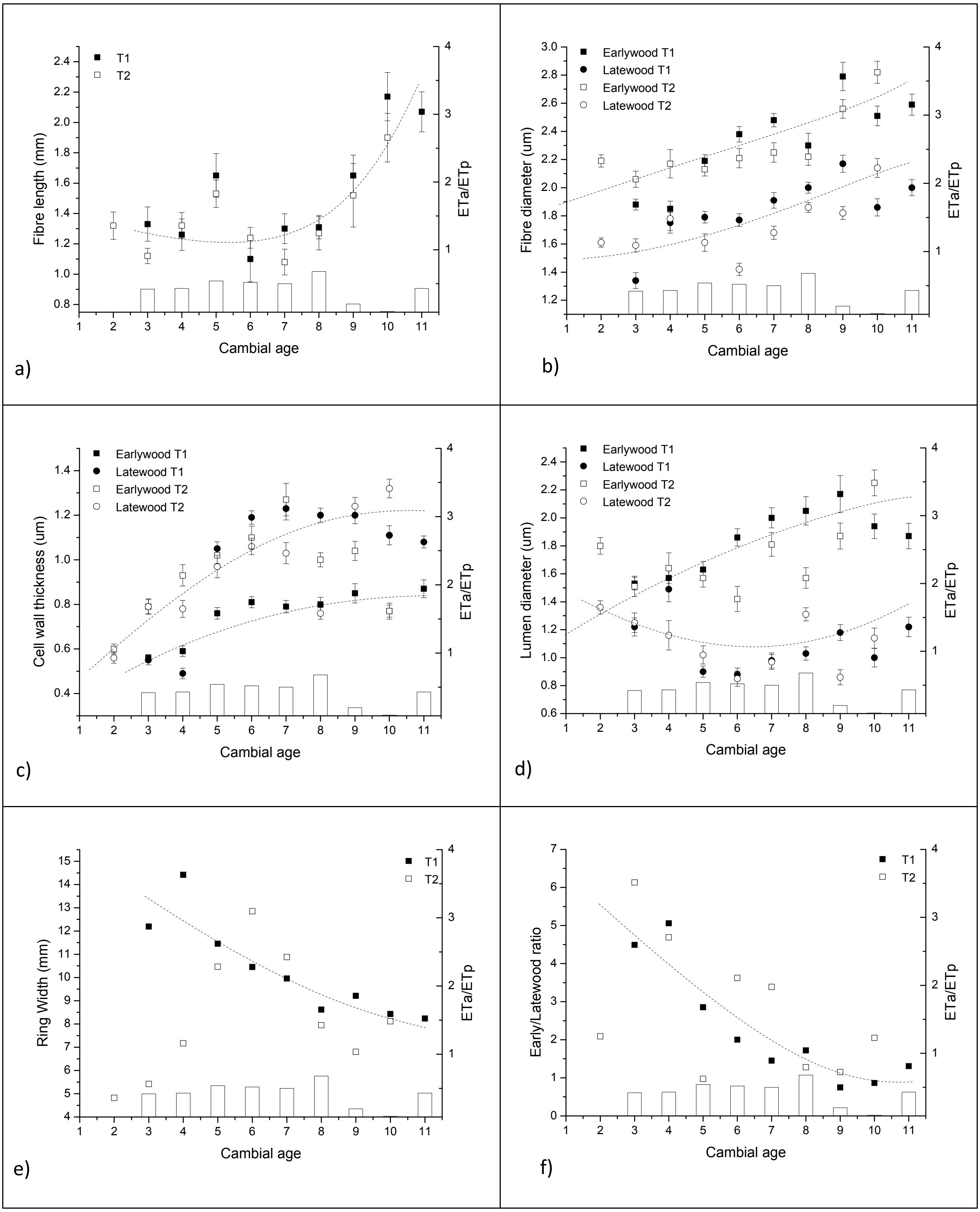


Figure 15: Yearly ETa/ETp values and a) fibre length, b) fibre diameter, c) cell wall thickness, d) lumen diameter, e) ring width and f) earlywood/latewood ratio of the two trees obtained from site G19. Dashed lines are for easier visibility.

4.2.6 Site G36

This site is located in Grabouw / Boland and is with a five year average ETa/ETp value of 0.17 the driest site of this study.

Figure 16 shows that the fibre length increased until an age of 8 years again, after which a sharp decline can be observed in both trees. From year 10 onwards the fibre length increases again. 2003 was a rather cold year with an average MAP, which could have caused the sudden decline. The fibre diameter was generally increasing with age, although the values are scattered widely. The cell wall thickness increased, as expected. The lumen diameter increased in earlywood up to an age of 6 years, after which it remained constant. In latewood the lumen diameter was scattered but generally decreased. The ring width and earlywood/latewood ratio decreased with age, as expected.

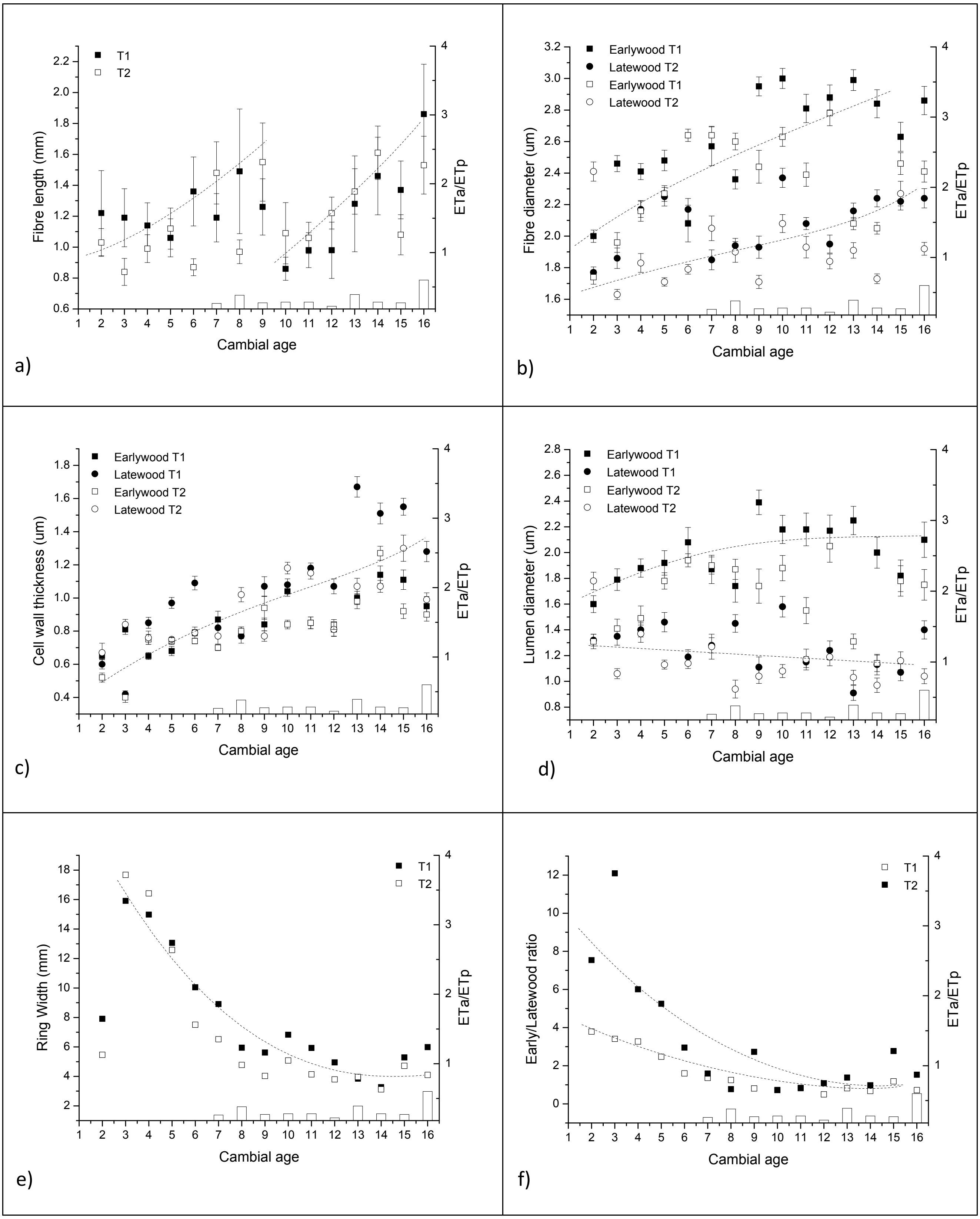


Figure 16: Yearly ETa/ETp values and a) fibre length, b) fibre diameter, c) cell wall thickness, d) lumen diameter, e) ring width and f) earlywood/latewood ratio of the two trees obtained from site G36. Dashed lines are for easier visibility.

The fibre length ranged from about 0.69 to 2.65 mm and increased in most sites with cambial age. In site D3 this trend was the least visible while in site D10 and G19 the increase only started after four years. In site G36 the increase was “disrupted” in year eight. This agrees with the results of Lindström (1997) on Norway spruce *(Picea abies)* and Malan (1989) on *Pinus radiata,* who showed that fibre length increased with increasing age.

The fibre diameter increased with increasing tree age in all sites but showed a decline or levelling in sites D3 and E18 after 7 years of age. Lindström (1997) found similar bahaviour in Norway spruce. His results indicate that tracheid length and diameter increase with increasing tree age.

The cell wall thickness increased with tree age on most sites and this effect was typically more pronounced in the latewood. Bowyer et al. (2003) and Walker (1993) mentioned that the proportion of the cell wall increases with age, because of the increasing of proportion of latewood and reduction of earlywood proportion with age.

The lumen diameter is expected to decrease with increasing tree age. This could only be observed in the latewood of trees from sites G19 and G36. In all earlywood and the remaining latewood samples, the lumen diameter increased until an age of about 6 to 8 years, after which it remained roughly constant. This could only partly be explained with the available weather data, and probably thinning effects also play a role. A response to thinning and the increased space is increased crown development and formation of wider growth rings, which might be lead to an increase of lumen diameter (Bowyer 2003).

The ring width decreased with increasing age on all sites, but in sites D10, E18, F14, G19 and G36 this decrease only started after 4 years of age, after an initial increase. The ring widths in site D3 were rather scattered. Malan’s (1989) results also indicate that ring width decreased linearly with increasing ring number.

The Ew/Lw ratio decreased with increasing age on all sites apart from site D10, where the values were scattered for both trees. Zobel and Sprague (1998) similarly found that there is usually an inherent increase in latewood proportion with cambial age. With increasing age and stand closure, crowns of trees gradually recede upwards, resulting in tree rings with a higher proportion of latewood than earlywood.

Deviations from the general trend could be explained with unusual weather patterns in those years in some cases.

An overview of all fibre properties as a function of tree age over all sites is given in Table 5. The properties that did not follow the expected trend are highlighted.

Table 5: Change of fibre properties with increasing cambial age. ↑: increase with age, ↓: decrease with age, →: no change, ↑↓: inconsistent pattern.

Sites	D3		D10		E18		F14		G19		G36	
Tree	1	2	1	2	1	2	1	2	1	2	1	2
FL	↑↓	→	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
FD-EW	↑↓	↑↓	↑	↑	↑	↑	↑↓	↑↓	↑	↑	↑	↑
FD-LW	↑↓	↑↓	↑	↑	↑	↑	↑↓	↑↓	↑	↑	↑	↑
CWT-EW	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
CWT-LW	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
LD-EW	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
LD-LW	↑	↑	→	→	→	→	→	→	↑↓	↑↓	→	→
RW	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
Ew/Lw ratio	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓

Note: FD-EW=fibre diameter of early wood, FD-LW=fibre diameter of late wood, LD-EW=lumen diameter of early wood, LD-LW= lumen diameter of late wood, CWT-EW=Cell wall thickness of early wood, CWT-LW=cell wall thickness of late wood, FL-EW fibre length of early wood, RW=ring width, Ew/Lw ratio=earlywood / latewood ratio

4.3 Fibre and ring properties as a function of water availability

In this chapter the result of the analyse fibre and ring properties of the two trees are presented for each site as a function of water availability, expressed by the ratio of actual to potential evapotranspiration (ETa/ETp). According to literature (see Chapter 2), fibre diameter (FD), lumen diameter (LD), early/latewood ratio (Ew/Lw) and ring width (RW) are expected to increase with increased water availability, whereas cell wall thickness (CWT) and fibre length (FL) are expected to decrease with decreased water availability.

Detrended ring and fibre properties were plotted against ETa/ETp values as described in Chapter 3.7. Figures 17 (ring width) and 18 (cell wall thickness of latewood) show examples of these correlation plots and no correlation could be found. The full set of correlation plots is shown in Appendix D.

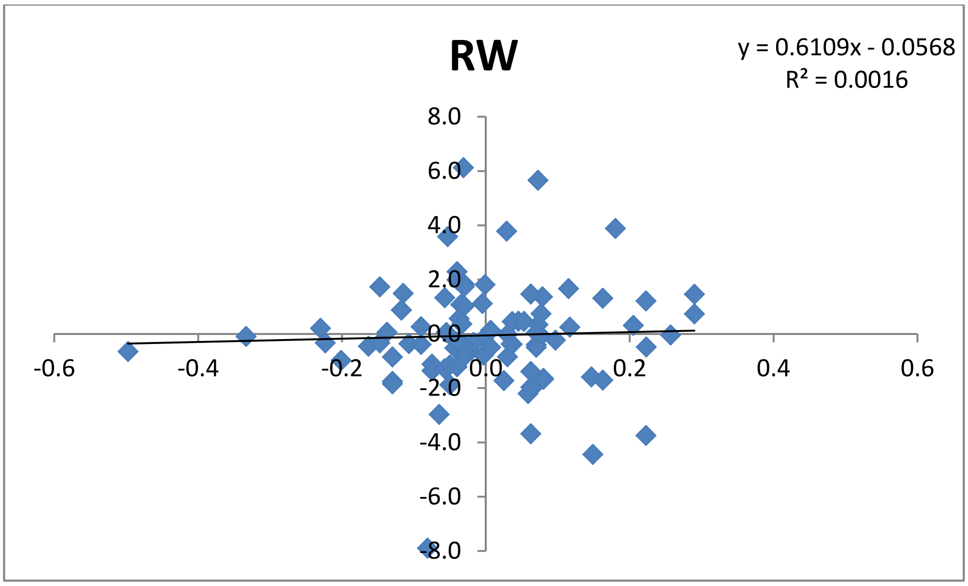


Figure 17: Correlation of ring width and ETa/ETp.

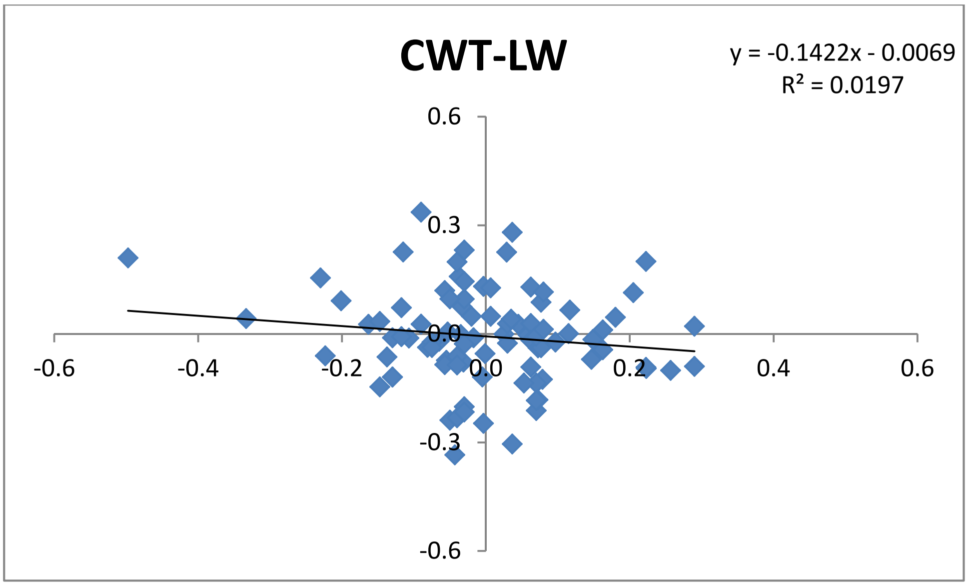


Figure 18: Correlation of cell wall thickness (latewood) and ETa/ETp.

As illustrated in Table 6 no significant correlations were found between any of the ring or fibre properties and water availability at a significance level of $p<0.05$.

This could be due to the fact that the sample trees used for this experiment were only half rotation age, which means that they contained a large portion of juvenile wood. Juvenile wood is generally characterized by low density, thin cell walls, short tracheids, small lumens, high grain angle, and high microfibril angle, when compared to mature wood (Macdonald and Hubert 2002). Harris (1965) indicated that the wood density of juvenile wood from 22 years old *radiata pine* was 330 kg/m^3 while that of the mature wood, near the bark was 430 kg/m^3. Bendtsen's (1978) research on Douglas-fir showed that juvenile wood had a specific gravity of 0.39 and that of mature wood 0.45. Wheeler *et al.* (1966) indicated that the tracheid length of juvenile wood of loblolly pine was shorter than mature wood: 3.38 mm compared to 4.44 mm. Barefoot *et al.* (1965) comprehensive research results showed that there were differences between the fibre properties of juvenile and mature wood. They indicated that the juvenile cell wall thickness of earlywood, cell diameter of earlywood, and lumen diameter of earlywood were 4.85 μm, 47.21μm, and 37.52 μm respectively, whereas for mature wood the cell wall thickness of earlywood, cell diameter of earlywood, and lumen diameter of earlywood were 5.02 μm, 53.50 μm, and 43.47 μm respectively.

Table 6: Correlation of fibre properties with water availability with a significance level of $p<0.05$

Wood property	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Ring width	.002	.147	1	89	**.703**	-.057	.611
Earlywood/latewood ratio	0	1	1	89	**.48**	-.019	-.740
Fibre length	.001	.086	1	89	**.770**	-.029	-.070
Fibre diameter (Earlywood)	.000	.004	1	89	**.948**	-.066	-.019
Fibre diameter (Latewood)	.008	.691	1	89	**.408**	.004	.108
Lumen diameter (Earlywood)	.001	.070	1	89	**.792**	-.013	-.041
Lumen diameter (Latewood)	.003	.237	1	89	**.628**	.000	.051
Cell wall thickness (Earlywood)	.005	.406	1	89	**.526**	.092	.129
Cell wall thickness (latewood)	.020	1.789	1	89	**.185**	-.007	-.142

4.4 Correlation of ring and fibre properties

In this chapter an attempt is made to correlate macroscopic ring properties with microscopic fibre properties, since ring properties are easily accessible via discs or cores and would provide excellent proxies to estimate fibre properties if tight correlations existed.

To correlate the ring width and Ew/Lw ratio with fibre properties, Pearson's and partial correlation coefficients were calculated (Table 7 and 8), at significance level of $P < 0.05$.

Based on Pearson's correlation coefficient significant positive correlations were found between ring width and Ew/Lw ratio, with a correlation coefficient of $r = 0.432$ ($p = 0.000$). A significant negative correlation was determined between ring width and fibre length with a correlation coefficient of $r = -0.173$ ($p = 0.044$) and between ring width and earlywood and latewood fibre diameter with a correlation coefficient of $r = -0.310$ ($p = 0.000$) and $r = -0.283$ ($p = 0.001$), respectively.
No correlation was found between ring width and lumen diameter of earlywood, however a positive correlation existed between ring width and the lumen diameter of latewood with a correlation coefficient of $r = 0.198$ ($p = 0.022$).

Between ring width and earlywood and latewood cell wall thickness a significant negative correlation was determined with correlation coefficients of $r = -0.352$ ($p = 0.000$) and $r = -0.419$ ($p = 0.000$), respectively.

Partial correlation analysis allowed for the use of age as a control variable (covariate) in order to eliminate its influence on the correlations of other variables.

Table 7: Pearson's correlation between ring and fibre properties. Significant correlations are highlighted

		ring width	E/L ratio	fibre length (earlywood)	fibre diameter (earlywood)	fibre diameter (latewood)	lumen diameter (earlywood)	lumen diameter (latewood)	cell wall thickness (earlywood)	cell wall thickness (latewood)
ring width	Pearson Correlation		**0.432**	**-0.173**	**-0.310**	**-0.283**	**-0.091**	**0.198**	**-0.352**	**-0.419**
	Sig. (2-tailed)		0.000	0.044	0.000	0.001	0.291	0.022	0.000	0.000
	N		136	136	135	135	135	135	135	135
E/L ratio	Pearson Correlation			**-0.219**	**-0.366**	**-0.298**	**-0.167**	**0.122**	**-0.421**	**-0.439**
	Sig. (2-tailed)			0.010	0.000	0.000	0.052	0.157	0.000	0.000
	N			136	135	135	135	135	135	135
fibre length (earlywood)	Pearson Correlation				**0.273**	**-0.051**	**0.186**	**-0.313**	**0.291**	**0.300**
	Sig. (2-tailed)				0.001	0.553	0.031	0.000	0.001	0.000
	N				135	135	135	135	135	135
fibre diameter (earlywood)	Pearson Correlation					**0.428**	**0.812**	**-0.132**	**0.307**	**0.586**
	Sig. (2-tailed)					0.000	0.000	0.127	0.000	0.000
	N					135	135	135	135	135
fibre diameter (latewood)	Pearson Correlation						**0.351**	**0.375**	**0.174**	**0.555**
	Sig. (2-tailed)						0.000	0.000	0.043	0.000
	N						135	135	135	135
lumen diameter (earlywood)	Pearson Correlation							**-0.002**	**-0.016**	**0.377**
	Sig. (2-tailed)							0.985	0.857	0.000
	N							135	135	135
lumen diameter (latewood)	Pearson Correlation								**-0.298**	**-0.403**
	Sig. (2-tailed)								0.000	0.000
	N								135	135
cell wall thickness (earlywood)	Pearson Correlation									**0.523**
	Sig. (2-tailed)									0.000
	N									135
cell wall thickness (latewood)	Pearson Correlation									
	Sig. (2-tailed)									
	N									

When a partial correlation was calculated with age as the control variable (Table 8), a negative correlation was found between ring width and E/L ratio, with a correlation coefficient of r = -0.183 (p = 0.034).
A significant negative correlation was found between Ew/Lw ratio and fibre length, with a correlation coefficient of r = -0.219 (p = 0.010) and between Ew/Lw ratio and earlywood and latewood fibre diameter with correlation coefficients of r = -0.366 (p = 0.000) and r = -0.298 (p = 0.000), respectively. No correlation existed between Ew/Lw ratio and lumen diameter of earlywood or latewood, whereas the Ew/Lw ratio and earlywood and latewood cell wall thickness were negatively correlated with correlation coefficients of r = -0.421 (p = 0.000) and r = -0.439 (p = 0.000), respectively.

No correlation was found between ring width and all the other fibre properties with age as a control variable.

A negative correlation was found between Ew/Lw ratio and cell wall thickness of earlywood with age as a control variable, with a correlation coefficient of r = -0.217 (p = 0.012). However, no correlation was found between the Ew/Lw ratio and all other fibre properties when age was used as a control variable.

This means that a positive correlation of ring width or Ew/Lw ratio with age creates ‘pseudo correlations’ with the other wood anatomical variables. This does not render ring properties useless as a proxy to predict anatomical features per se as long as it is kept in mind that the cambial age is the true correlation and ring width only the covariate. However, this limits the application of the obtained correlations to growth conditions and silvicultural regimes similar to the ones in our data.

Table 8: Partial correlation between ring and fibre properties. Significant correlations are highlighted.

Control Variables			ring width	E/L ratio	fibre length (earlywood)	fibre diameter (earlywood)	fibre diameter (latewood)	lumen diameter (earlywood)	lumen diameter (latewood)	cell wall thickness (earlywood)	cell wall thickness (latewood)
age	ring width	Correlation		**.183**	**-.086**	**.019**	**-.095**	**.030**	**.022**	**-.088**	**-.062**
		Significance (2-tailed)		.034	.322	.826	.276	.728	.799	.313	.478
		df		132	132	132	132	132	132	132	132
	E/L ratio	Correlation			**-.133**	**-.107**	**-.136**	**-.077**	**-.050**	**-.217**	**-.149**
		Significance (2-tailed)			.126	.220	.116	.375	.564	.012	.086
		df			132	132	132	132	132	132	132
	fibre length (earlywood)	Correlation				**.206**	**-.129**	**.155**	**-.273**	**.231**	**.235**
		Significance (2-tailed)				.017	.137	.073	.001	.007	.006
		df				132	132	132	132	132	132
	fibre diameter (earlywood)	Correlation					**.304**	**.856**	**.035**	**.066**	**.379**
		Significance (2-tailed)					.000	.000	.687	.445	.000
		df					132	132	132	132	132
	fibre diameter (latewood)	Correlation						**.309**	**.538**	**.006**	**.459**
		Significance (2-tailed)						.000	.000	.943	.000
		df						132	132	132	132
	lumen diameter (earlywood)	Correlation							**.059**	**-.125**	**.337**
		Significance (2-tailed)							.496	.149	.000
		df							132	132	132
	lumen diameter (latewood)	Correlation								**-.184**	**-.289**
		Significance (2-tailed)								.033	.001
		df								132	132
	cell wall thickness (earlywood)	Correlation									**.322**
		Significance (2-tailed)									.000
		df									132
	cell wall thickness (latewood)	Correlation									
		Significance (2-tailed)									
		df									

5. Conclusion and Outlook

The results presented in section 4.1 showed that on most sites the ring and fibre properties changed as expected with cambial age; this indicates that the age has a strong effect on the properties of young *P. radiata* trees and a reduction of rotation period as currently practiced in South African forestry will have an effect of the properties of the wood resource (Crickmay and Associates 2004). Based on the obtained results at mid-rotation, the effect of water availability on ring and fibre properties, however, seems to be insignificant, as no correlations between ETa/ETp and any of the ring or fibre properties could be found (section 4.3). This does not necessarily mean that water availability has no effect on wood quality of *P. radiata*, as the trees used in this experiment were rather young and contained a large portion of juvenile wood. Blair *et al*. (1976), Larson *et al*. (2001), Van Lear *et al*. (1973) indicated that the properties of juvenile wood are less predictable than of mature wood. Considering that the sampling for this project was done at the lower end of the log (dbh), the wood material considered in this study can be considered to be representative for the cambial age of the timber.

A modeling of the change in wood quality that could be expected with climate change from the data obtained in this project was, however, not possible.

A further objective of this project was the correlation of ring and fibre properties, to determine the feasibility of using ring properties as a descriptive proxy for wood and fibre quality. Without taking age effects into consideration, a significant negative correlation was found between ring width and Ew/Lw ratio and most fibre properties, except the lumen diameter of earlywood.
However, when age was used as control variable (covariate) in a partial correlation, a significant negative correlation was only found between ring width and Ew/Lw ratio. All other wood anatomical variables showed no significant correlation to ring width. This does not render tree ring width useless as a proxy to predict anatomical features per se, as long as it is kept in mind that the cambial age is the true correlation and ring width only the covariate.

The major limitations of this project were the young sample trees, which were with 15 years around half rotation age. Furthermore, the samples size was with six sites and only two trees per site rather limited. To obtain more significant information about the expected change in wood quality of *Pinus radiata,* further studies should be conducted with a larger sample size and on older trees to capture the full range of age and site related variability.

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Appendix A

Climate data of all sites

Table 9: Climate data of site D3 and D10

Year	MAP (mm)	T max (°C)	T min (°C)	MAT (°C)	Wind (m/s)
2002	961	20.16	12.63	16.39	2.9
2003	1105	20.29	12.92	16.6	3.2
2004	1107	20.79	13.06	16.92	2.8
2005	894	20.45	12.74	16.59	-
2006	1427	19.94	12.66	16.3	-
2007	1452	20.28	12.36	16.32	-
2008	950	19.96	12.34	16.15	-
2009	582	20.77	13.01	16.89	-
2010	892	21.36	11.65	16.5	-

Table 10: Climate data of site E18

Year	MAP (mm)	T max (°C)	T min (°C)	MAT (°C)	Wind (m/s)
2004	873	21.93	9.64	15.78	1.585
2005	1192	22.44	9.55	15.99	1.94
2006	1224	22.01	8.57	15.29	1.23
2007	1525	22.55	8.83	15.69	1.28
2008	1366	22.53	8.73	15.63	1.46
2009	950	22.72	9.3	16.01	1.87
2010	754	22.25	8.86	15.55	1.63

Appendix A (continued)

Table 11: Climate data of site F14 and G19

Year	MAP (mm)	T max (^oC)	T min (^oC)	MAT (^oC)	Wind (m/s)
2002	890	22.83	13.07	17.95	3.9
2003	1000	22.38	13.19	17.79	3.88
2004	1205	22.85	13.44	18.15	3.88
2005	657	21.13	12.83	16.98	4.5
2006	1111	20.73	12.93	16.83	3.6
2007	1132	20.81	13.25	17.03	3.8
2008	191	20.47	13.64	17.05	3.6
2009	144	21.04	13.79	17.41	3.7
2010	895	21.6	13.7	17.65	-

Table 12: Climate data of site G36

Year	MAP (mm)	T max (^oC)	T min (^oC)	MAT (^oC)	Wind (m/s)
1998	903.4	21.85	11.57	16.71	1.47
1999	851.2	22.93	12.57	17.75	1.55
2000	757	22.29	12.05	17.17	1.46
2001	1135	22.05	12.25	17.15	1.53
2002	1150	22	11.45	16.72	1.48
2003	708	22.17	11.73	16.95	1.5
2004	569	22.88	12.11	17.49	1.33
2005	938	22.06	11.87	16.96	1.52
2006	817	22.05	11.73	16.89	1.41
2007	1241	22.17	11.74	16.95	1.64
2008	1204	21.88	11.74	16.81	1.65
2009	1024	22.18	12.22	17.2	1.59
2010	864	22.23	12.04	17.13	-

Appendix B

Soil classification and information of all sites

Table 13: Soil characteristics of site D3

Site	D3
Plantation	Bluelilliesbush
Soil form	Longlands 1000
Estimated Soil Depth	80 cm
Soil Profile Wilting point (Vol %)	2.7
Soil profile Field Capacity (vol %)	13.6

Sample	Depth (cm)	Clay (%)	Silt (%)	Total Sand (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Classification	% Coarse fragments
D3d/1	0 - 10cm	1.8	6.4	91.8	86.4	4.8	0.6	Sa	0
D3d/2	10 - 30cm	0.8	16.4	82.8	73.72	7.6	1.48	LmSa	0
D3d/3	30 - 45cm	3.2	18	78.8	70.6	7	1.2	LmSa	0
D3d/4	60 - 70cm	13.2	12	74.8	37.18	14.02	23.6	SaLm	0.9456

Table 14: Soil characteristics of site D10

Site	D10
Plantation	Bluelilliesbush
Soil form	Cartref 1200
Estimated Soil Depth	50 cm
Soil Profile Wilting point (Vol %)	2.0
Soil profile Field Capacity (vol %)	10.0

Sample	Depth (cm)	Clay (%)	Silt (%)	Total Sand (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Classification	% Coarse fragments
D10/1	0 - 10cm	3.40	2.40	94.20	76.12	13.28	4.80	Sa	0.00
D10/2	10 - 20cm	3.00	8.00	89.00	65.40	20.20	3.40	Sa	18.45
D10/3	20 - 50cm	3.00	9.00	88.00	60.92	21.60	5.48	Sa	6.54

Table 15: Soil characteristics of site E18

Site	E18
Plantation	Grabouw
Soil form	Cartref 1200
Estimated Soil Depth	200 cm
Soil Profile Wilting point (Vol %)	3.15
Soil Profile Field Capacity (Vol %)	8.6

Sample	Depth (cm)	Clay (%)	Silt (%)	Total Sand (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Classification	% Coarse fragments
E 18/1	0 - 10cm	2.4	0.4	97.2	55.18	23.8	18.22	Sa	0.00
E 18/2	10 - 20cm	2.2	2.2	95.6	36.2	30	29.4	Sa	0.00
E 18/3	20 - 30cm	2.2	0.2	67.6	38.16	3	26.44	Sa	0.00
E 18/4	30 - 70cm	2	2	96	22.6	23.6	49.8	Sa	17.18
E 18/5	70 - 80cm	2.2	2.2	125.6	50.96	16.64	58	Sa	39.53
E 18/6	80 - 100cm	2	1	97	30.2	16.6	50.2	Sa	50.77
E 18/7	100 - 110cm	2	1	97	32.14	21.66	43.2	Sa	47.06
E 18/8	110 - 120cm	4	8	88	52.16	28.8	7.04	LmSa	16.74
E 18/9	120 - 130cm	8	8	84	55.4	24	4.6	LmSa	8.89
E 18/10	130 - 140cm	8	8	84	49.54	31.4	3.06	LmSa	5.05
E 18/11	140 - 170cm	10	8	82	51.34	26.46	4.2	LmSa	2.64
E 18/12	170 - 180cm	10	8	82	32.12	23.08	26.8	LmSa	3.32
E 18/13	180 - 190cm	12	6	82	50.6	27.4	4	LmSa	3.93
E 18/14	190 - 200cm	8	8	84	57.2	22	4.8	LmSa	3.03

Table 16: Soil characteristics of site F14

Site	F14
Plantation	Kruisfontein
Soil form	Kroonstad 2000
Estimated Soil Depth	180 cm
Soil Profile Wilting point (Vol %)	3.4
Soil profile Field Capacity (vol %)	16.7

Sample	Depth (cm)	Clay (%)	Silt (%)	Total Sand (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Classification	% Coarse fragments
F14c/1	0 - 10cm	1	14	85	76.28	8.28	0.44	LmSa	0.1
F14c/2	10 - 50cm	5	9	86	76.32	9.48	0.2	LmSa	0.0
F14c/3	50 - 70cm	7	10.4	82.6	74	8.4	0.2	LmSa	0.1
F14c/4	70 - 80cm	10	7.4	82.6	72.8	9.6	0.2	LmSa	0.0
F14c/5	80 - 100cm	9	10	81	73.2	7.6	0.2	LmSa	0.2
F14c/6	100 - 140cm	19.2	7.8	73	65.4	7.4	0.2	SaLm	0.2
F14c/7	140 - 180cm	21	8	71	58.72	11.4	0.88	SaKlLm	0.4

Table 17: Soil characteristics of site G19

Site	G19
Plantation	Kruisfontein
Soil form	Sepane 2210
Estimated Soil Depth	190 cm
Soil Profile Wilting point (Vol %)	1
Soil profile Field Capacity (vol %)	5.05

Sample	Depth (cm)	Clay (%)	Silt (%)	Total Sand (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Classification	% Coarse fragments
G19d/1	0 - 10cm	5.00	11.00	84.00	70.96	10.40	2.64	LmSa	0.00
G19d/2	10 - 50cm	7.00	12.00	81.00	65.40	12.00	3.60	LmSa	0.00
G19d/3	50 - 70cm	10.00	12.00	78.00	64.60	11.20	2.20	SaLm	0.00
G19d/4	70 - 90cm	19.00	8.00	73.00	60.80	10.00	2.20	SaLm	0.17
G19d/5	90 - 110cm	21.00	6.00	73.00	63.36	8.00	1.64	SaKlLm	0.37
G19d/6	110 - 130cm	27.00	7.00	66.00	63.40	2.40	0.20	SaKlLm	0.56
G19d/7	130 - 150cm	25.00	12.00	63.00	62.20	0.60	0.20	SaKlLm	0.00
G19d/8	150 - 170cm	17.00	10.00	73.00	63.34	9.00	0.66	SaLm	0.00
G19d/9	170 - 190cm	3.20	24.80	72.00	67.20	4.20	0.60	LmSa	0.00

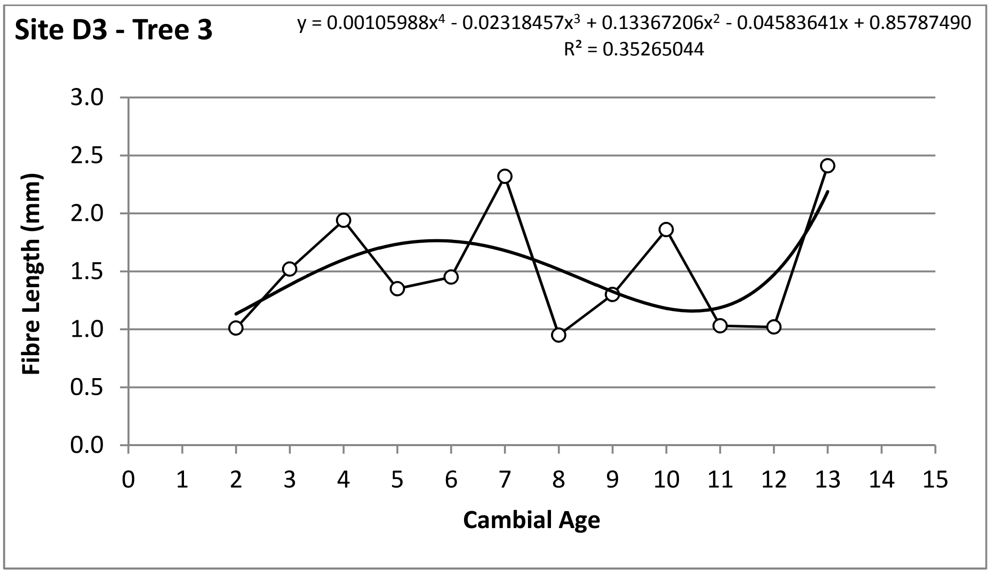
Table 18: Soil characteristics of site G36

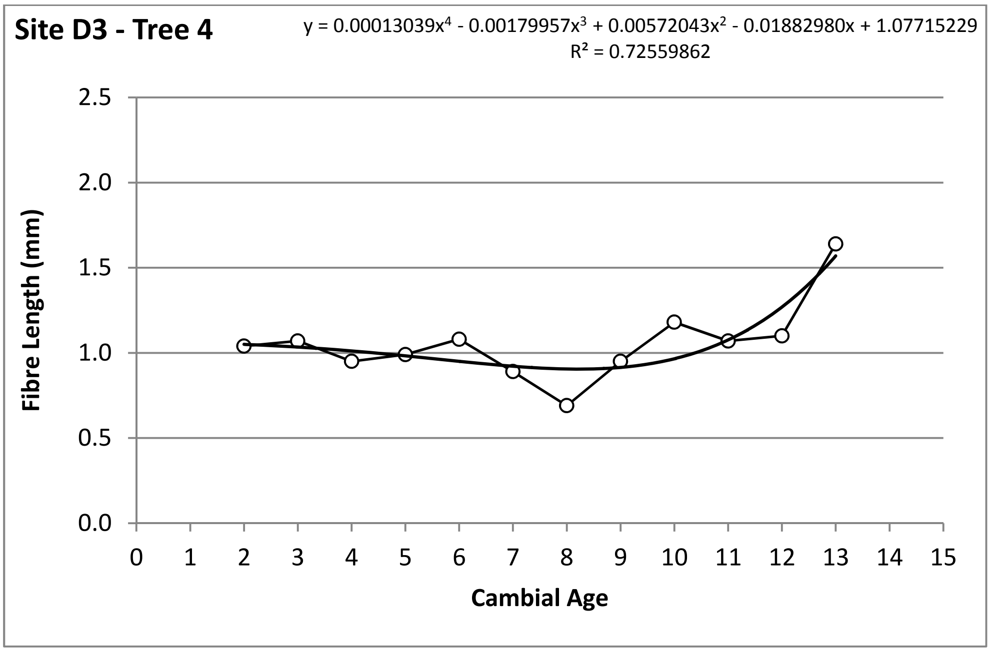
Site	G36
Plantation	Grabouw
Soil form	Bainsvlei 1100
Estimated Soil Depth	45cm
Soil Profile Wilting point (Vol %)	8.4
Soil profile Field Capacity (vol %)	24.8

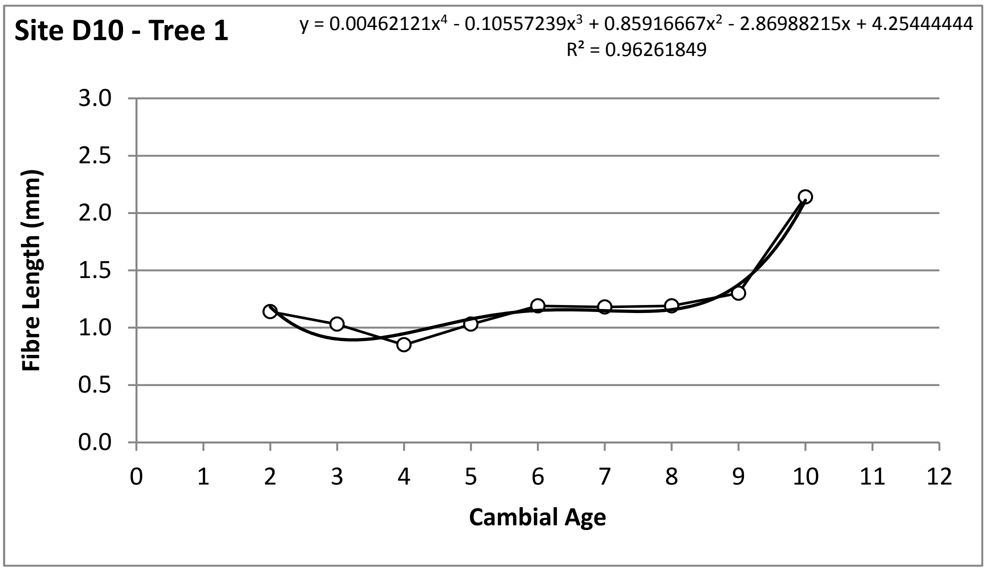
Sample	Depth (cm)	Clay (%)	Silt (%)	Total Sand (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Classification	% Coarse fragments
G 36/1	0-10cm	8	26	66	61.94	1.46	2.6	LmSa	5.394605
G 36/2	10- 20cm	18	26	56	47.56	4.44	4	SaLm	2.638191
G 36/3	20 - 40cm	24	28	48	42.6	0.8	4.6	SaKlLm	40.6071

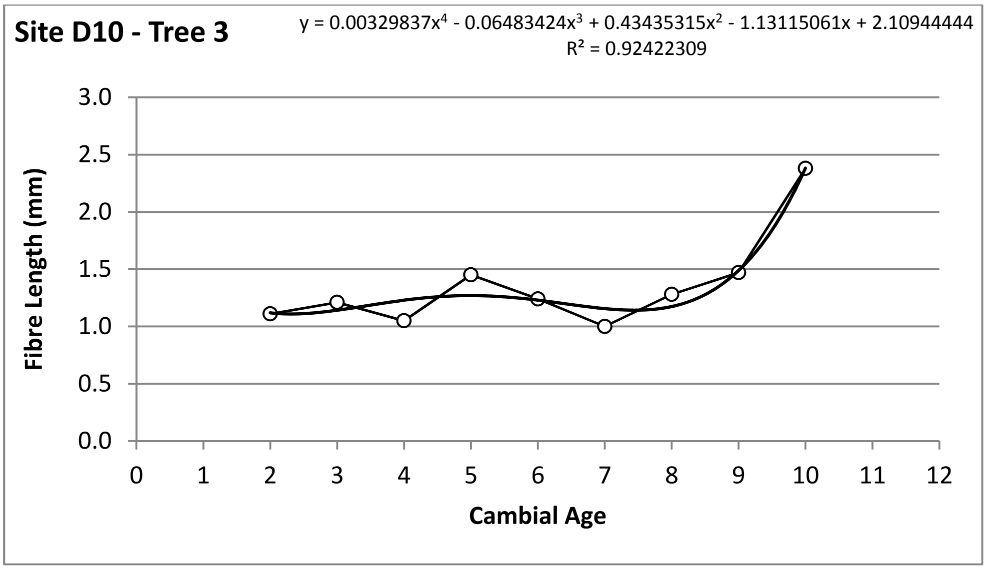
Appendix C

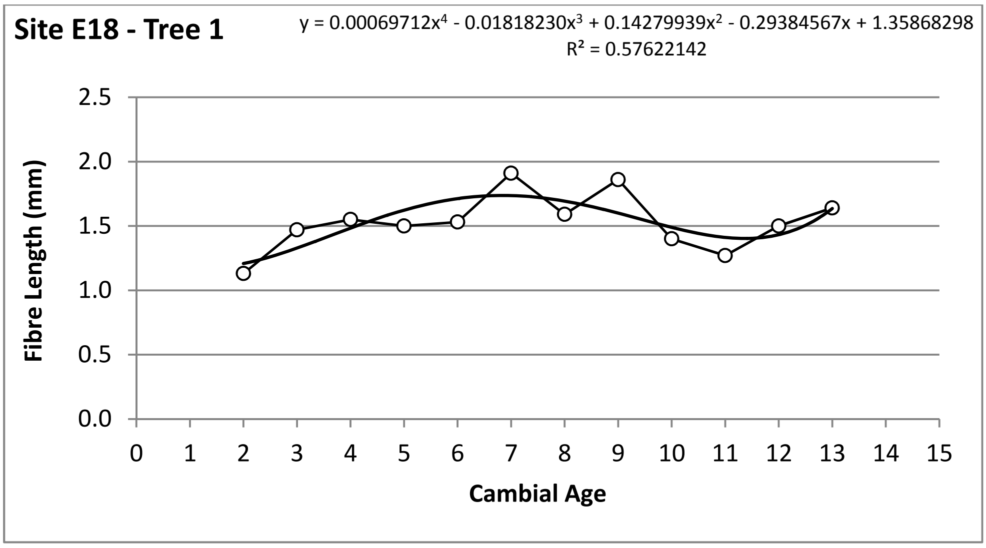
Detrending functions for ring and fibre properties

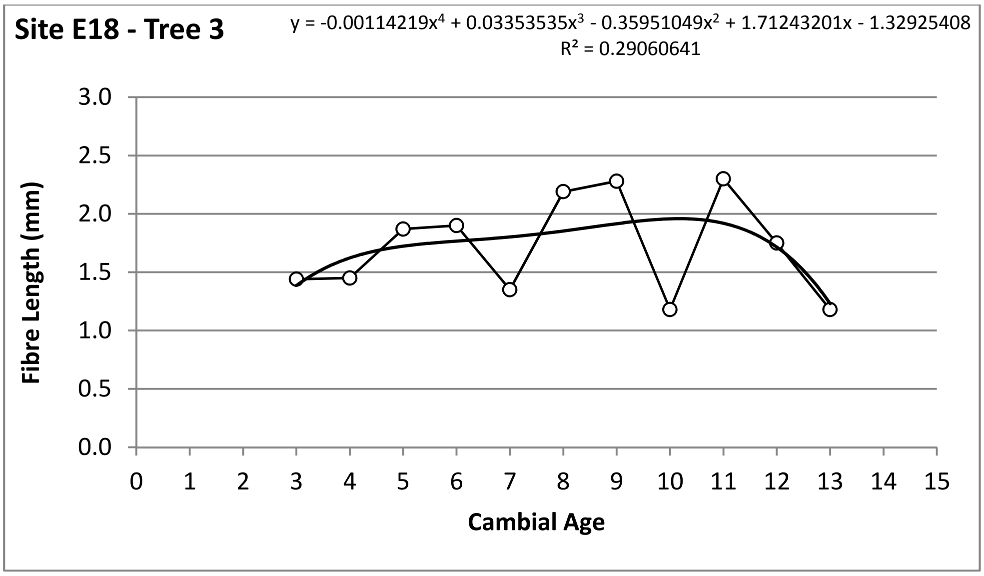


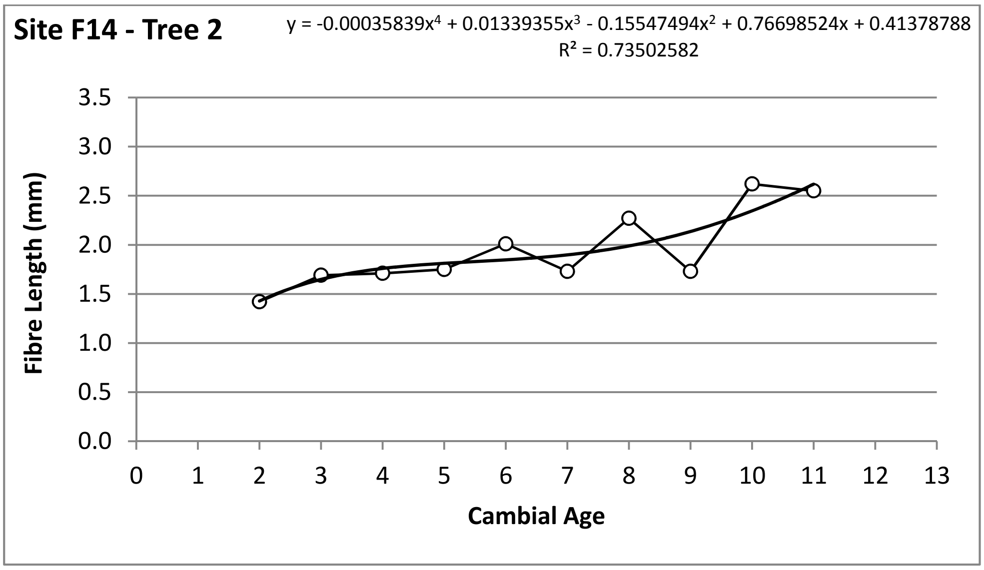


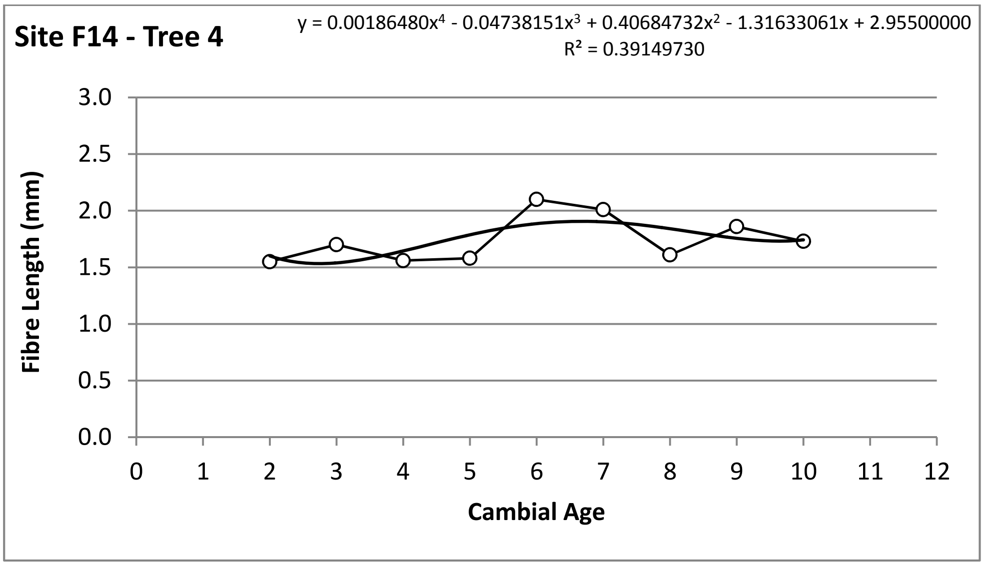

Site D10 - Tree 1
y = 0.00462121x⁴ - 0.10557239x³ + 0.85916667x² - 2.86988215x + 4.25444444
R² = 0.96261849
Fibre Length (mm)
Cambial Age

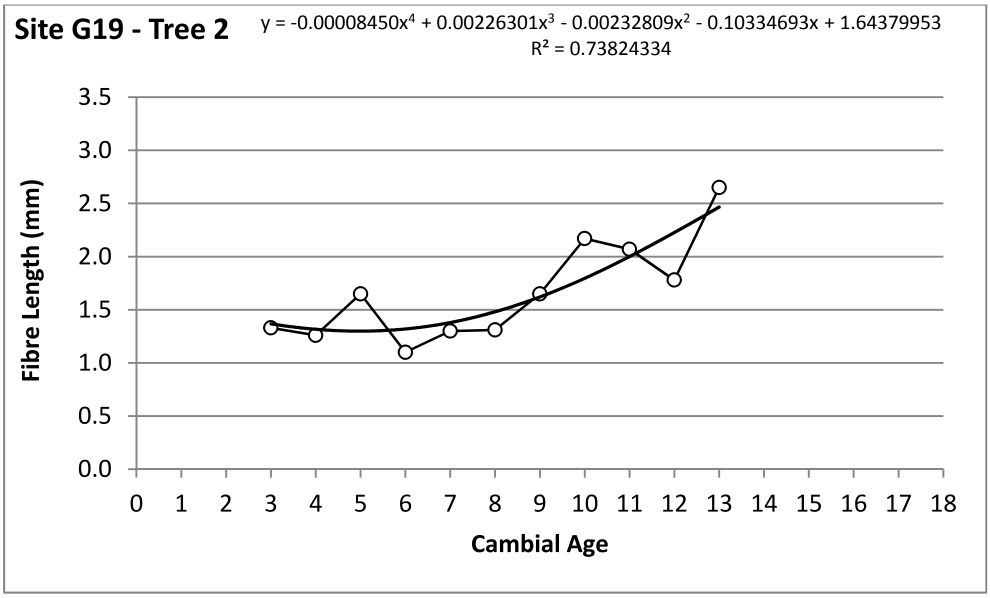

Site D10 - Tree 3
y = 0.00329837x⁴ - 0.06483424x³ + 0.43435315x² - 1.13115061x + 2.10944444
R² = 0.92422309
Fibre Length (mm)
Cambial Age


Site E18 - Tree 1
y = 0.00069712x⁴ - 0.01818230x³ + 0.14279939x² - 0.29384567x + 1.35868298
R² = 0.57622142
Fibre Length (mm)
Cambial Age

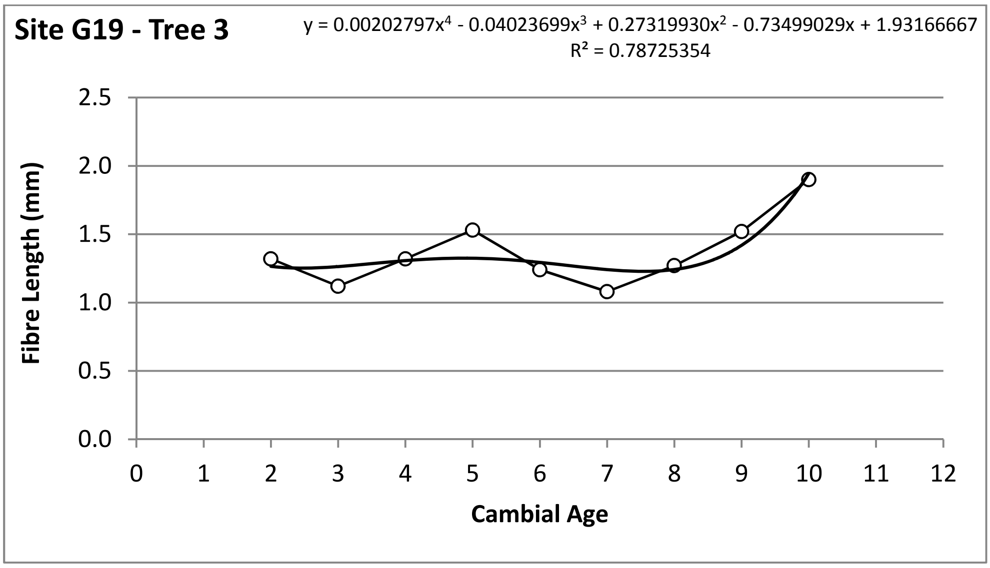

Site E18 - Tree 3
y = -0.00114219x⁴ + 0.03353535x³ - 0.35951049x² + 1.71243201x - 1.32925408
R² = 0.29060641
Fibre Length (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age


Site F14 - Tree 2
y = -0.00035839x⁴ + 0.01339355x³ - 0.15547494x² + 0.76698524x + 0.41378788
R² = 0.73502582
Fibre Length (mm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Cambial Age

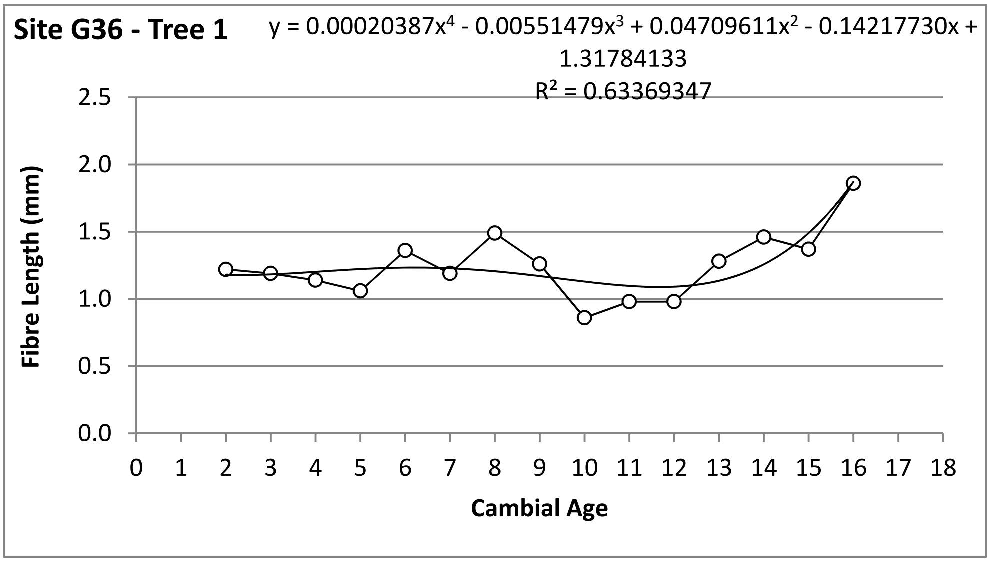

Site F14 - Tree 4
y = 0.00186480x⁴ - 0.04738151x³ + 0.40684732x² - 1.31633061x + 2.95500000
R² = 0.39149730
Fibre Length (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age



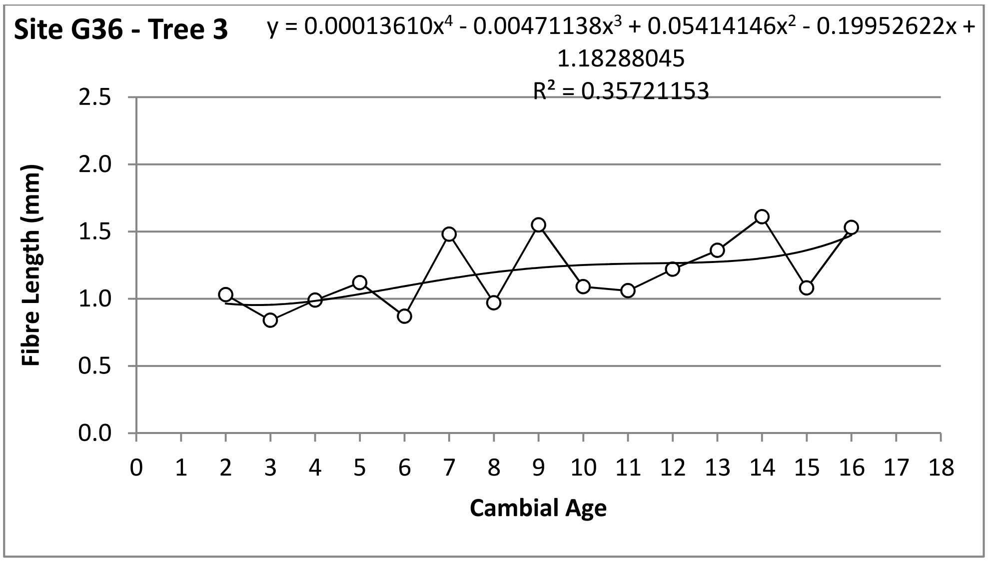
Site G19 - Tree 2
y = -0.00008450x⁴ + 0.00226301x³ - 0.00232809x² - 0.10334693x + 1.64379953
R² = 0.73824334
Fibre Length (mm)
Cambial Age

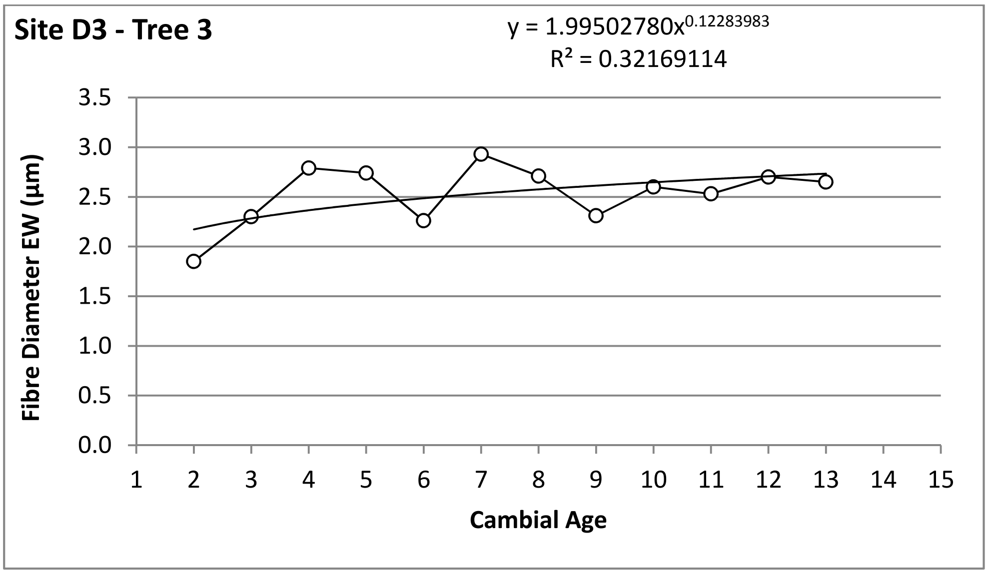


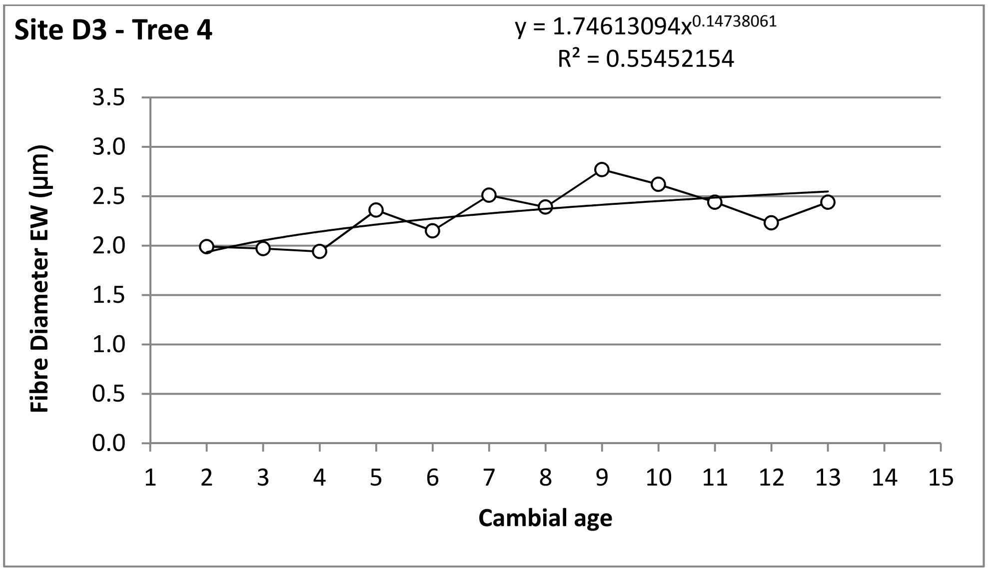
Site G19 - Tree 3
y = 0.00202797x⁴ - 0.04023699x³ + 0.27319930x² - 0.73499029x + 1.93166667
R² = 0.78725354
Fibre Length (mm)
Cambial Age

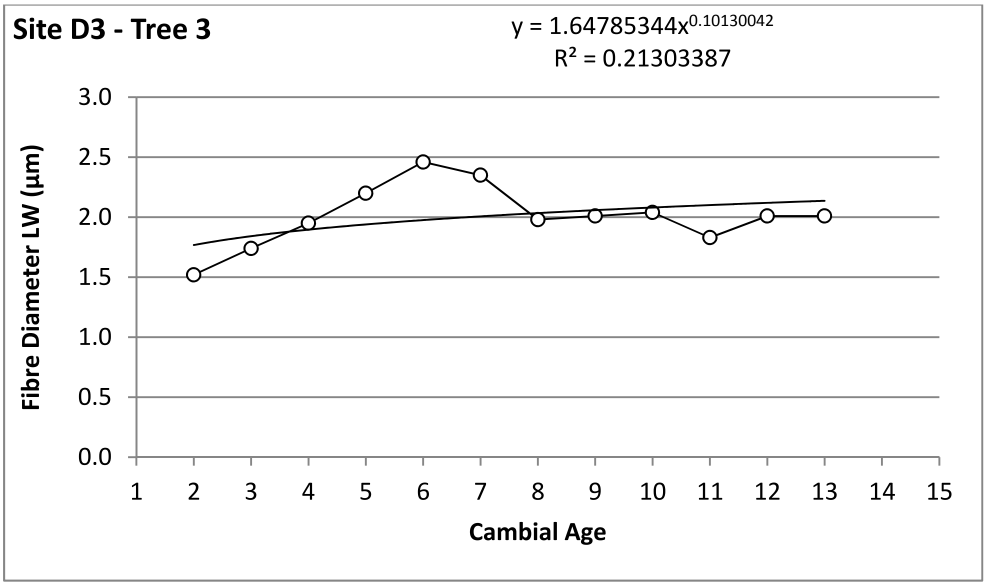


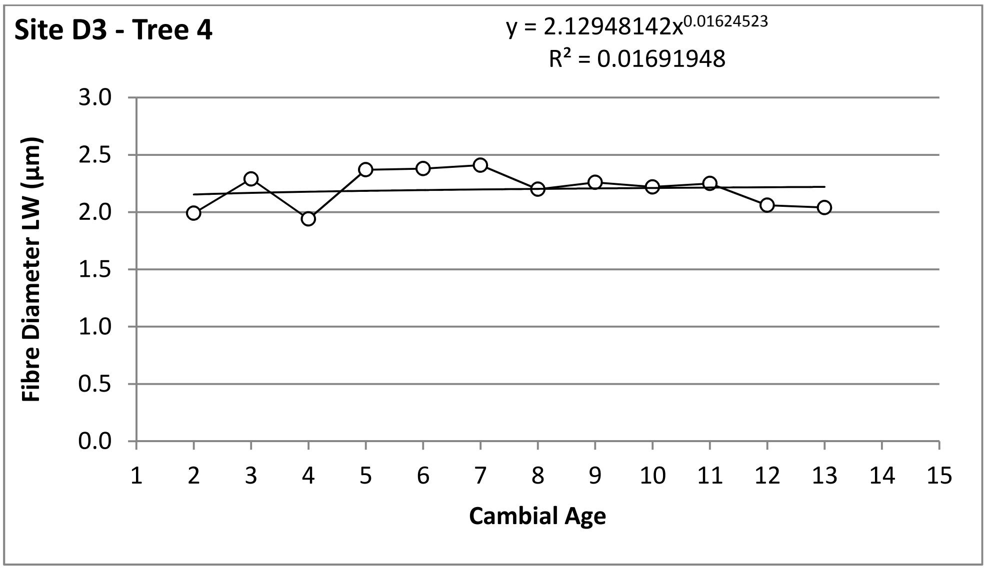
Site G36 - Tree 1
y = 0.00020387x⁴ - 0.00551479x³ + 0.04709611x² - 0.14217730x + 1.31784133
R² = 0.63369347
Fibre Length (mm)
Cambial Age

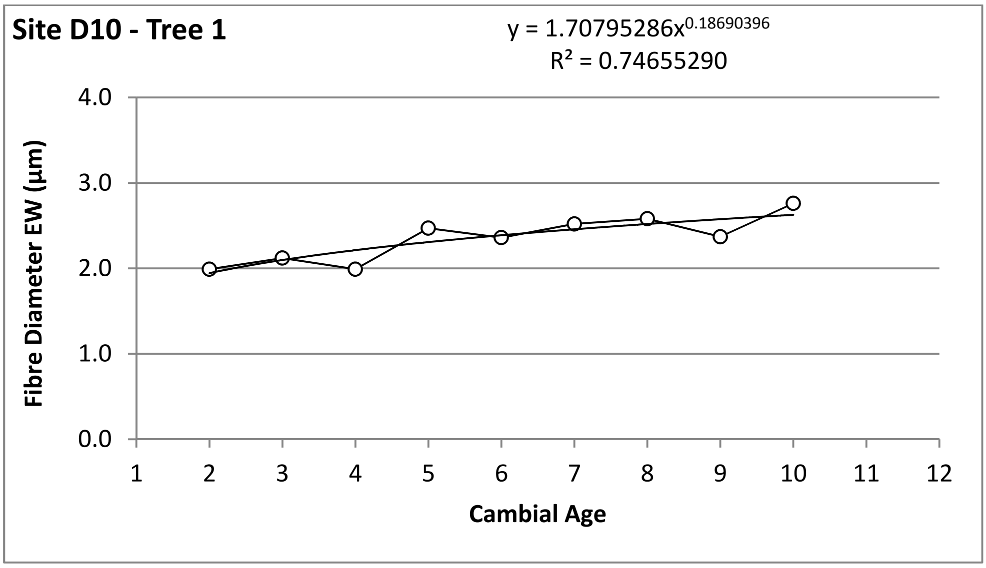

Site G36 - Tree 3
y = 0.00013610x⁴ - 0.00471138x³ + 0.05414146x² - 0.19952622x + 1.18288045
R² = 0.35721153
Fibre Length (mm)
2.5
2.0
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

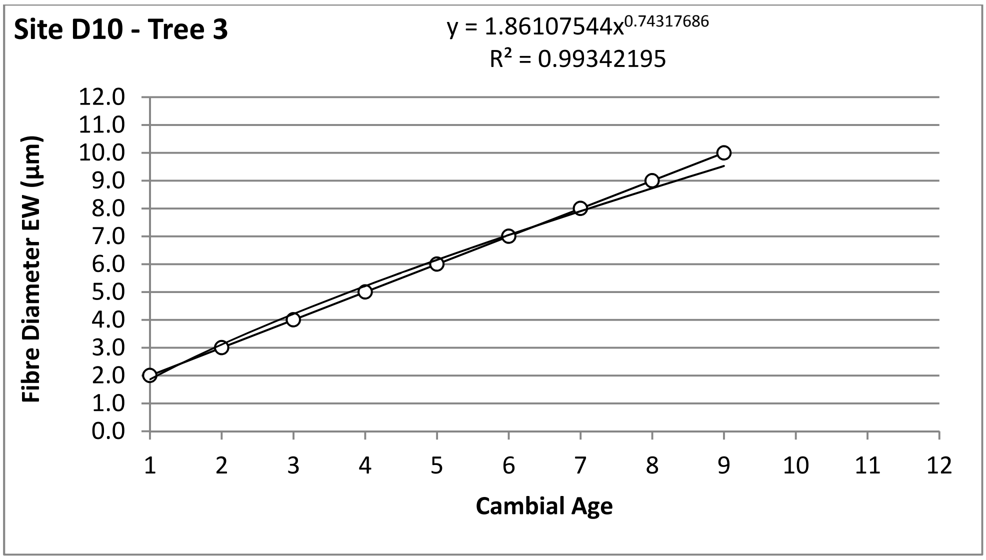

Site D3 - Tree 3
y = 1.99502780x^0.12283983
R² = 0.32169114
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

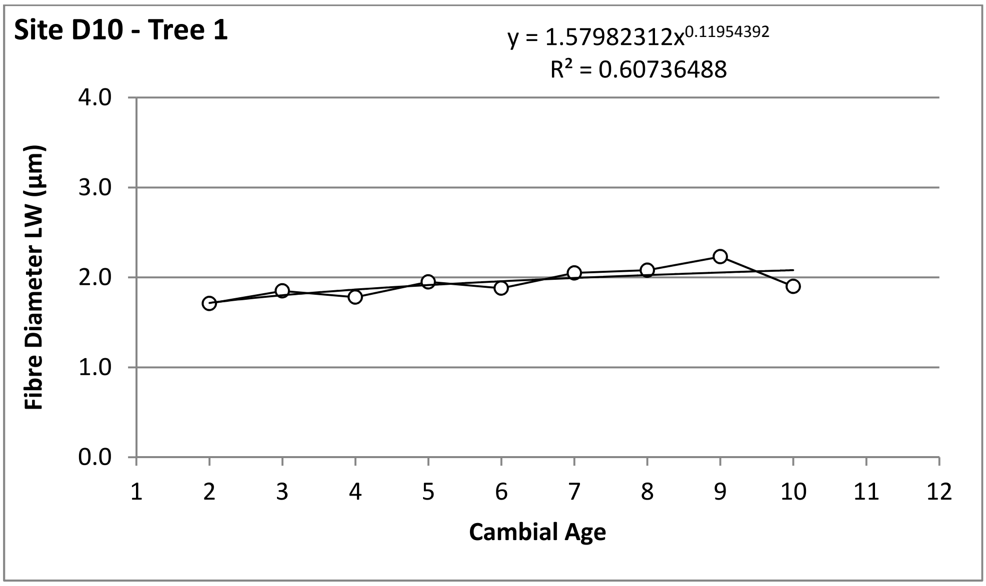

Site D3 - Tree 4
y = 1.74613094x^0.14738061
R² = 0.55452154
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial age

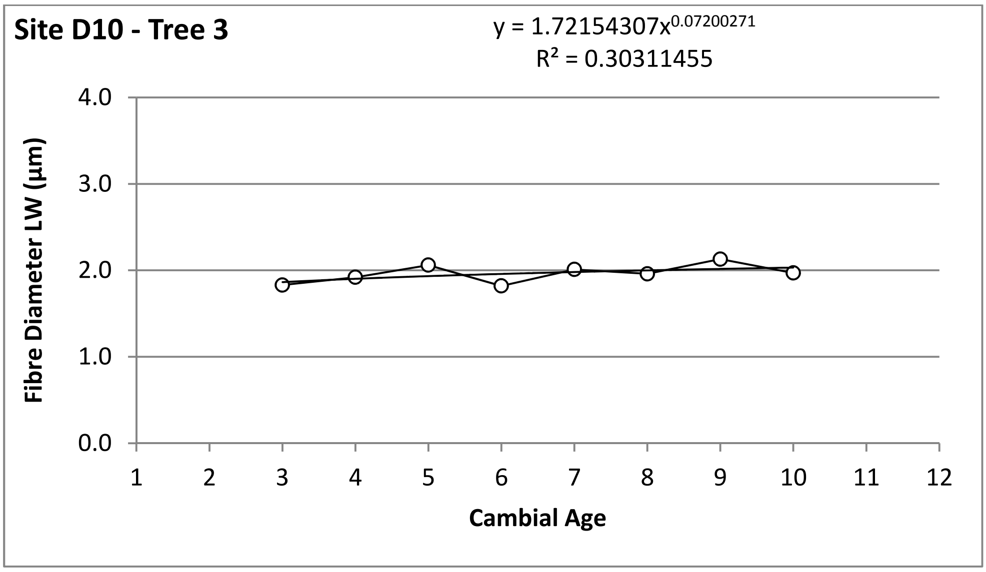

Site D3 - Tree 3
y = 1.64785344x^0.10130042
R² = 0.21303387
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

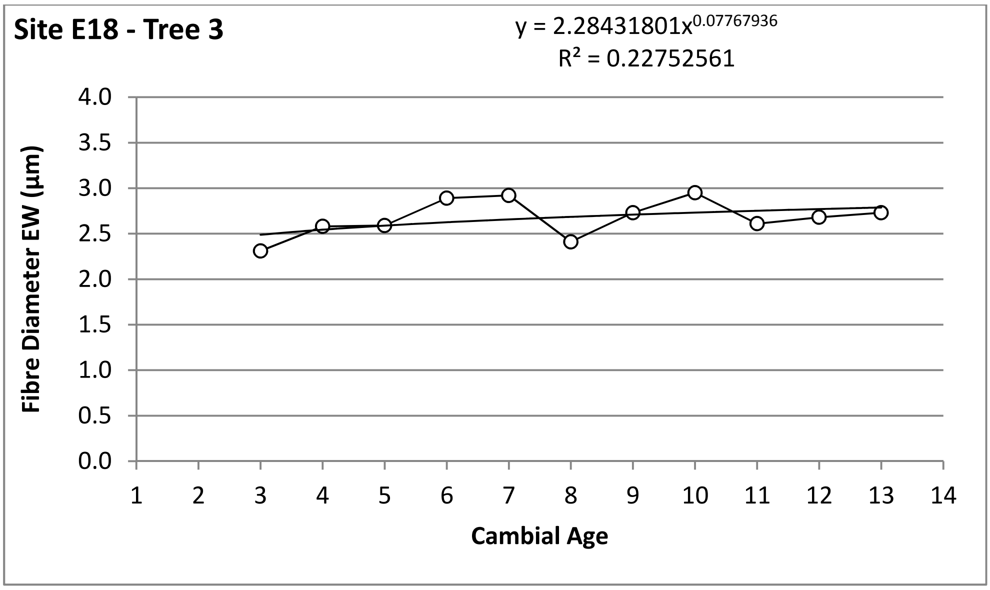

Site D3 - Tree 4
y = 2.12948142x^0.01624523
R² = 0.01691948
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

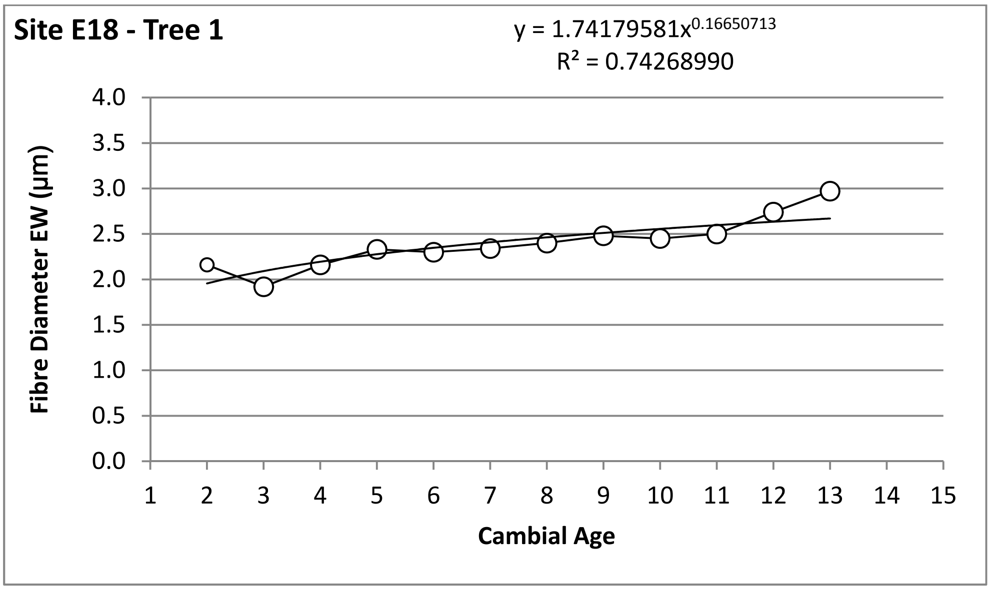

Site D10 - Tree 1
y = 1.70795286x^0.18690396
R² = 0.74655290
Fibre Diameter EW (µm)
4.0
3.0
2.0
1.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

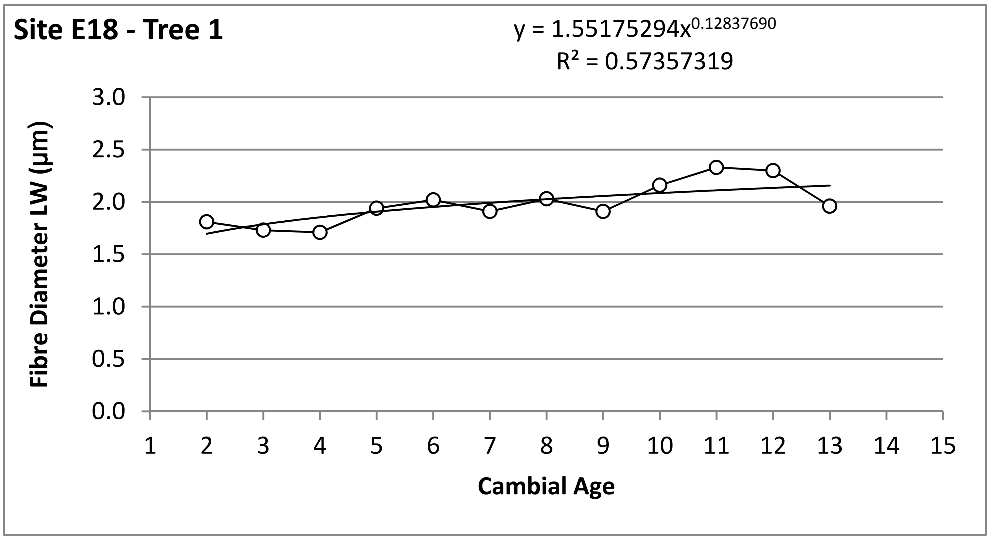

Site D10 - Tree 3
y = 1.86107544x^0.74317686
R² = 0.99342195
Fibre Diameter EW (µm)
Cambial Age

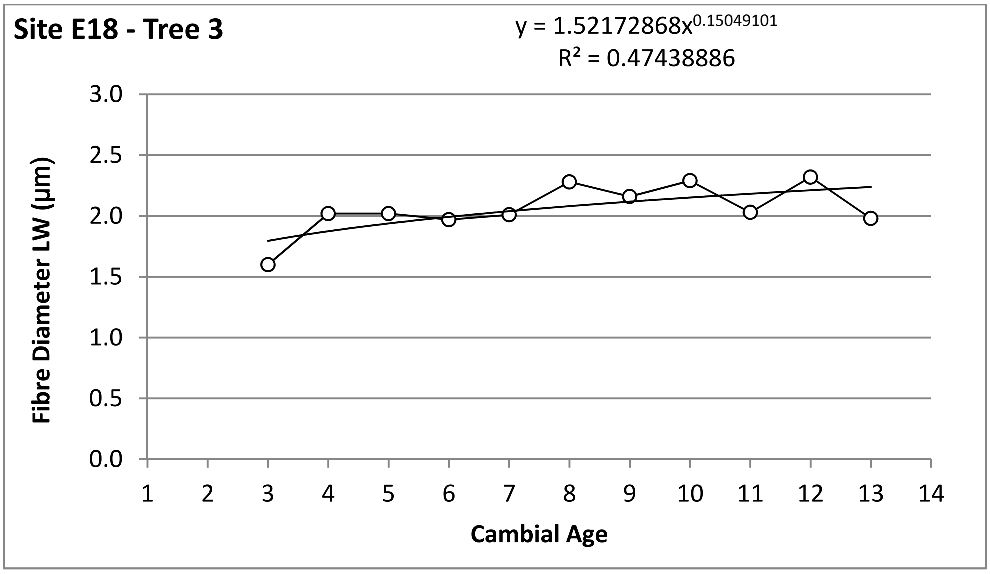

Site D10 - Tree 1
y = 1.57982312x^0.11954392
R² = 0.60736488
Fibre Diameter LW (µm)
Cambial Age


Site D10 - Tree 3
y = 1.72154307x^0.07200271
R² = 0.30311455
Fibre Diameter LW (µm)
Cambial Age


Site E18 - Tree 3
y = 2.28431801x^0.07767936
R² = 0.22752561
Fibre Diameter EW (µm)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Cambial Age


Site E18 - Tree 1
y = 1.74179581x^0.16650713
R² = 0.74268990
Fibre Diameter EW (µm)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age


Site E18 - Tree 1
y = 1.55175294x^0.12837690
R² = 0.57357319
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age


Site E18 - Tree 3
y = 1.52172868x^0.15049101
R² = 0.47438886
Fibre Diameter LW (µm)
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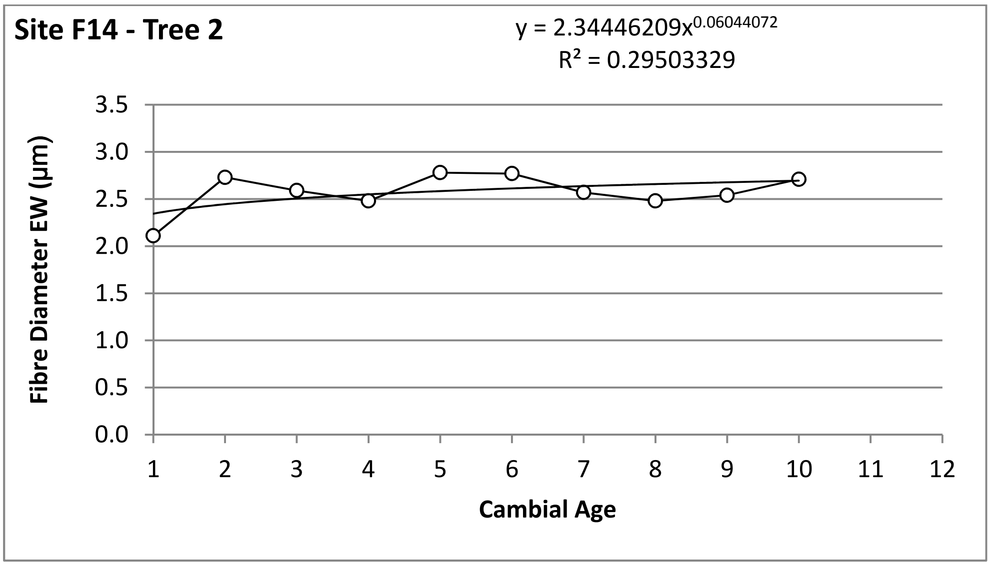
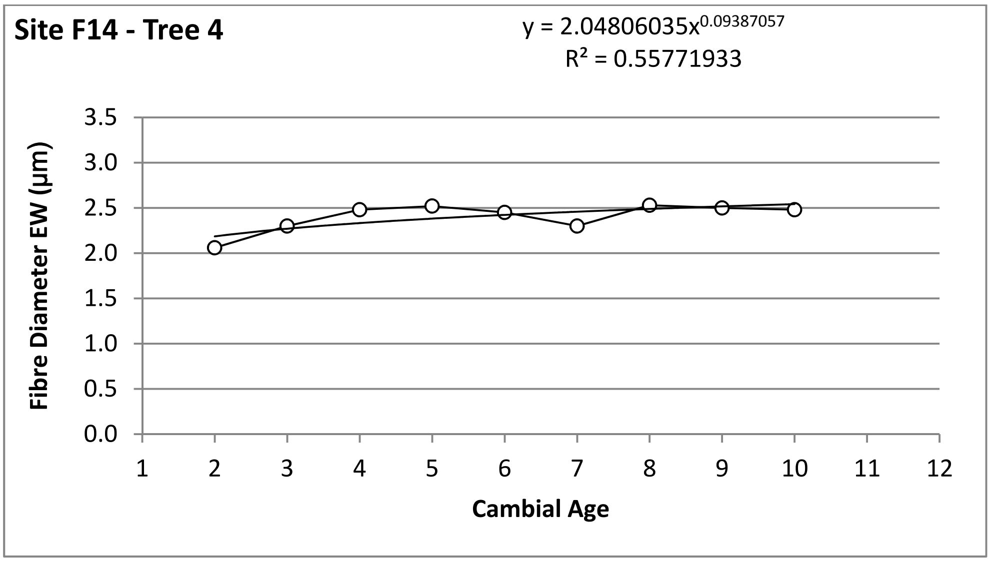
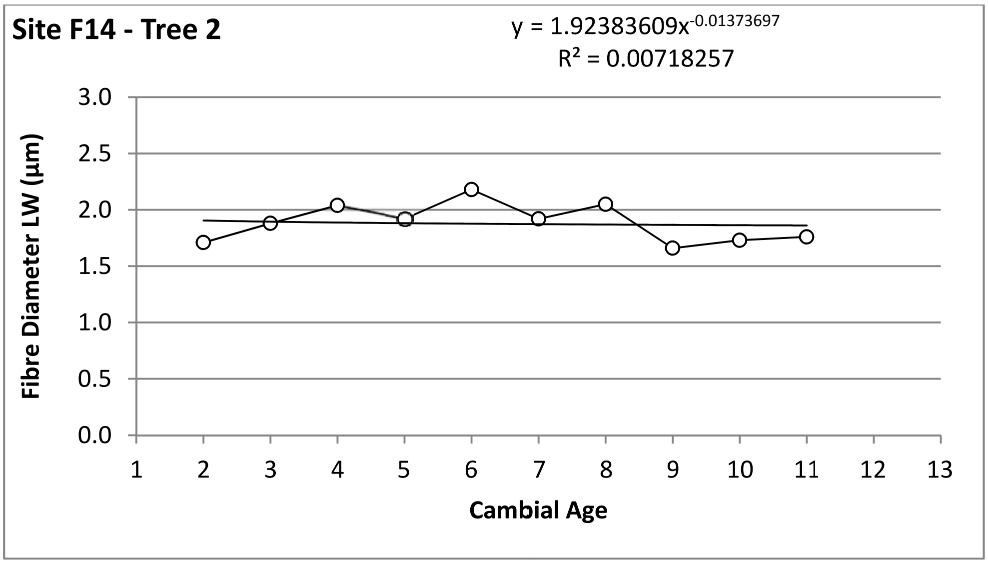
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Cambial Age


Site F14 - Tree 2
y = 2.34446209x^0.06044072
R² = 0.29503329
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age


Site F14 - Tree 4
y = 2.04806035x^0.09387057
R² = 0.55771933
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age


Site F14 - Tree 2
y = 1.92383609x-0.01373697
R² = 0.00718257
Fibre Diameter LW (µm)
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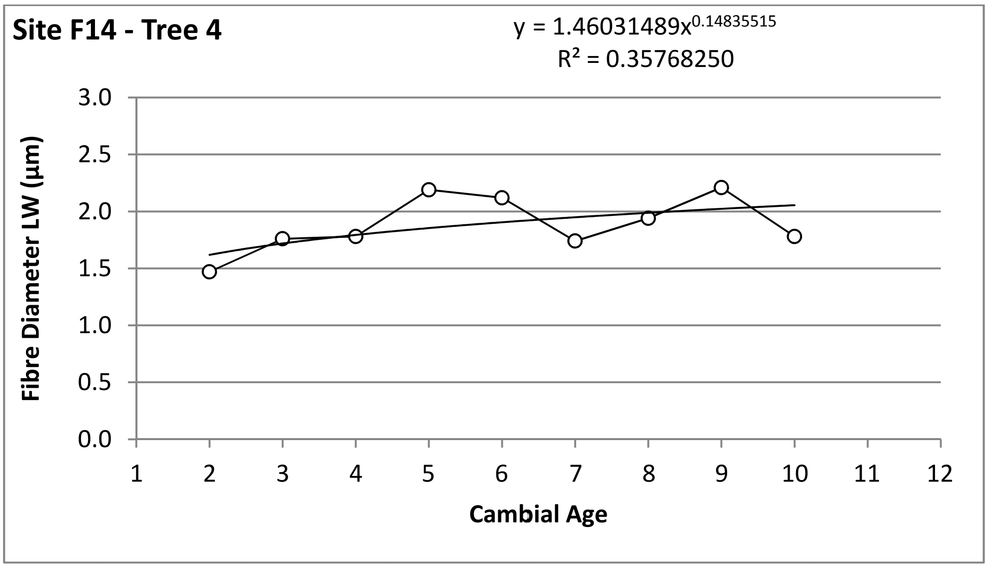
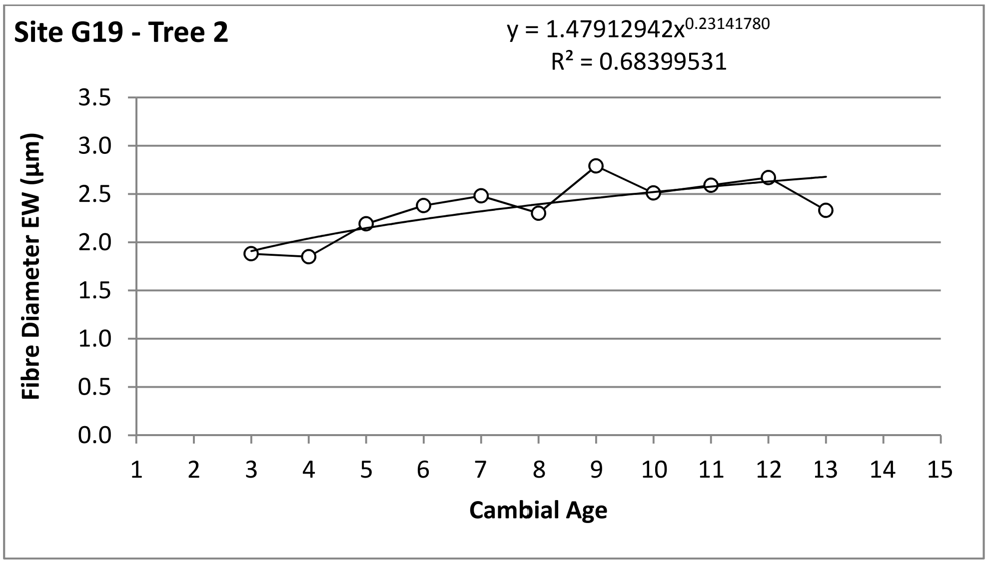
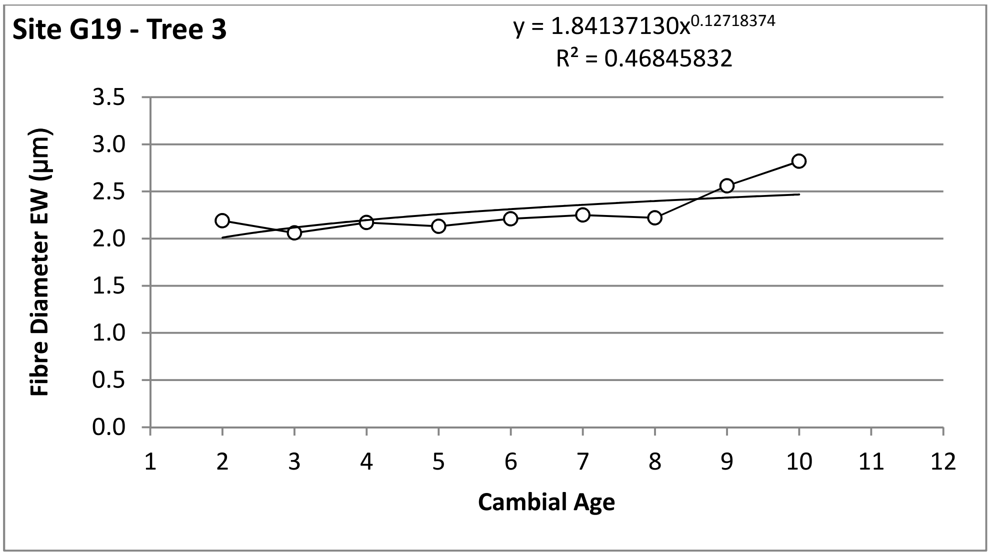
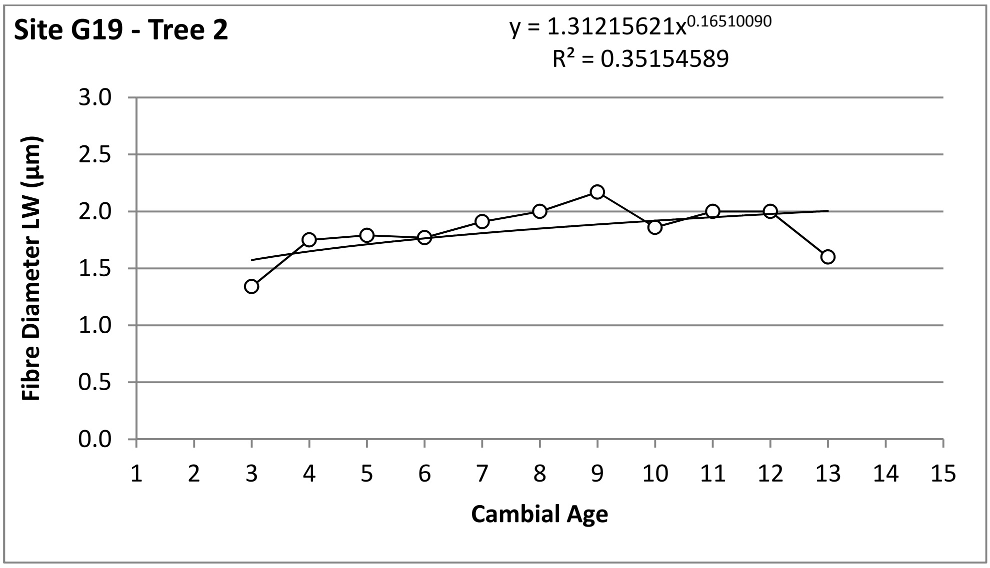
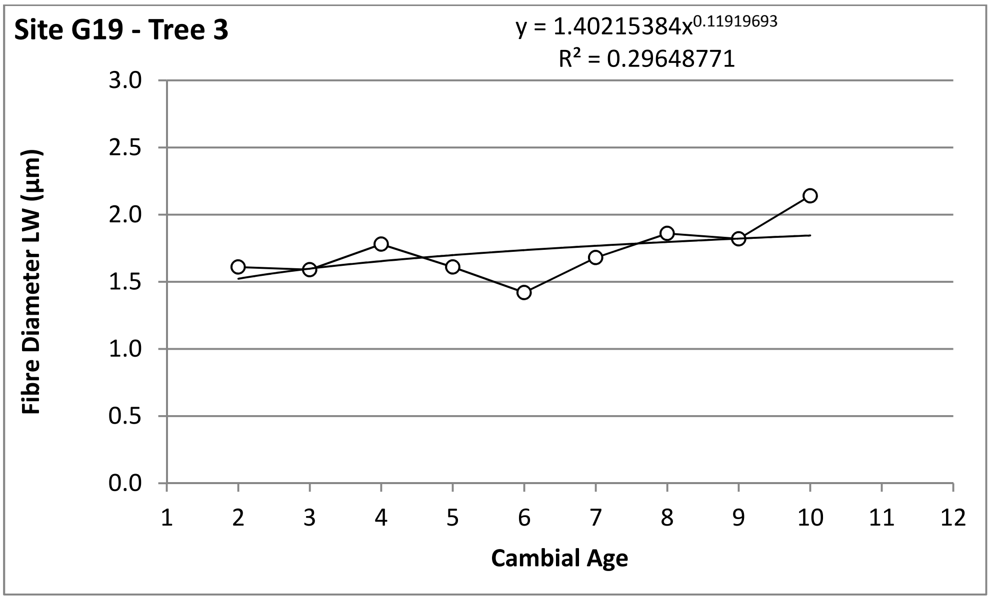
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Cambial Age

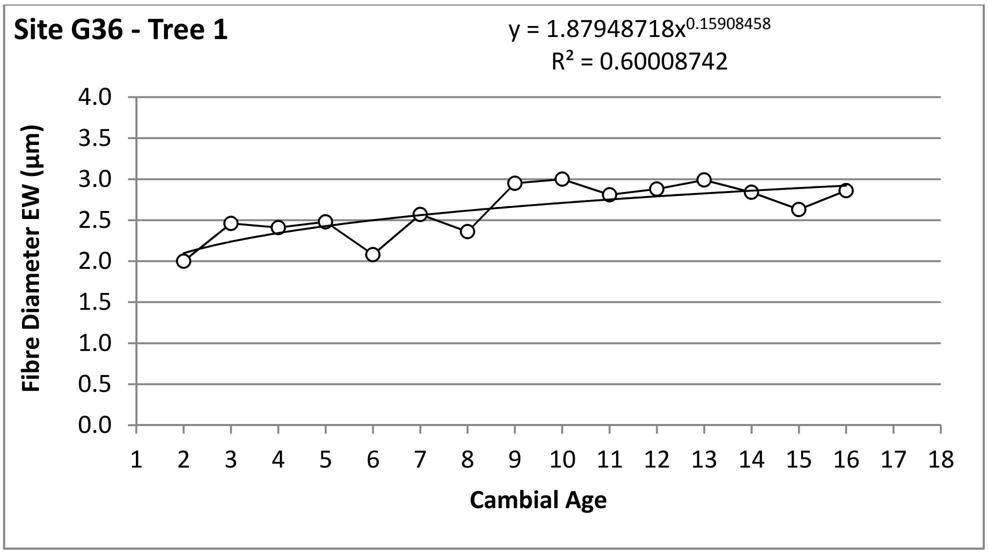

Site F14 - Tree 4
y = 1.46031489x0.14835515
R² = 0.35768250
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

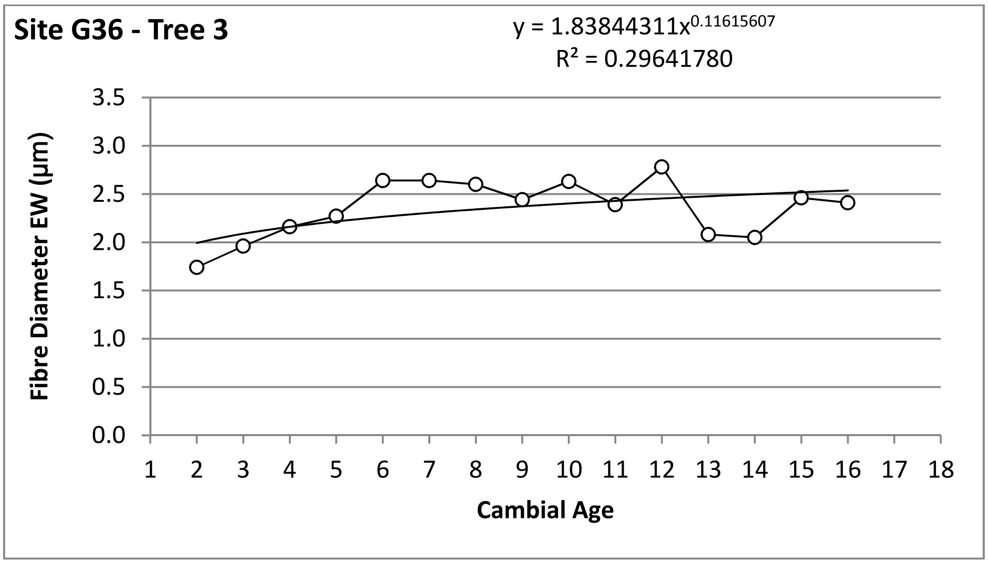

Site G19 - Tree 2
y = 1.47912942x0.23141780
R² = 0.68399531
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

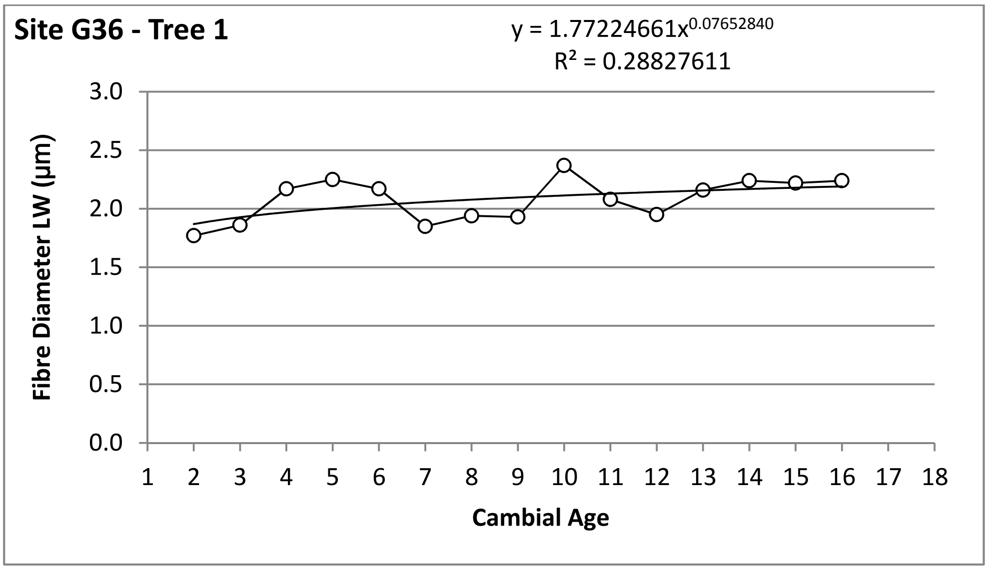

Site G19 - Tree 3
y = 1.84137130x^0.12718374
R² = 0.46845832
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

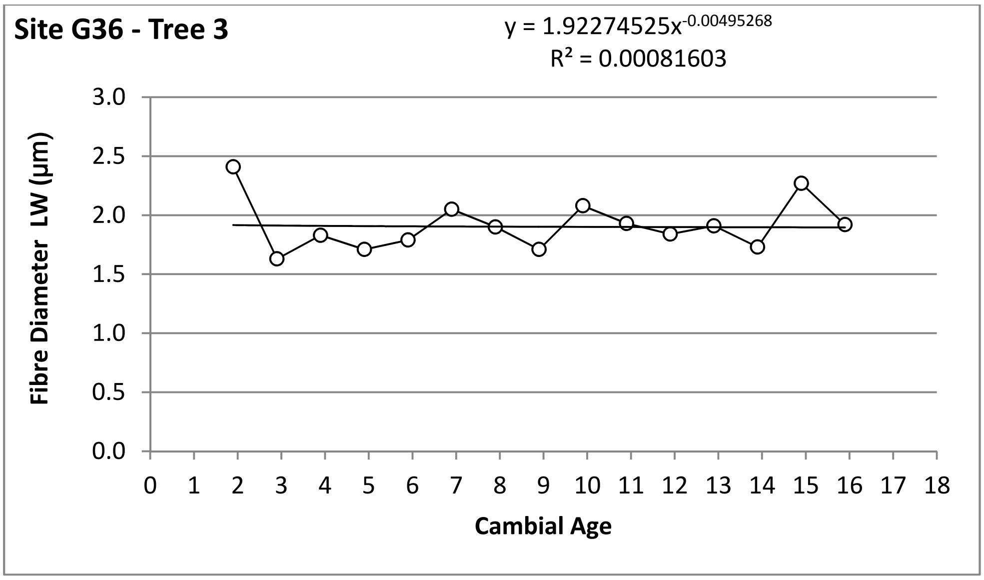

Site G19 - Tree 2
y = 1.31215621x^0.16510090
R² = 0.35154589
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

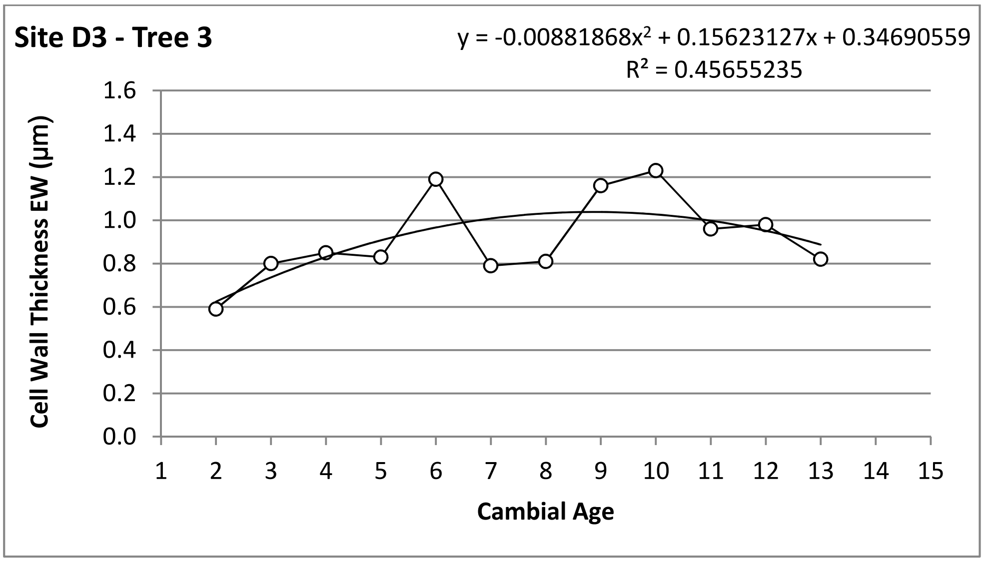

Site G19 - Tree 3
y = 1.40215384x^0.11919693
R² = 0.29648771
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

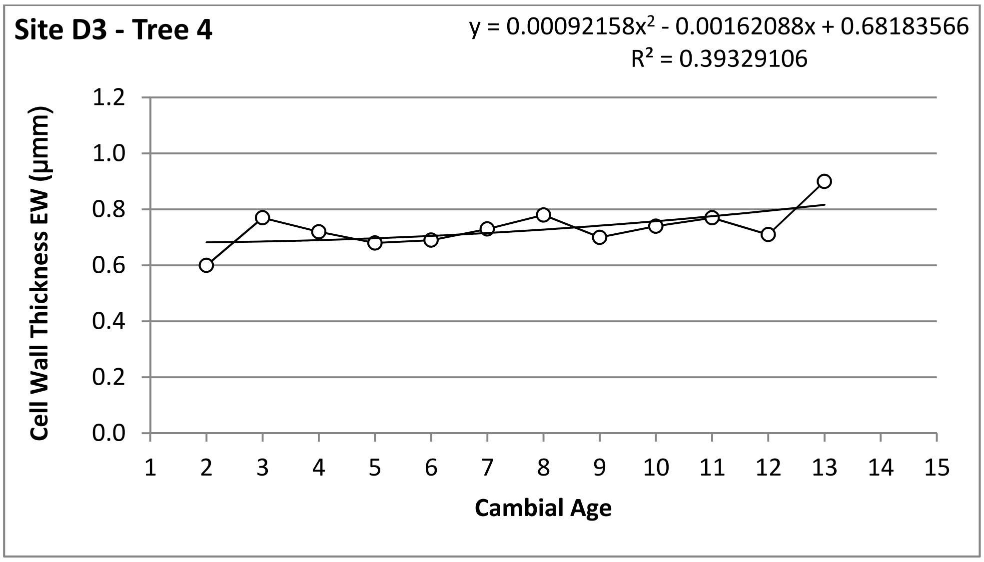

Site G36 - Tree 1
y = 1.87948718x^0.15908458
R² = 0.60008742
Fibre Diameter EW (µm)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

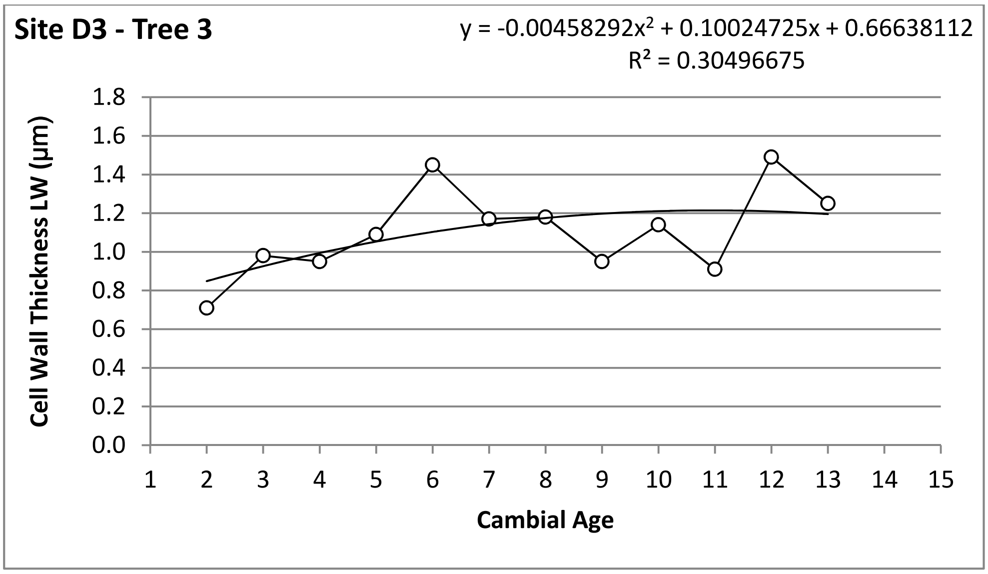

Site G36 - Tree 3
y = 1.83844311x^0.11615607
R² = 0.29641780
Fibre Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

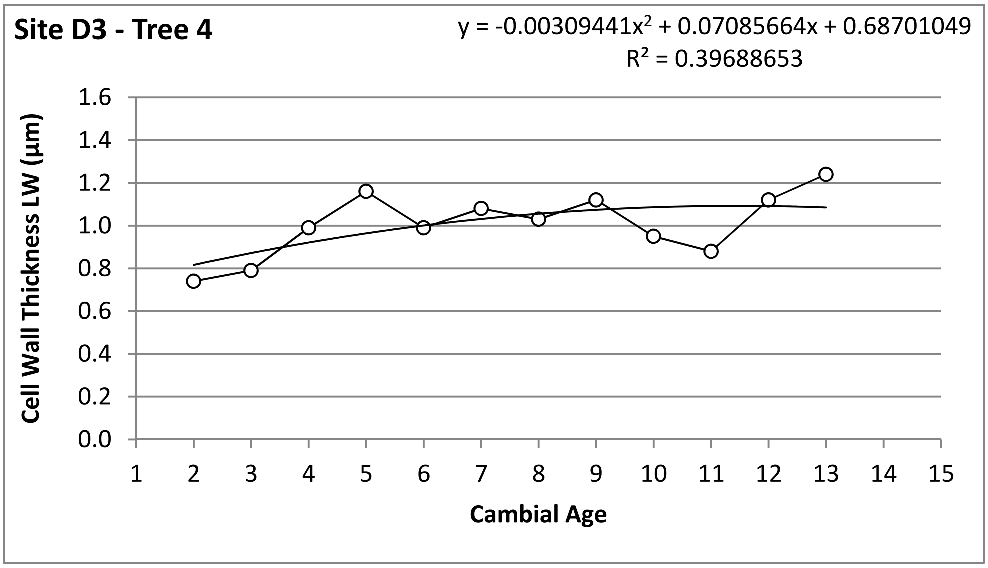

Site G36 - Tree 1
y = 1.77224661x^0.07652840
R² = 0.28827611
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

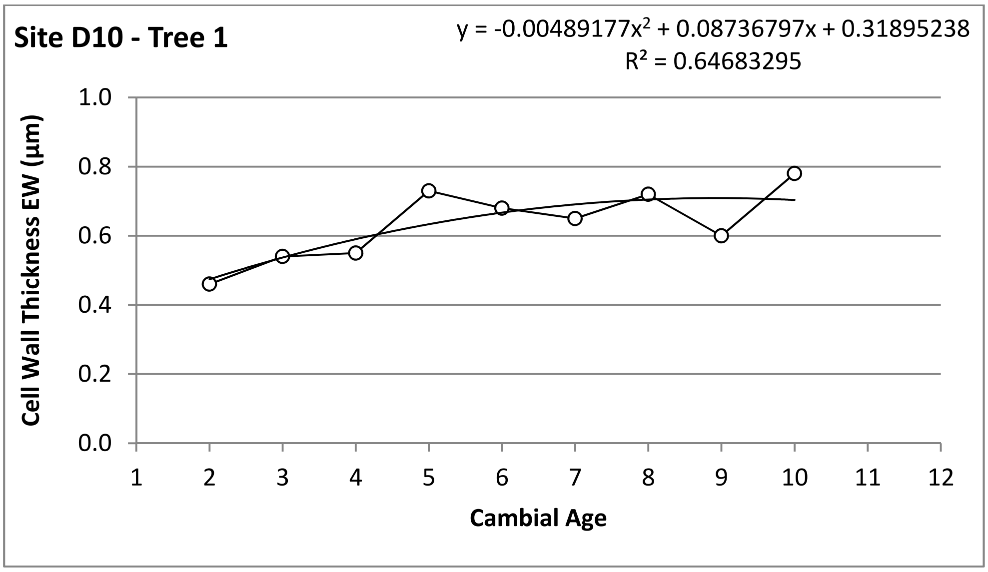

Site G36 - Tree 3
y = 1.92274525x^-0.00495268
R² = 0.00081603
Fibre Diameter LW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

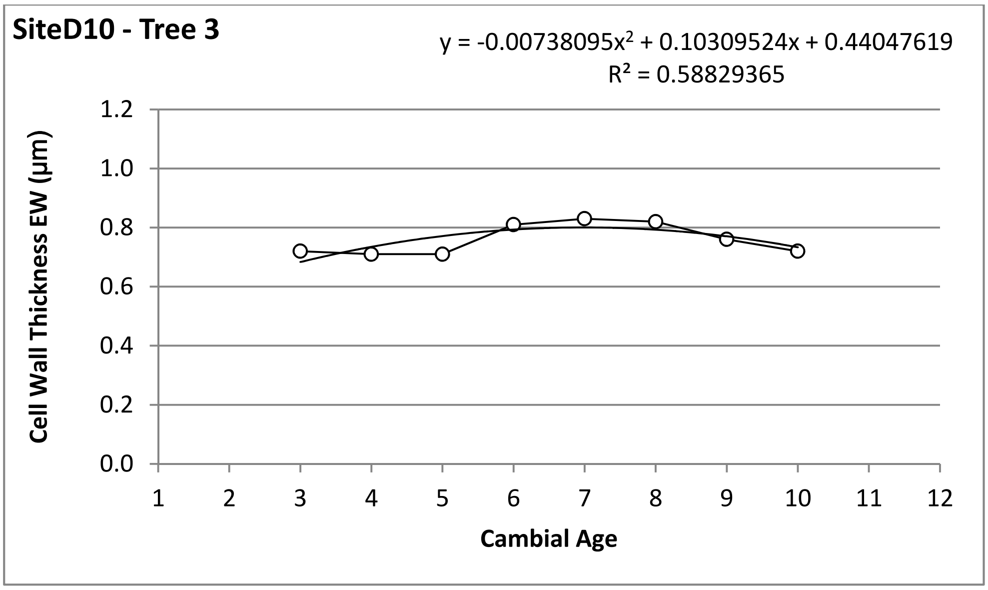

Site D3 - Tree 3
y = -0.00881868x² + 0.15623127x + 0.34690559
R² = 0.45655235
Cell Wall Thickness EW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

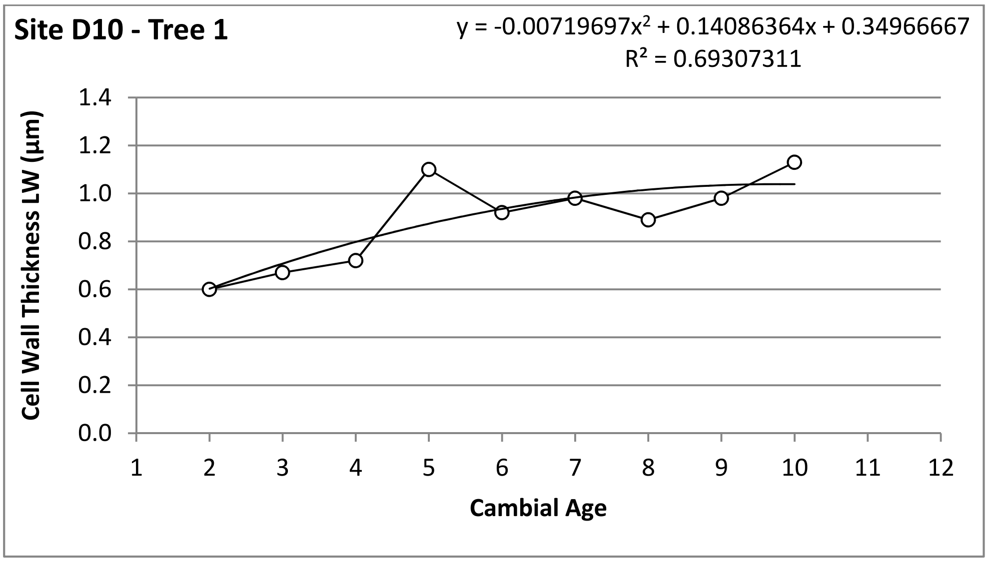

Site D3 - Tree 4
y = 0.00092158x² - 0.00162088x + 0.68183566
R² = 0.39329106
Cell Wall Thickness EW (µmm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

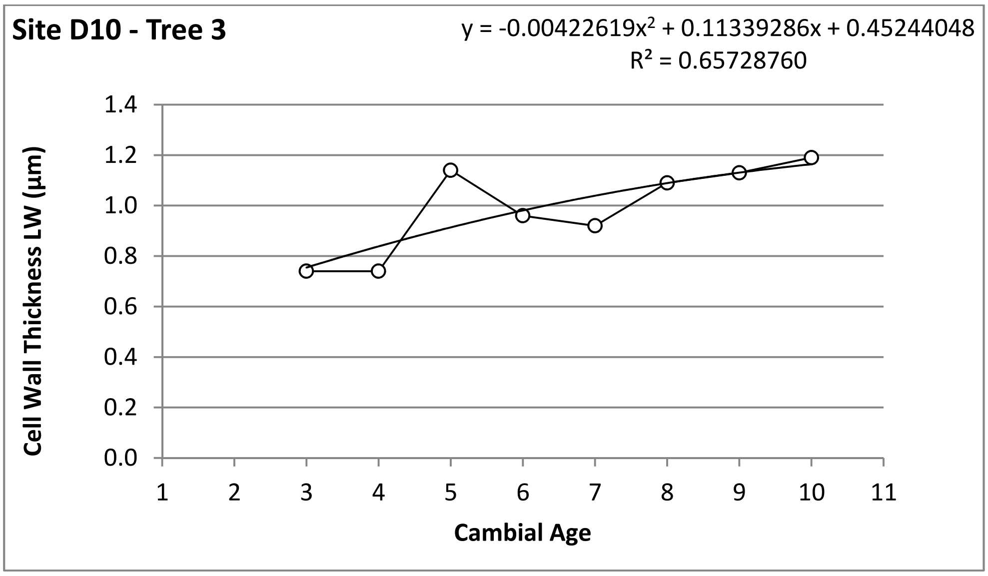

Site D3 - Tree 3
y = -0.00458292x² + 0.10024725x + 0.66638112
R² = 0.30496675
Cell Wall Thickness LW (µm)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

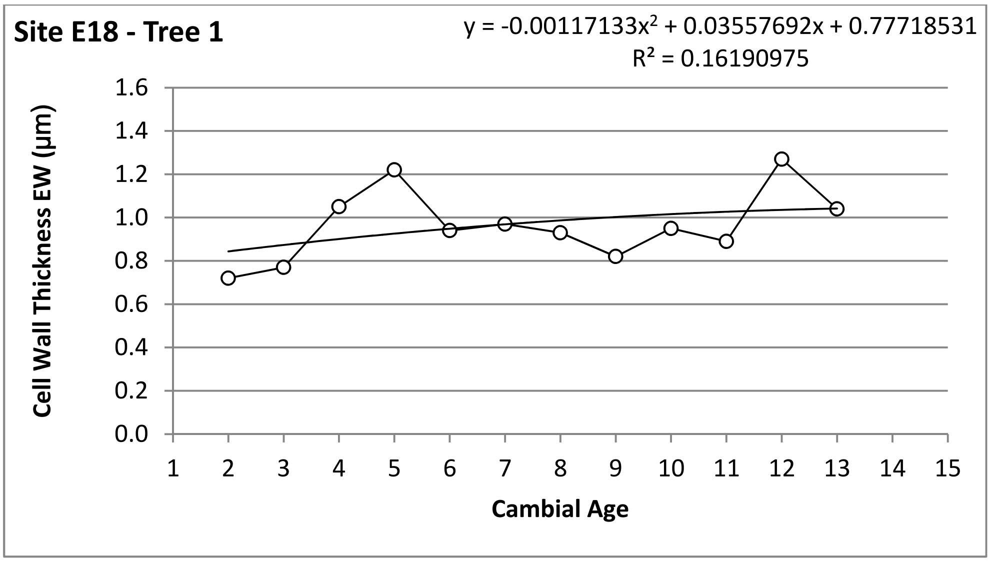

Site D3 - Tree 4
y = -0.00309441x² + 0.07085664x + 0.68701049
R² = 0.39688653
Cell Wall Thickness LW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

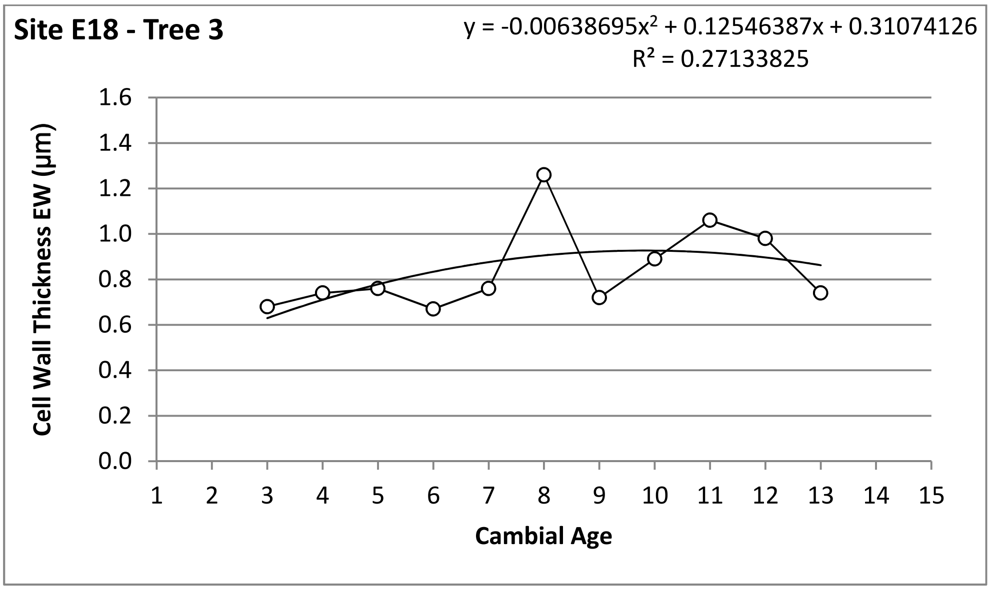

Site D10 - Tree 1
y = -0.00489177x² + 0.08736797x + 0.31895238
R² = 0.64683295
Cell Wall Thickness EW (µm)
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

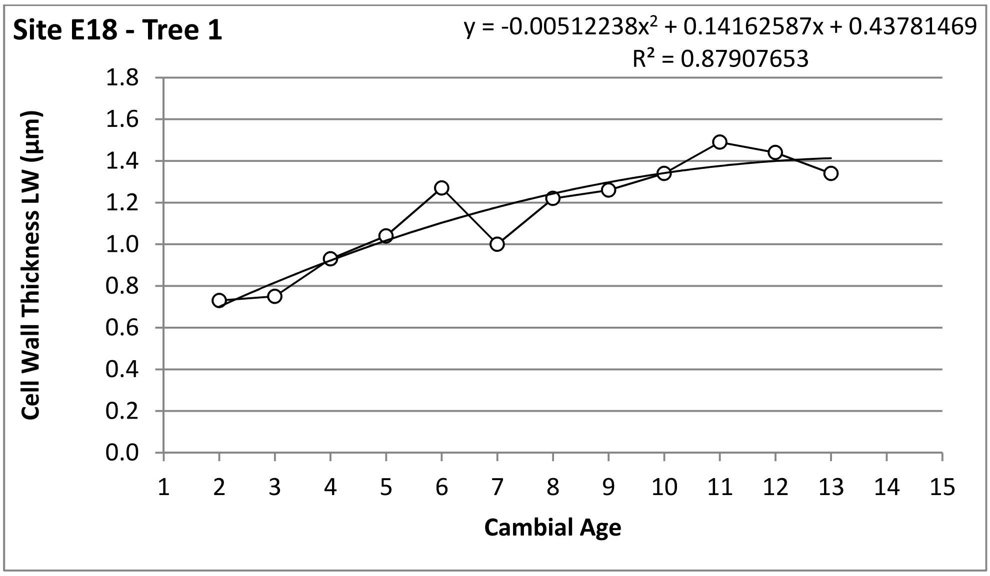

SiteD10 - Tree 3
y = -0.00738095x² + 0.10309524x + 0.44047619
R² = 0.58829365
Cell Wall Thickness EW (µm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

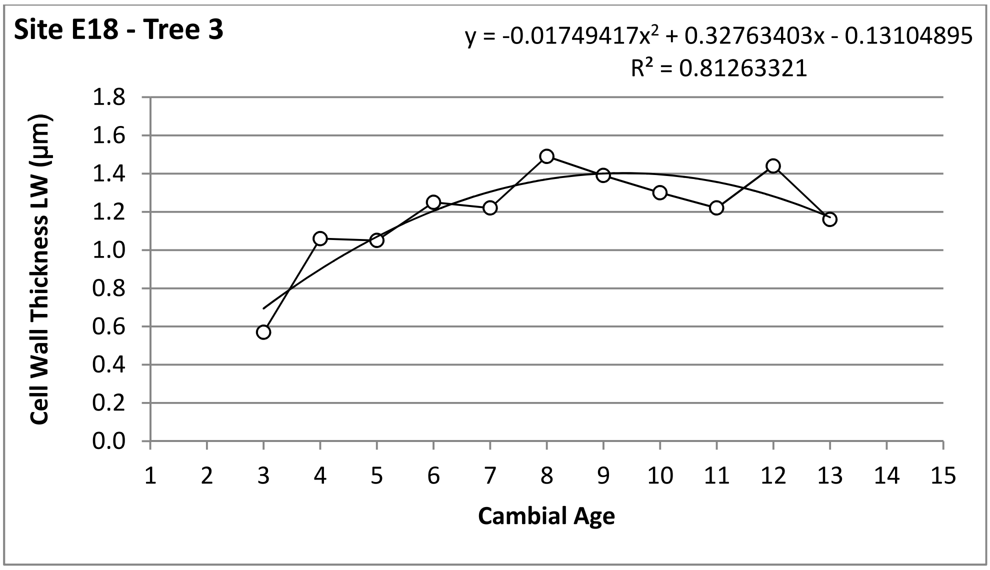

Site D10 - Tree 1
y = -0.00719697x² + 0.14086364x + 0.34966667
R² = 0.69307311
Cell Wall Thickness LW (µm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

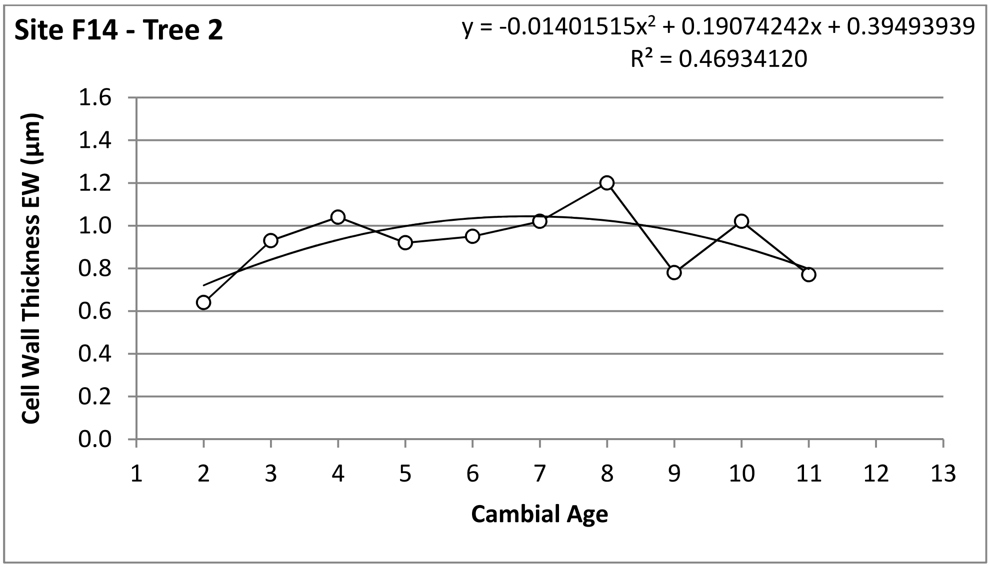

Site D10 - Tree 3
y = -0.00422619x² + 0.11339286x + 0.45244048
R² = 0.65728760
Cell Wall Thickness LW (µm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11
Cambial Age

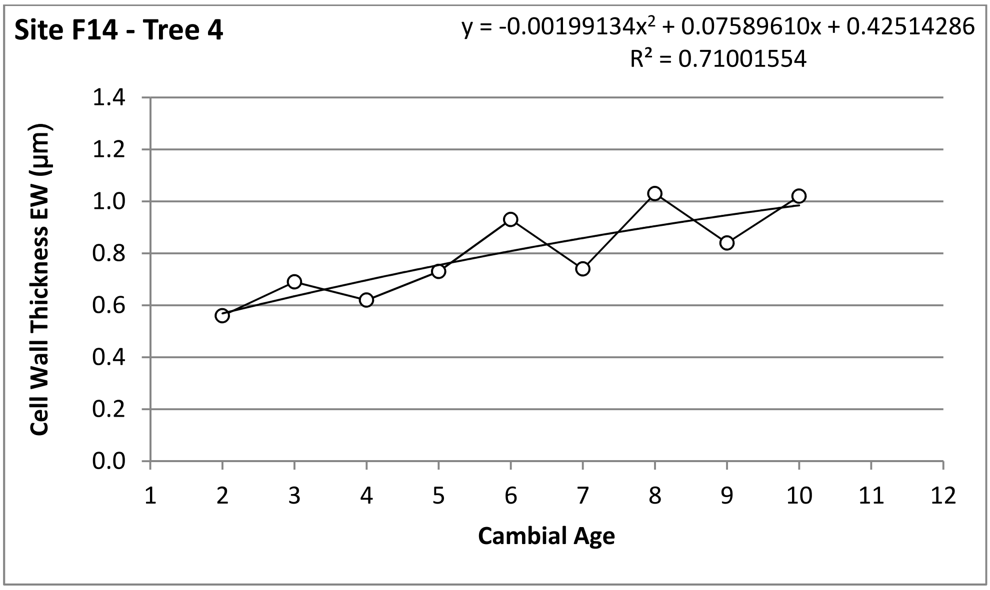

Site E18 - Tree 1
y = -0.00117133x² + 0.03557692x + 0.77718531
R² = 0.16190975
Cell Wall Thickness EW (µm)
Cambial Age

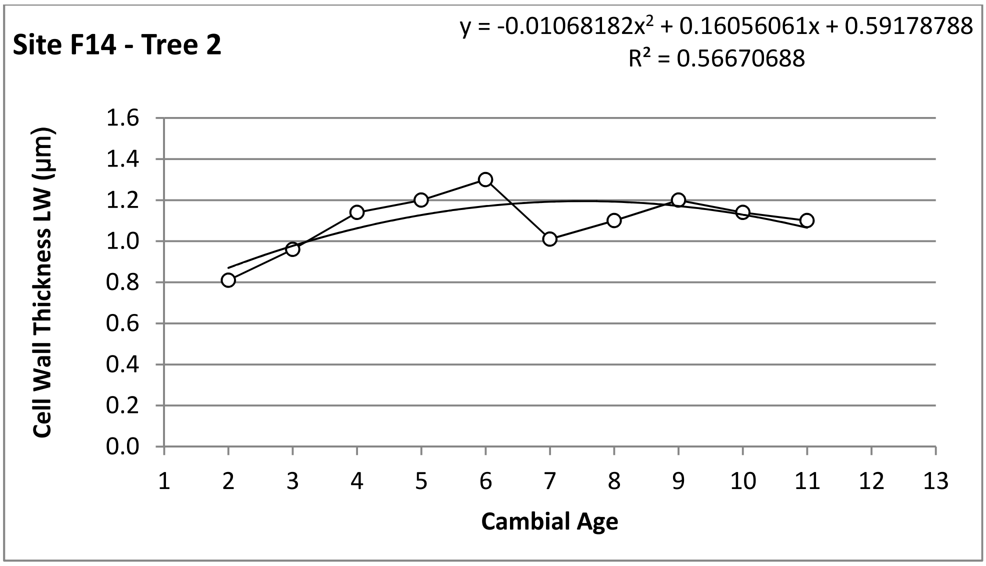

Site E18 - Tree 3
y = -0.00638695x² + 0.12546387x + 0.31074126
R² = 0.27133825
Cell Wall Thickness EW (µm)
Cambial Age

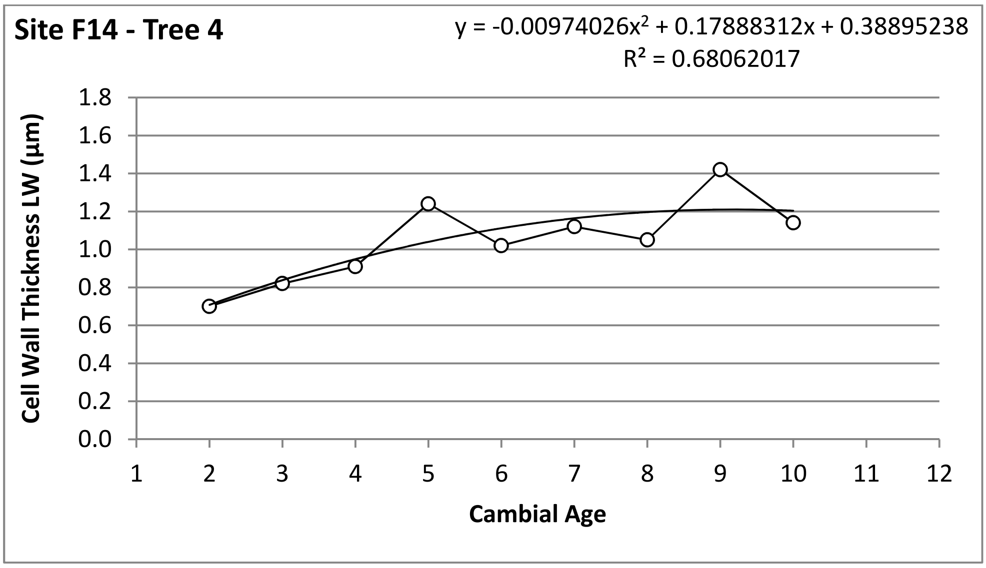

Site E18 - Tree 1
y = -0.00512238x² + 0.14162587x + 0.43781469
R² = 0.87907653
Cell Wall Thickness LW (µm)
Cambial Age

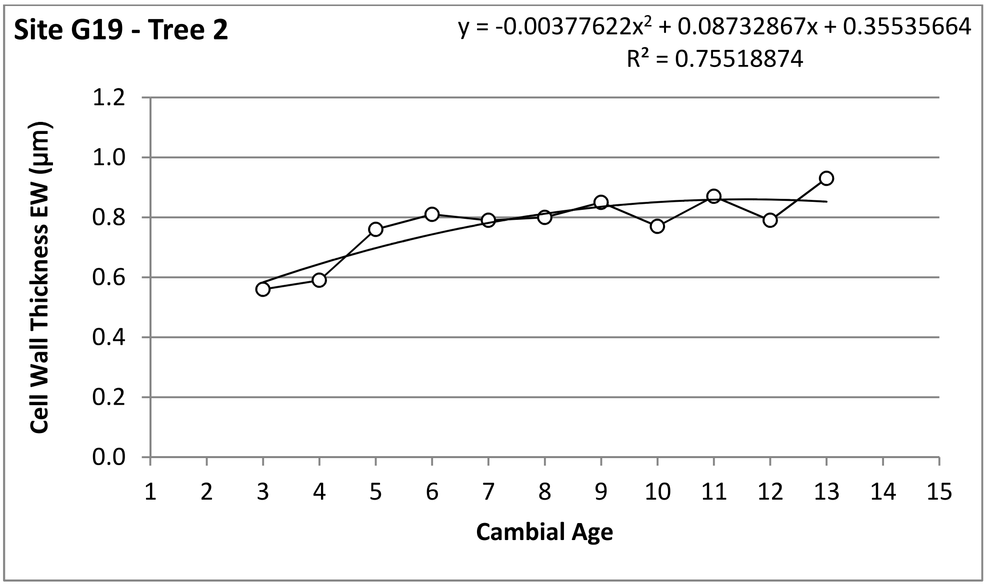

Site E18 - Tree 3
y = -0.01749417x² + 0.32763403x - 0.13104895
R² = 0.81263321
Cell Wall Thickness LW (µm)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

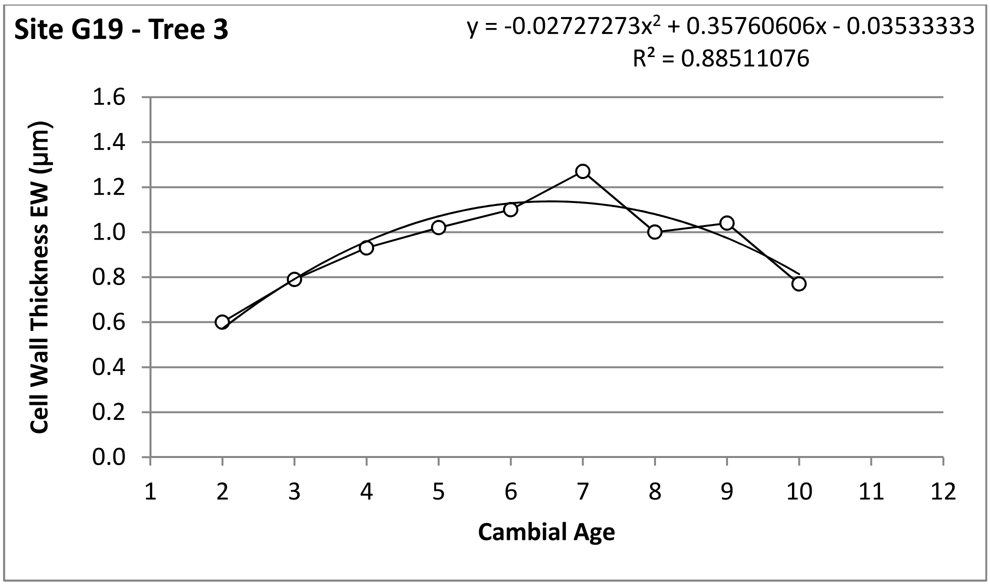

Site F14 - Tree 2
y = -0.01401515x² + 0.19074242x + 0.39493939
R² = 0.46934120
Cell Wall Thickness EW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Cambial Age

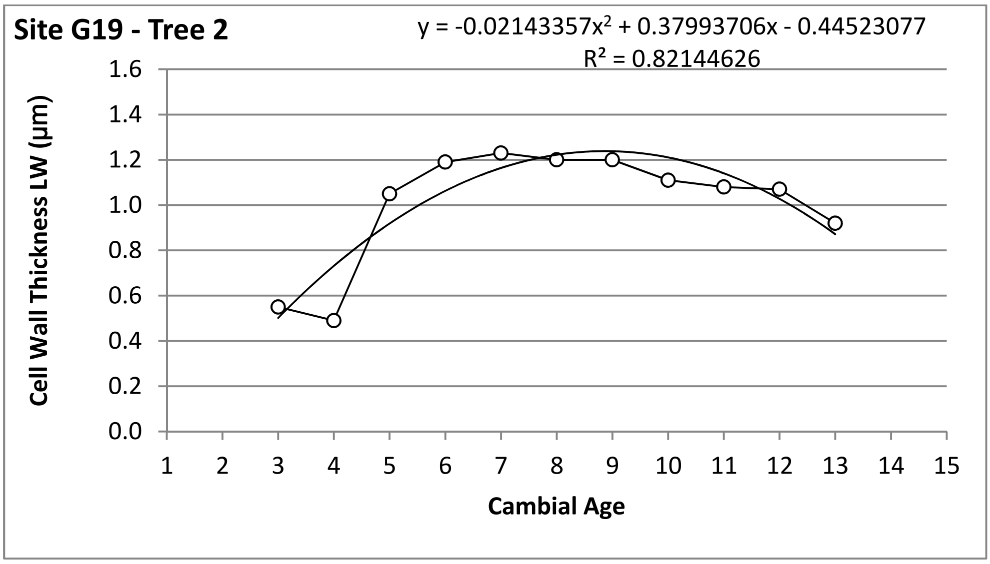

Site F14 - Tree 4
y = -0.00199134x² + 0.07589610x + 0.42514286
R² = 0.71001554
Cell Wall Thickness EW (µm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

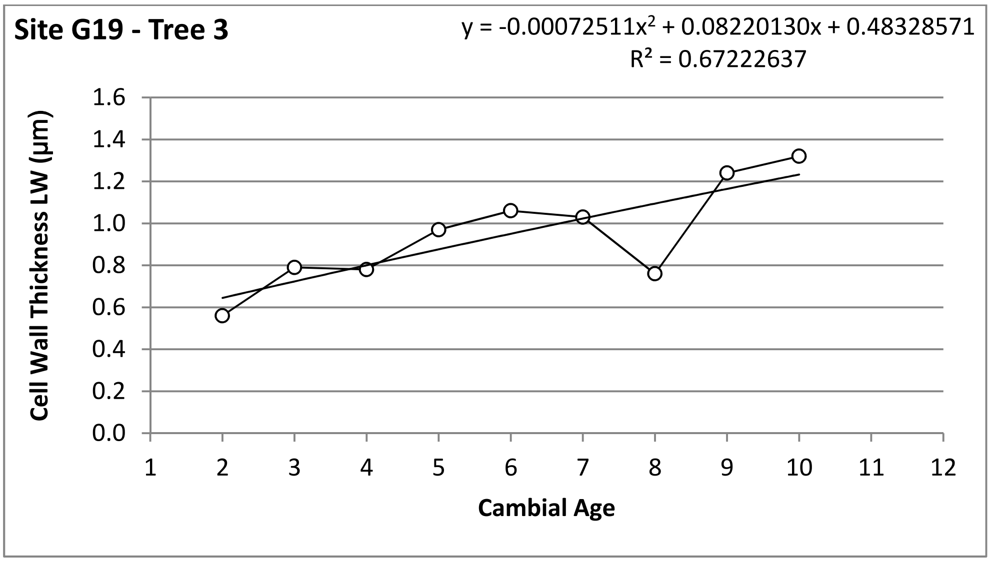

Site F14 - Tree 2
y = -0.01068182x² + 0.16056061x + 0.59178788
R² = 0.56670688
Cell Wall Thickness LW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Cambial Age

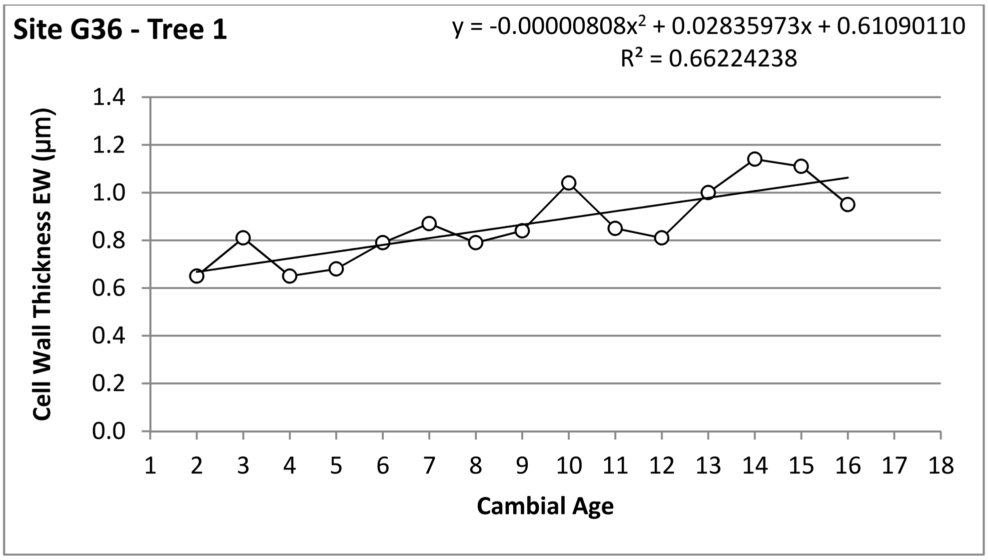

Site F14 - Tree 4
y = -0.00974026x² + 0.17888312x + 0.38895238
R² = 0.68062017
Cell Wall Thickness LW (µm)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

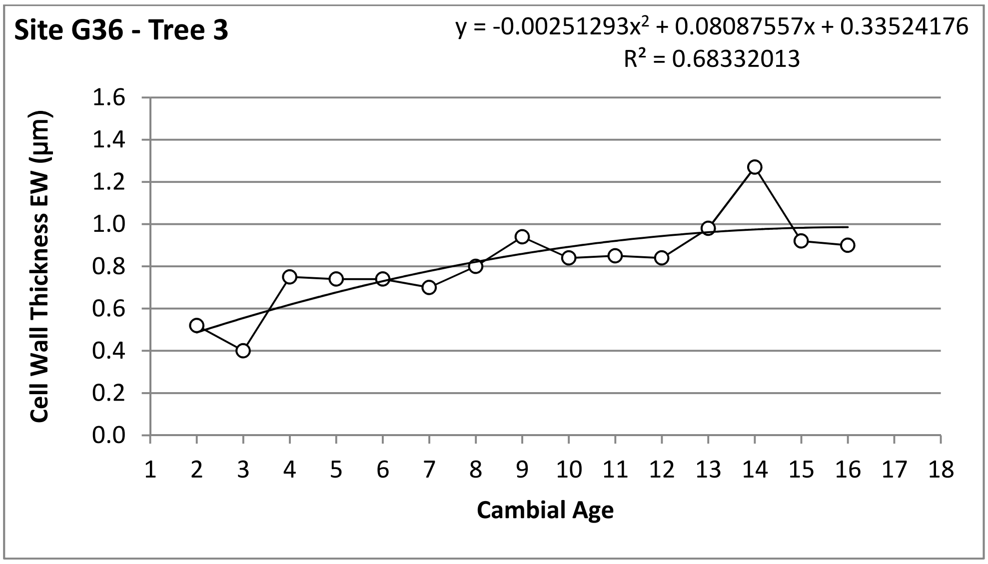

Site G19 - Tree 2
y = -0.00377622x² + 0.08732867x + 0.35535664
R² = 0.75518874
Cell Wall Thickness EW (µm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

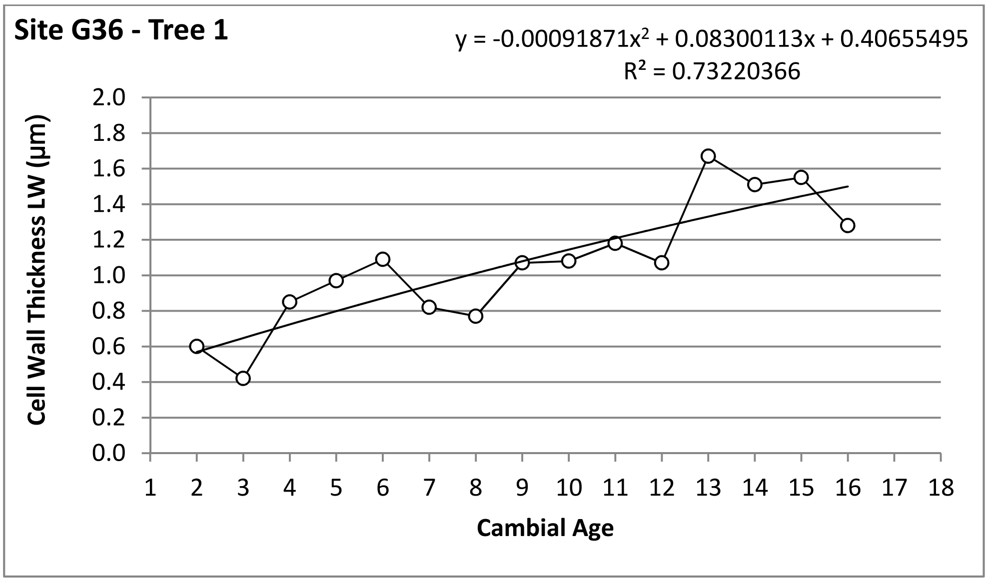

Site G19 - Tree 3
y = -0.02727273x² + 0.35760606x - 0.03533333
R² = 0.88511076
Cell Wall Thickness EW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

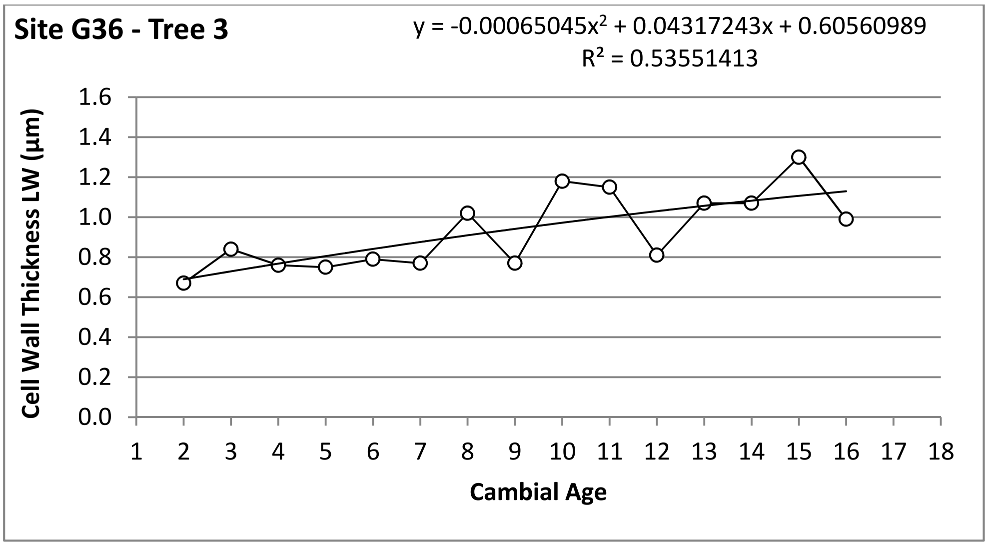

Site G19 - Tree 2
y = -0.02143357x² + 0.37993706x - 0.44523077
R² = 0.82144626
Cell Wall Thickness LW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

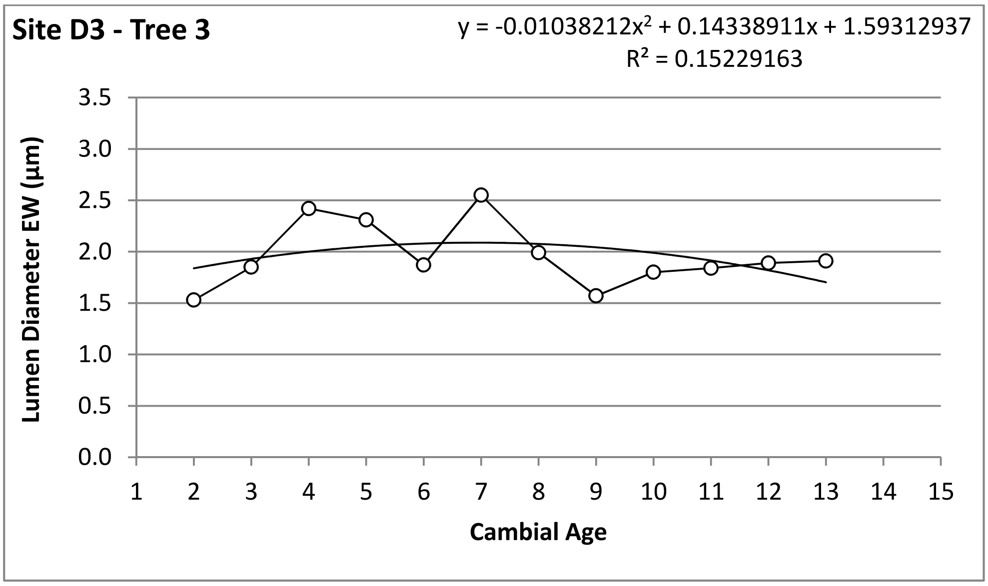

Site G19 - Tree 3
y = -0.00072511x² + 0.08220130x + 0.48328571
R² = 0.67222637
Cell Wall Thickness LW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

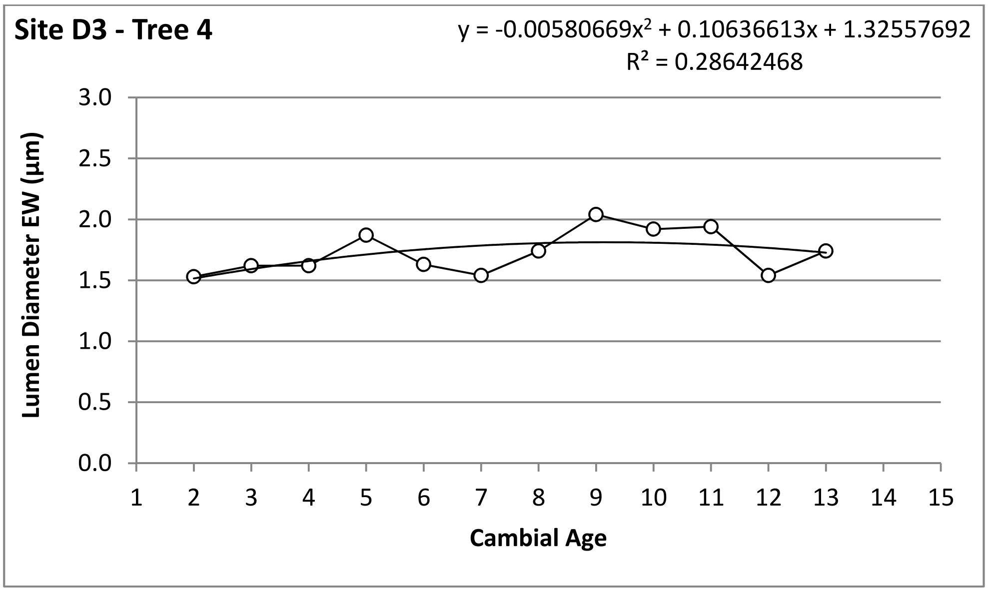

Site G36 - Tree 1
y = -0.00000808x² + 0.02835973x + 0.61090110
R² = 0.66224238
Cell Wall Thickness EW (µm)
Cambial Age

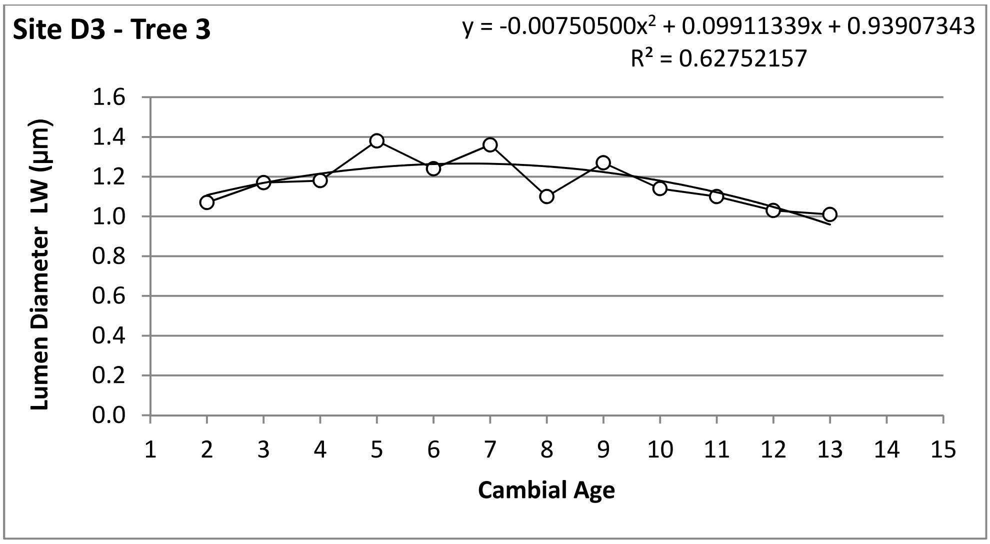

Site G36 - Tree 3
y = -0.00251293x² + 0.08087557x + 0.33524176
R² = 0.68332013
Cell Wall Thickness EW (µm)
Cambial Age

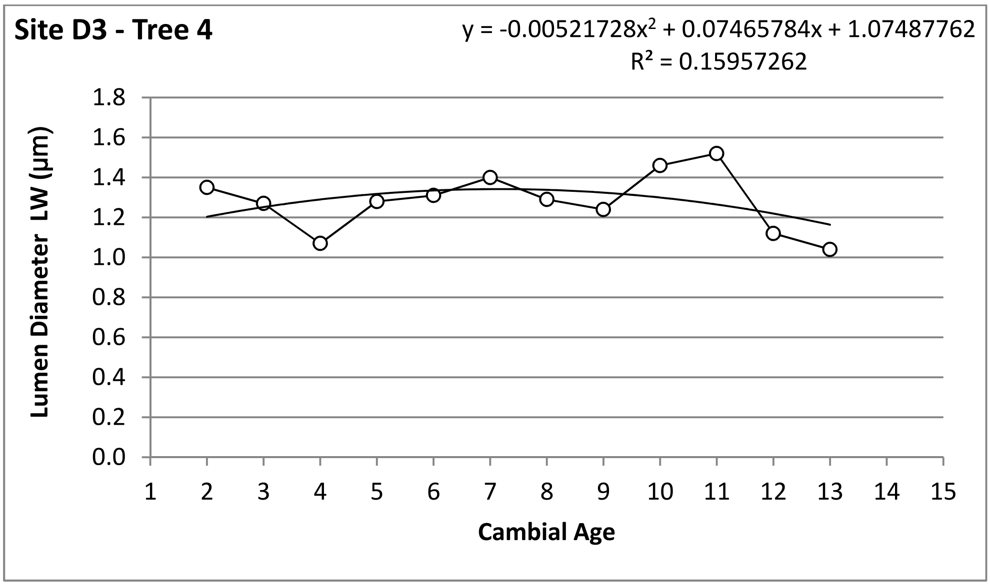

Site G36 - Tree 1
y = -0.00091871x² + 0.08300113x + 0.40655495
R² = 0.73220366
Cell Wall Thickness LW (µm)
Cambial Age

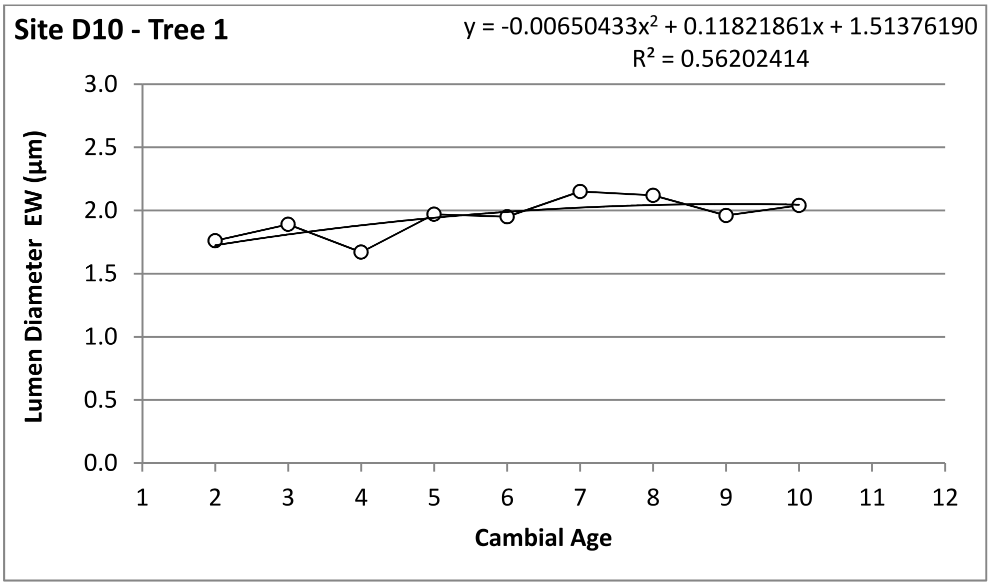

Site G36 - Tree 3
y = -0.00065045x² + 0.04317243x + 0.60560989
R² = 0.53551413
Cell Wall Thickness LW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

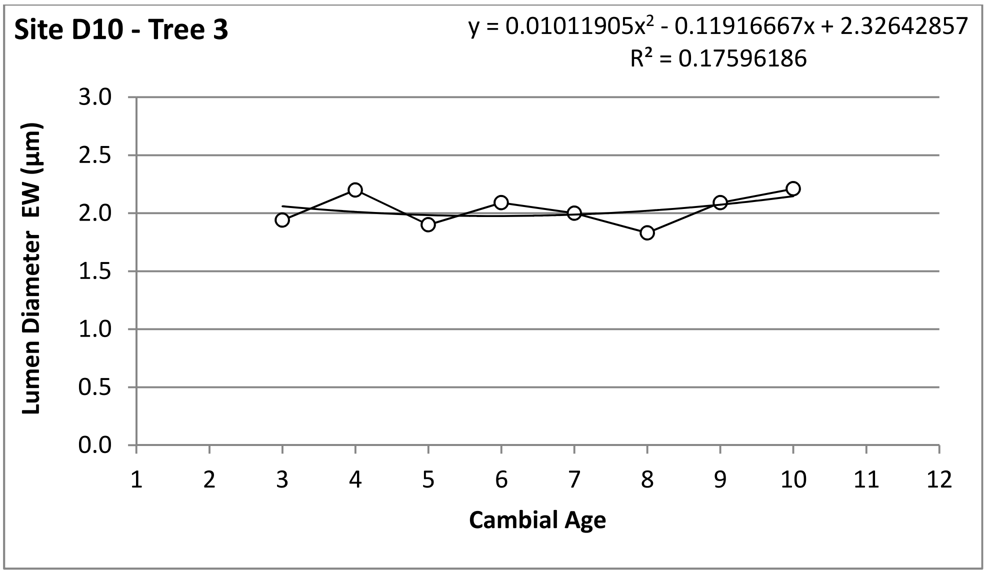

Site D3 - Tree 3
y = -0.01038212x² + 0.14338911x + 1.59312937
R² = 0.15229163
Lumen Diameter EW (µm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age


Site D3 - Tree 4
y = -0.00580669x² + 0.10636613x + 1.32557692
R² = 0.28642468
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

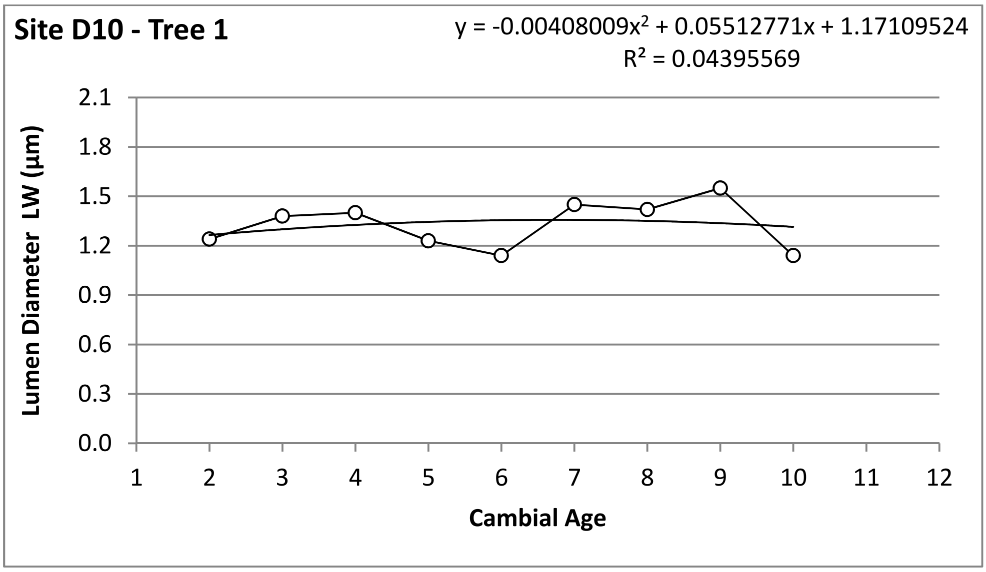

Site D3 - Tree 3
y = -0.00750500x² + 0.09911339x + 0.93907343
R² = 0.62752157
Lumen Diameter LW (µm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age


Site D3 - Tree 4
y = -0.00521728x² + 0.07465784x + 1.07487762
R² = 0.15957262
Lumen Diameter LW (µm)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

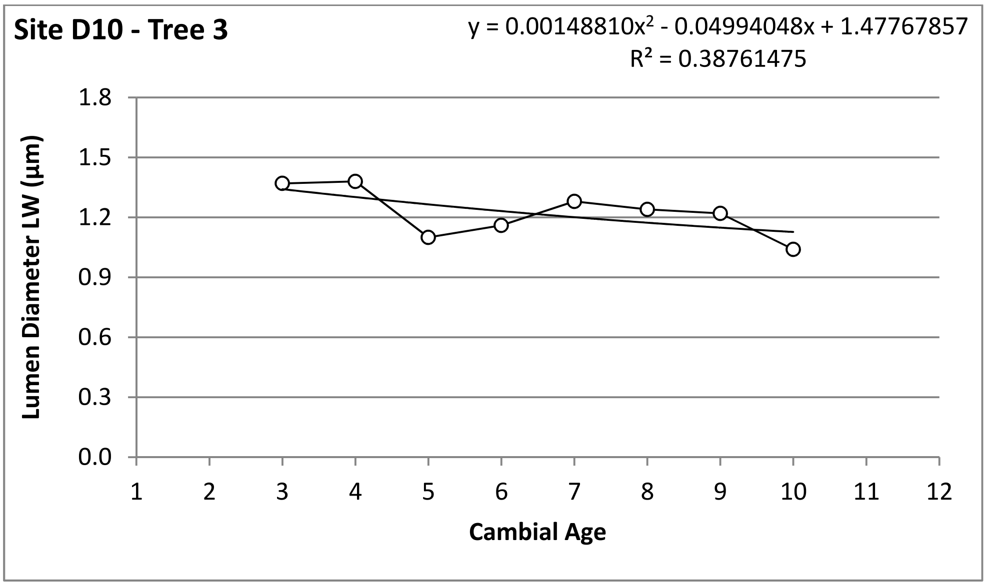

Site D10 - Tree 1
y = -0.00650433x² + 0.11821861x + 1.51376190
R² = 0.56202414
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age



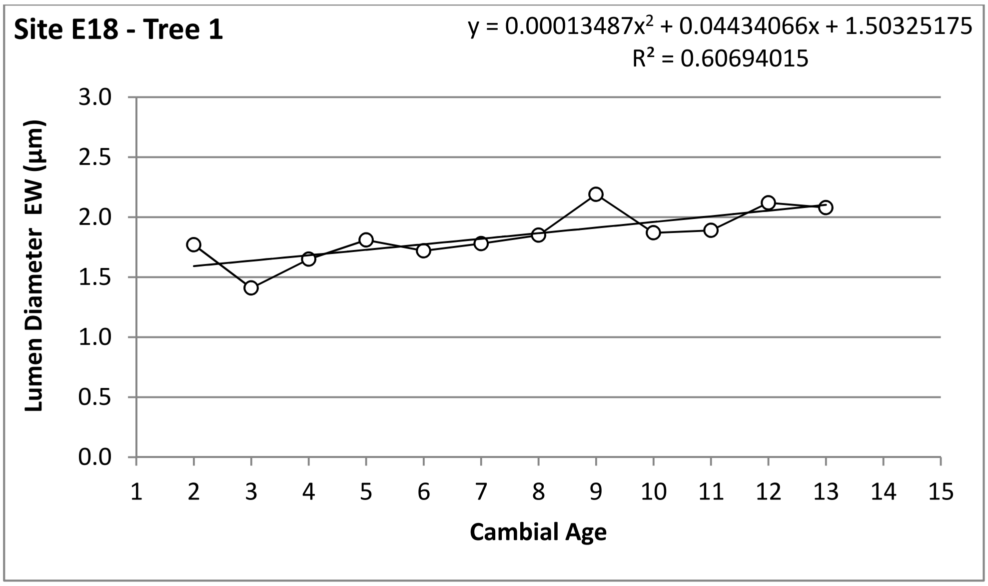
Site D10 - Tree 3
y = 0.01011905x² - 0.11916667x + 2.32642857
R² = 0.17596186
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Cambial Age

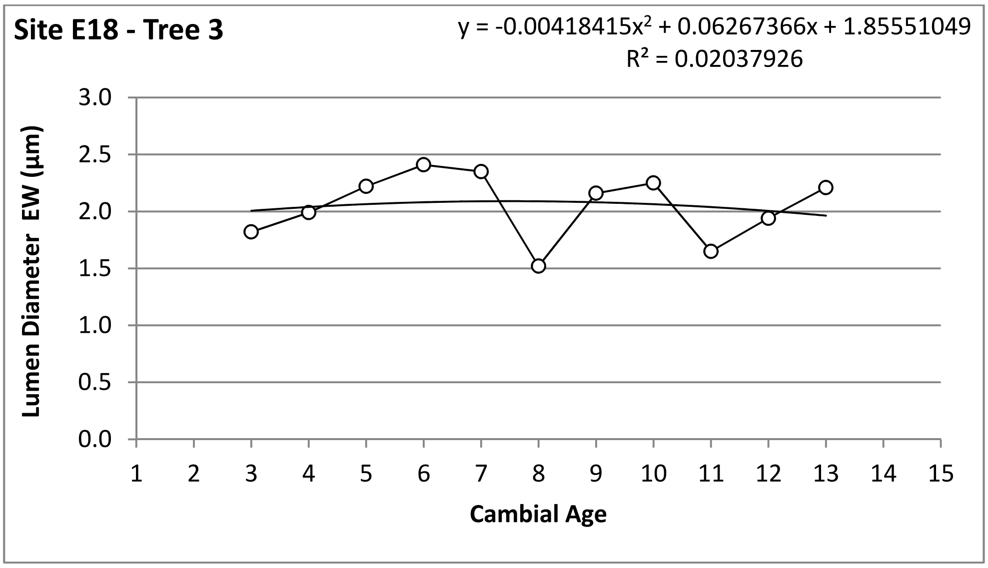


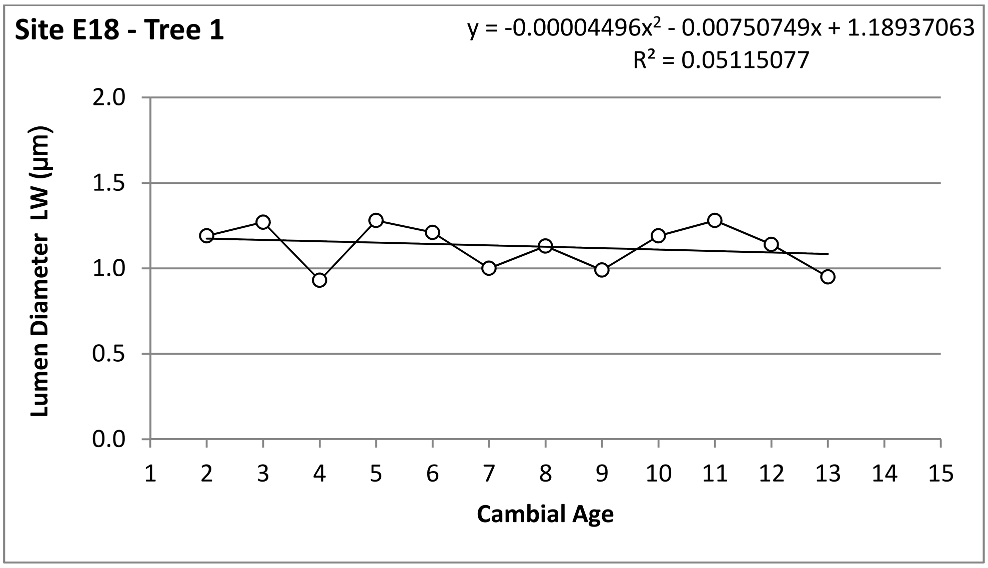
Site D10 - Tree 1
y = -0.00408009x² + 0.05512771x + 1.17109524
R² = 0.04395569
Lumen Diameter LW (µm)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Cambial Age

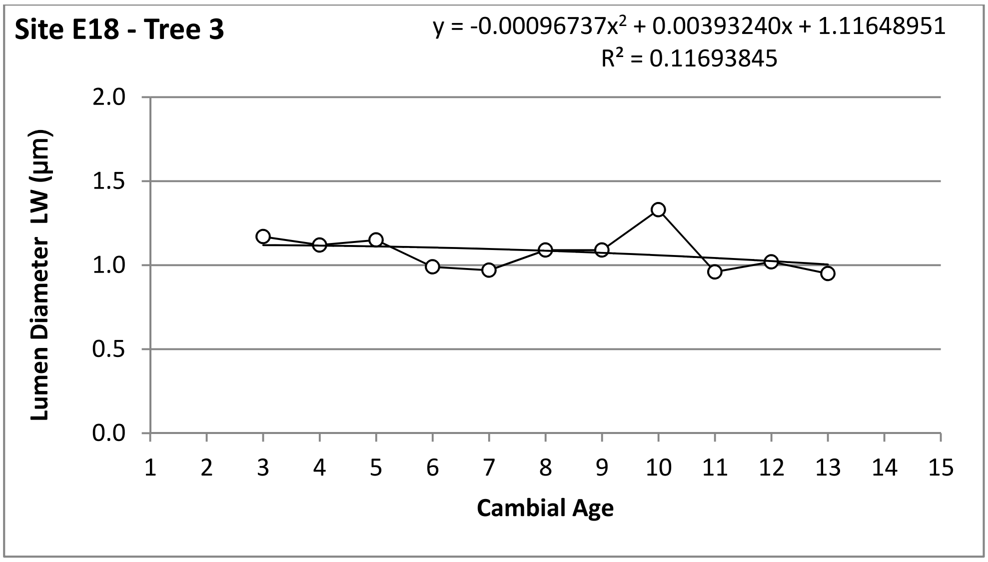


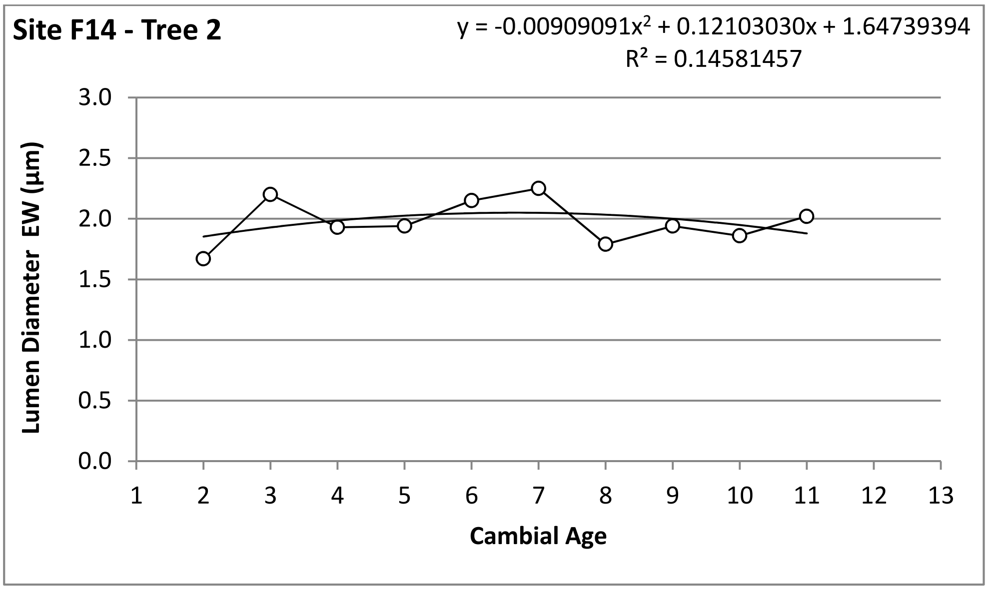
Site D10 - Tree 3
y = 0.00148810x² - 0.04994048x + 1.47767857
R² = 0.38761475
Lumen Diameter LW (µm)
1.8
1.5
1.2
0.9
0.6
0.3
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Cambial Age

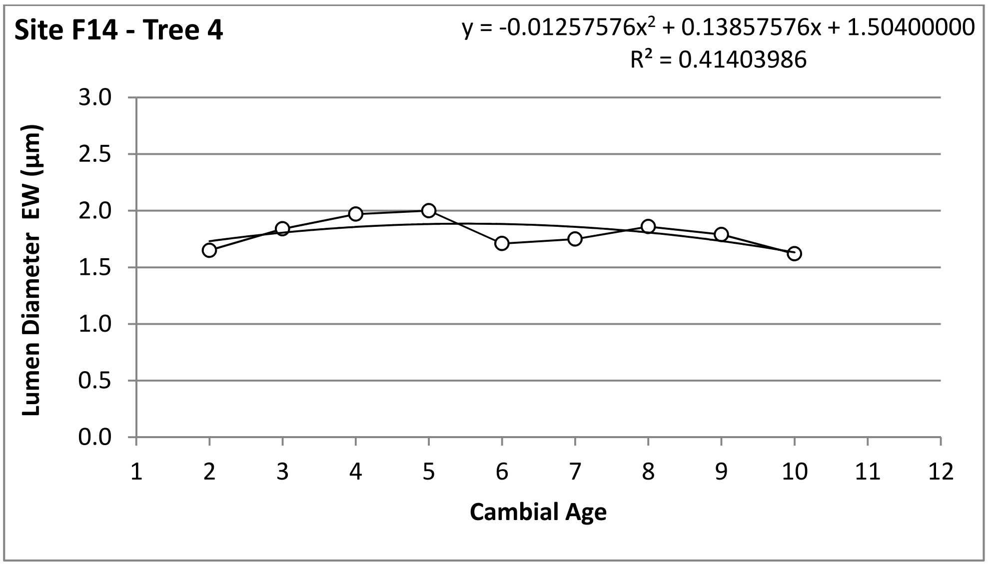

Site E18 - Tree 1
y = 0.00013487x² + 0.04434066x + 1.50325175
R² = 0.60694015
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

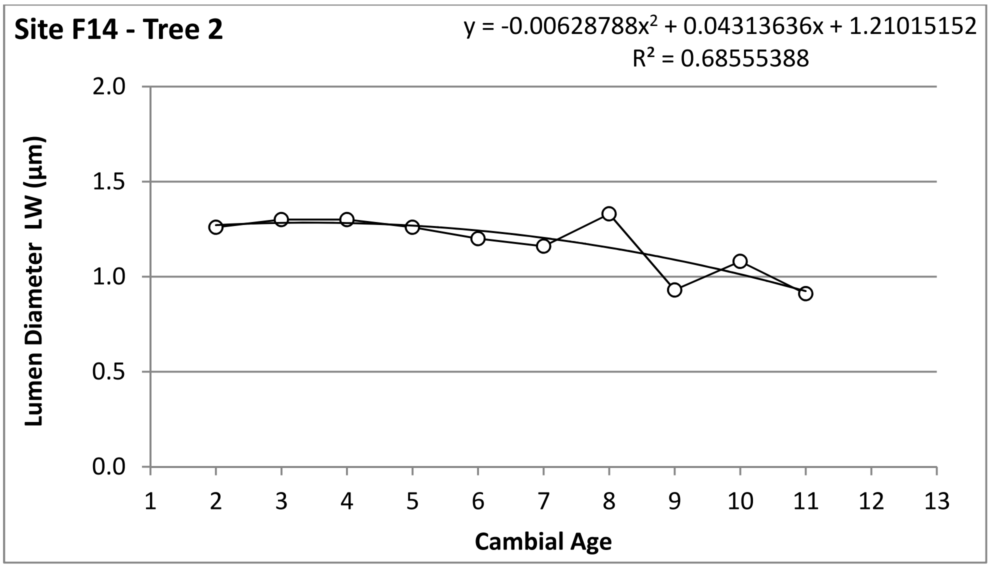

Site E18 - Tree 3
y = -0.00418415x² + 0.06267366x + 1.85551049
R² = 0.02037926
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

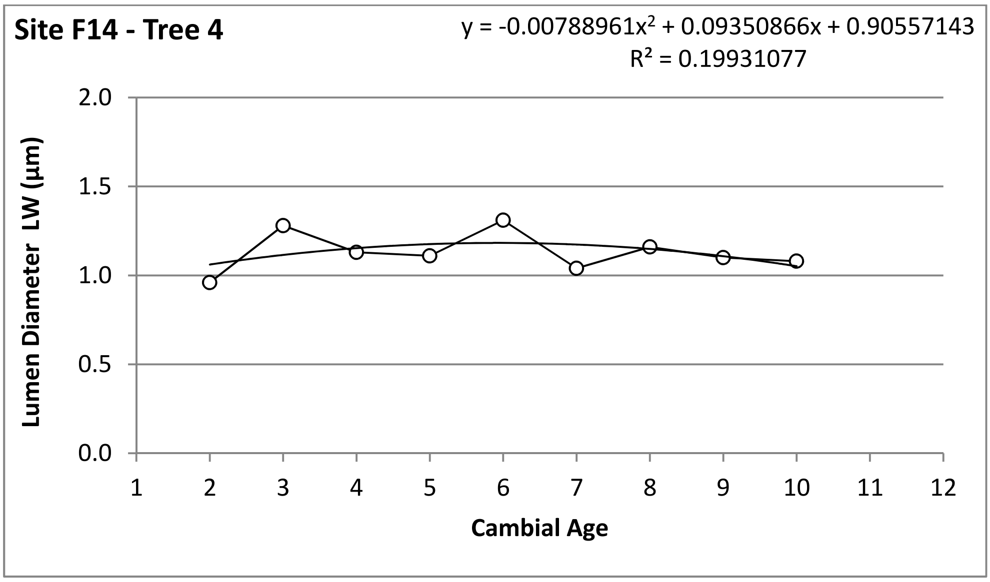

Site E18 - Tree 1
y = -0.00004496x² - 0.00750749x + 1.18937063
R² = 0.05115077
Lumen Diameter LW (µm)
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

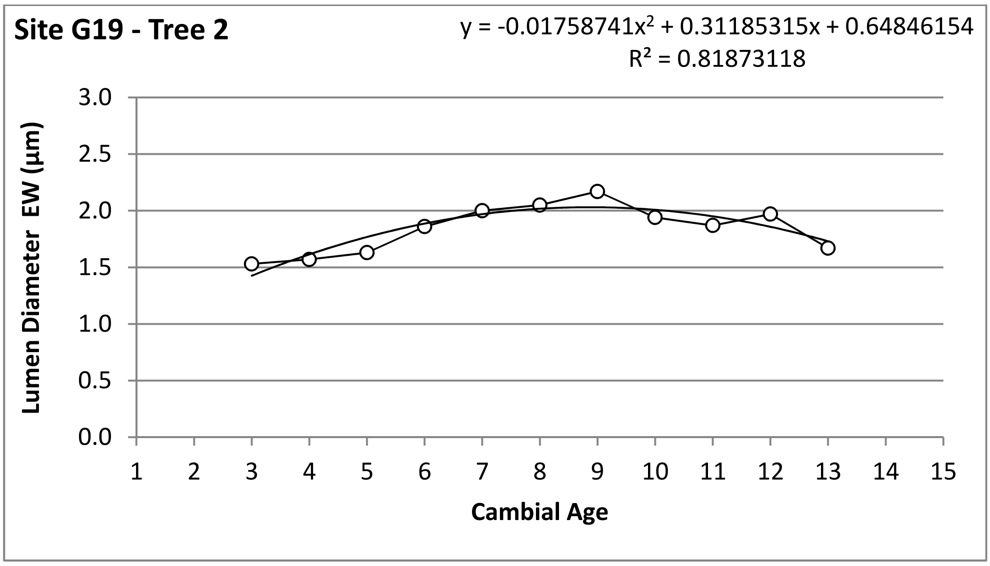

Site E18 - Tree 3
y = -0.00096737x² + 0.00393240x + 1.11648951
R² = 0.11693845
Lumen Diameter LW (µm)
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

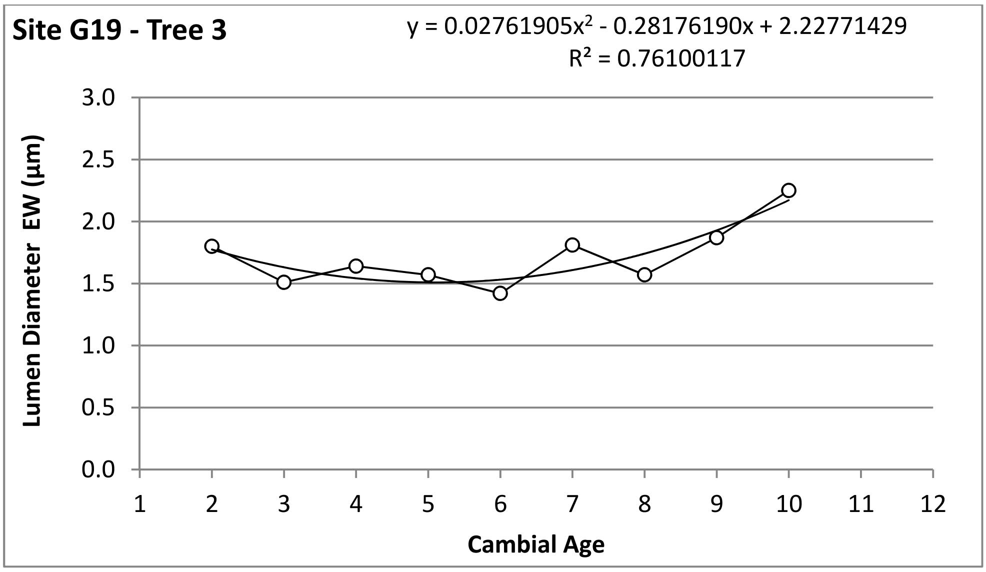

Site F14 - Tree 2
y = -0.00909091x² + 0.12103030x + 1.64739394
R² = 0.14581457
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Cambial Age

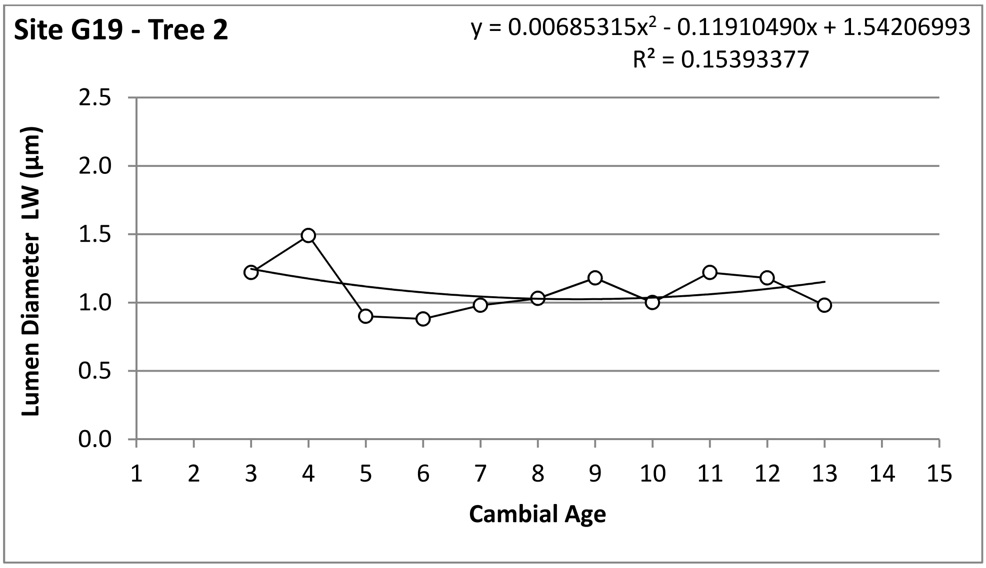

Site F14 - Tree 4
y = -0.01257576x² + 0.13857576x + 1.50400000
R² = 0.41403986
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age

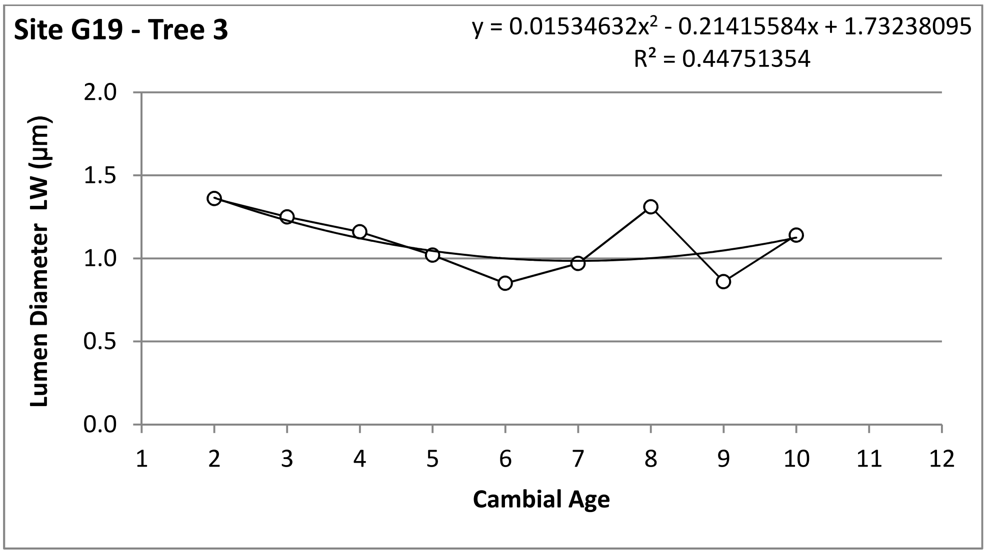

Site F14 - Tree 2
y = -0.00628788x² + 0.04313636x + 1.21015152
R² = 0.68555388
Lumen Diameter LW (µm)
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Cambial Age

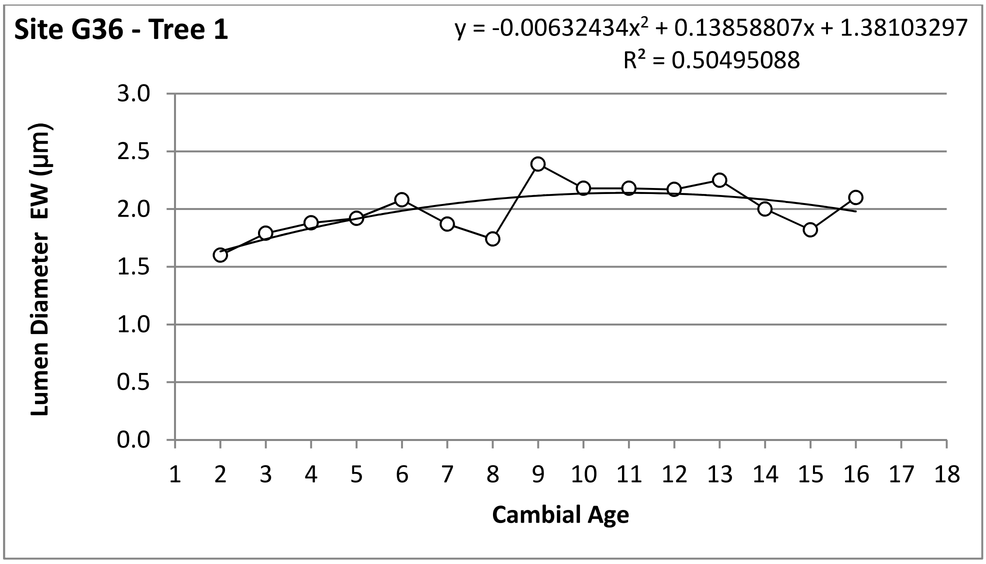

Site F14 - Tree 4
y = -0.00788961x² + 0.09350866x + 0.90557143
R² = 0.19931077
Lumen Diameter LW (µm)
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12
Cambial Age


Site G19 - Tree 2
y = -0.01758741x² + 0.31185315x + 0.64846154
R² = 0.81873118
Lumen Diameter EW (µm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

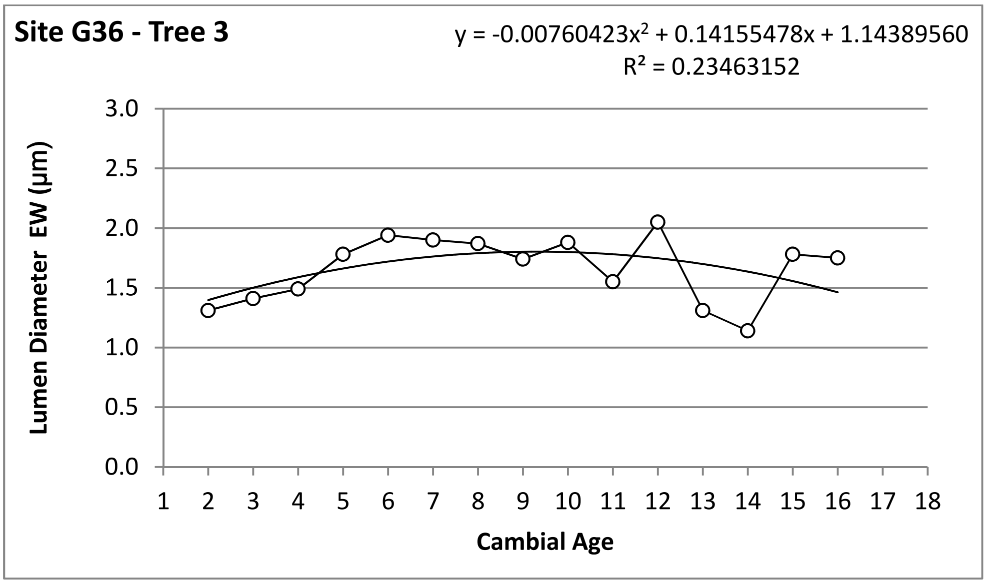

Site G19 - Tree 3
y = 0.02761905x² - 0.28176190x + 2.22771429
R² = 0.76100117
Lumen Diameter EW (µm)
Cambial Age


Site G19 - Tree 2
y = 0.00685315x² - 0.11910490x + 1.54206993
R² = 0.15393377
Lumen Diameter LW (µm)
Cambial Age

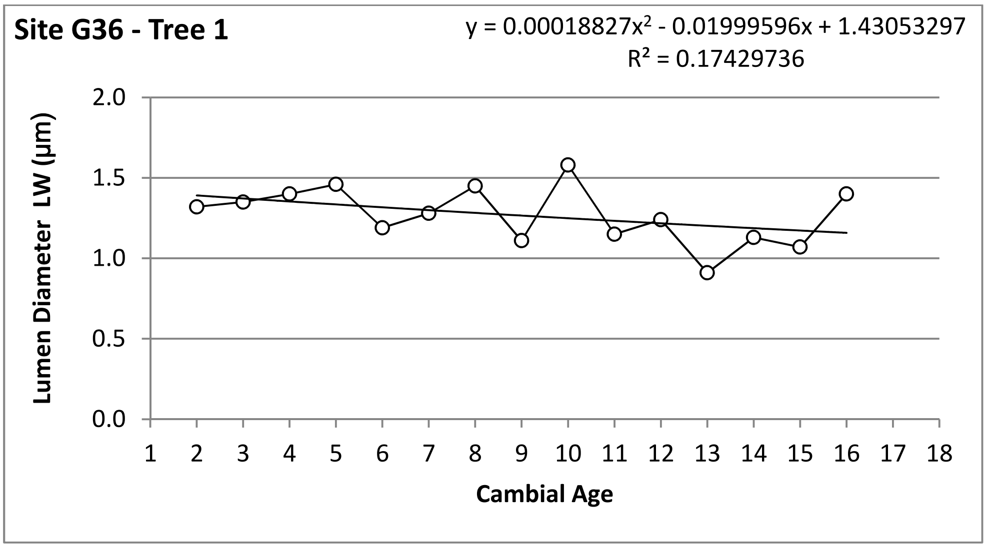

Site G19 - Tree 3
y = 0.01534632x² - 0.21415584x + 1.73238095
R² = 0.44751354
Lumen Diameter LW (µm)
Cambial Age



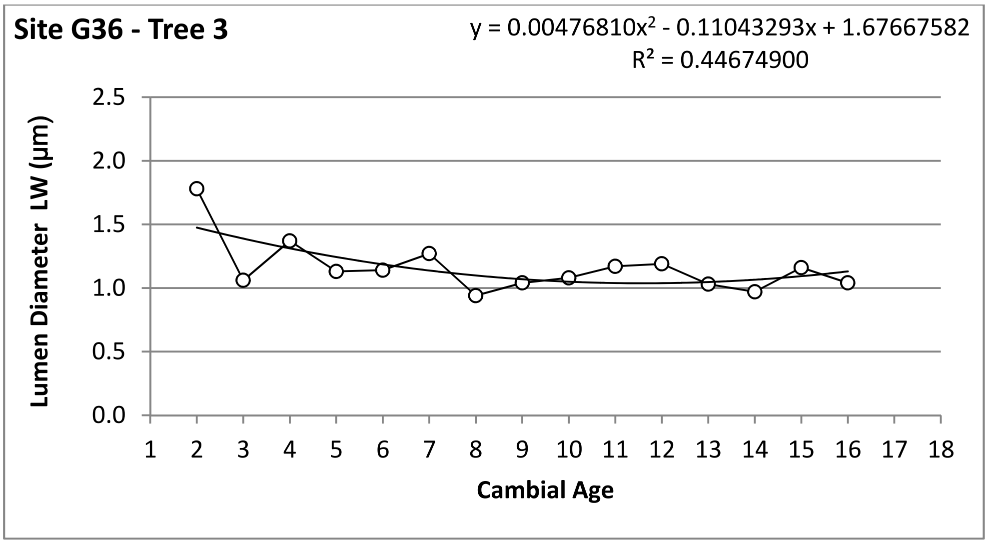
Site G36 - Tree 1
$y = -0.00632434x^2 + 0.13858807x + 1.38103297$
$R^2 = 0.50495088$
Lumen Diameter EW (µm)
Cambial Age

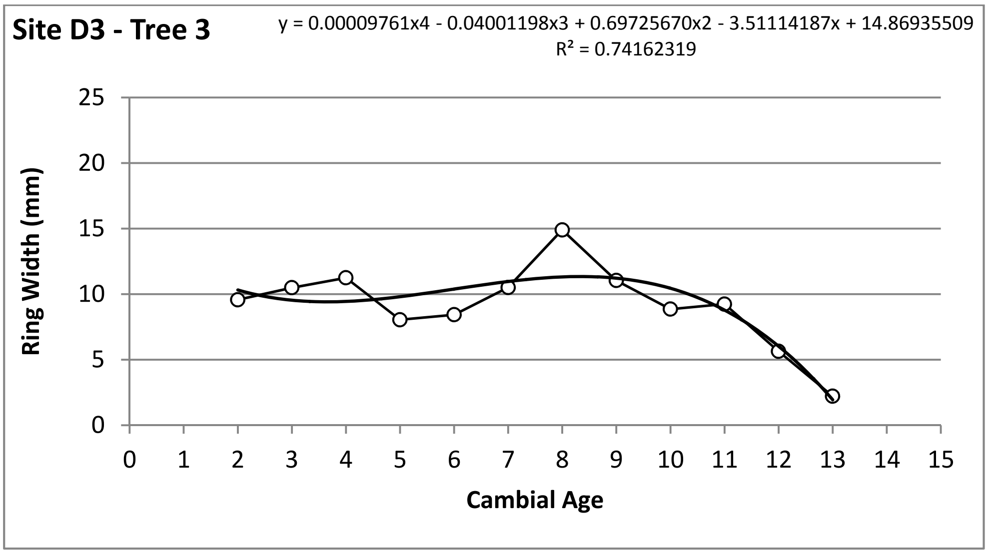


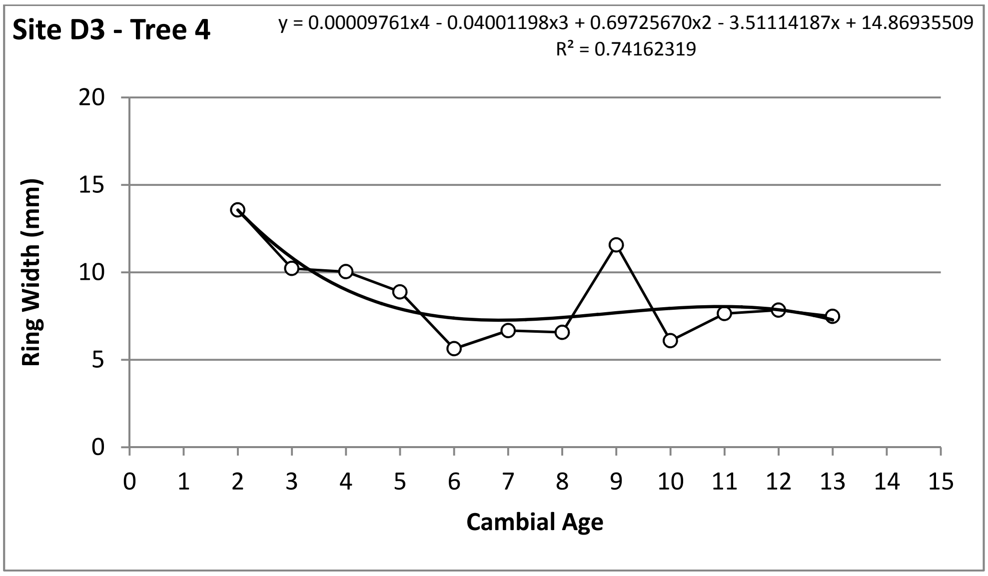
Site G36 - Tree 3
$y = -0.00760423x^2 + 0.14155478x + 1.14389560$
$R^2 = 0.23463152$
Lumen Diameter EW (µm)
Cambial Age

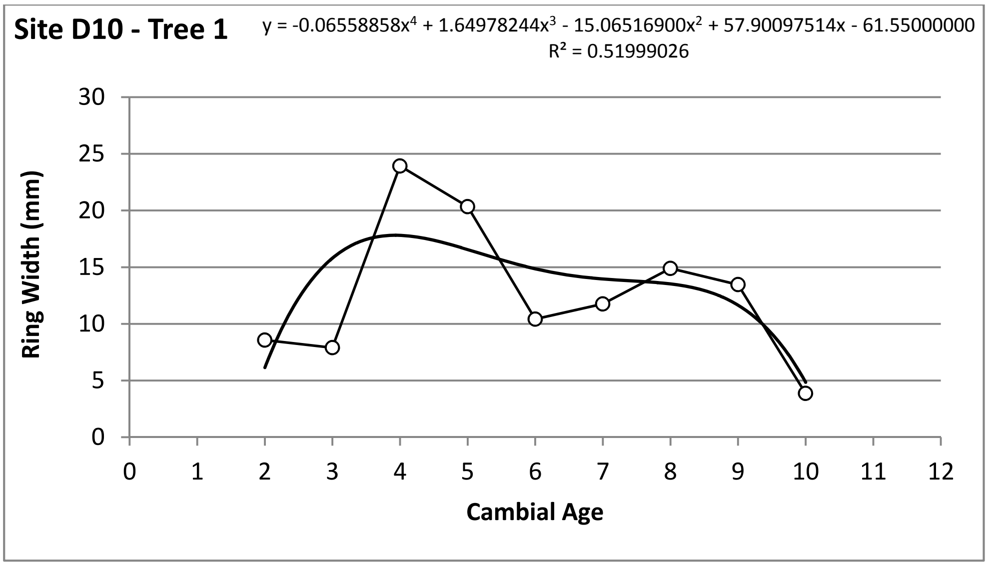


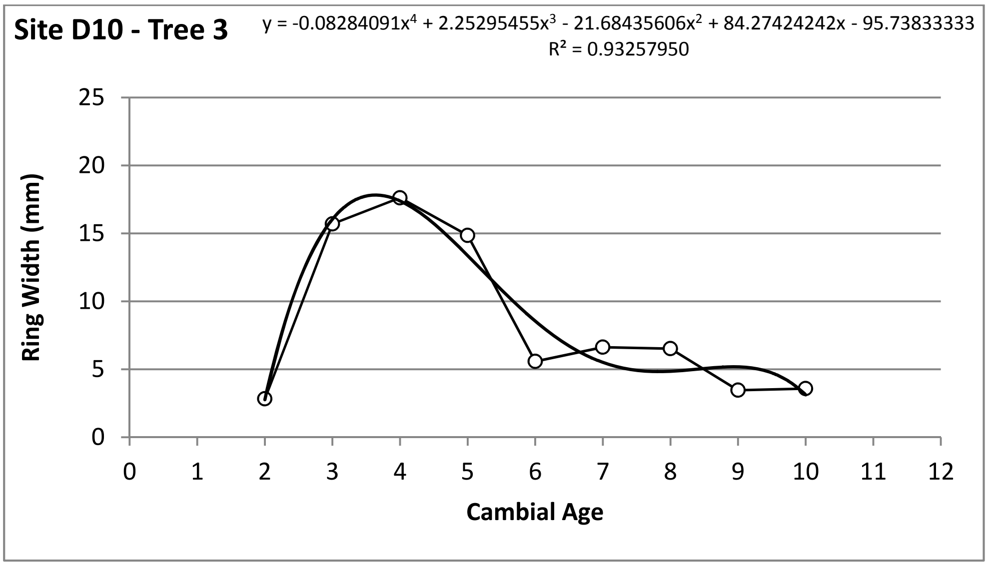
Site G36 - Tree 1
$y = 0.00018827x^2 - 0.01999596x + 1.43053297$
$R^2 = 0.17429736$
Lumen Diameter LW (µm)
Cambial Age

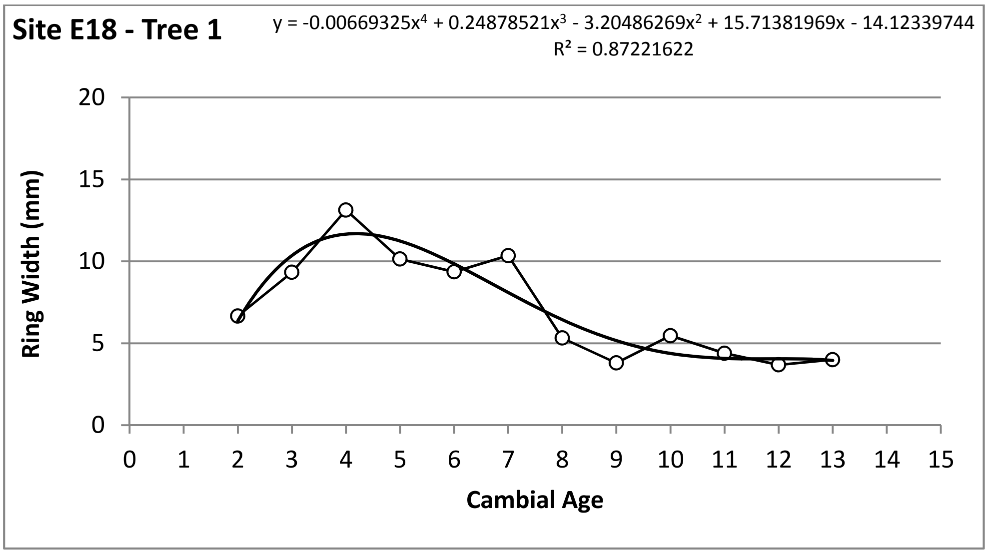

Site G36 - Tree 3
y = 0.00476810x² - 0.11043293x + 1.67667582
R² = 0.44674900
Lumen Diameter LW (μm)
2.5
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

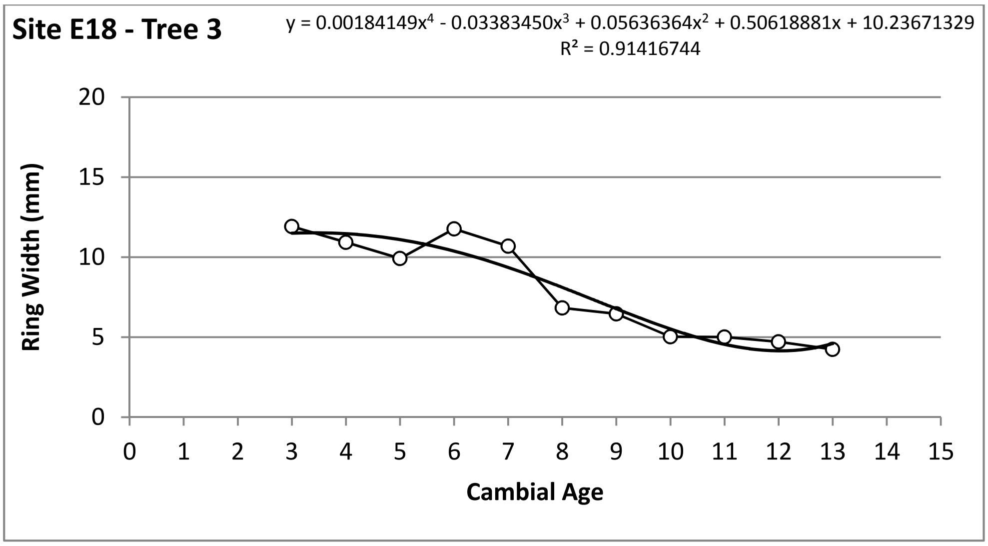

Site D3 - Tree 3
y = 0.00009761x4 - 0.04001198x3 + 0.69725670x2 - 3.51114187x + 14.86935509
R² = 0.74162319
Ring Width (mm)
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

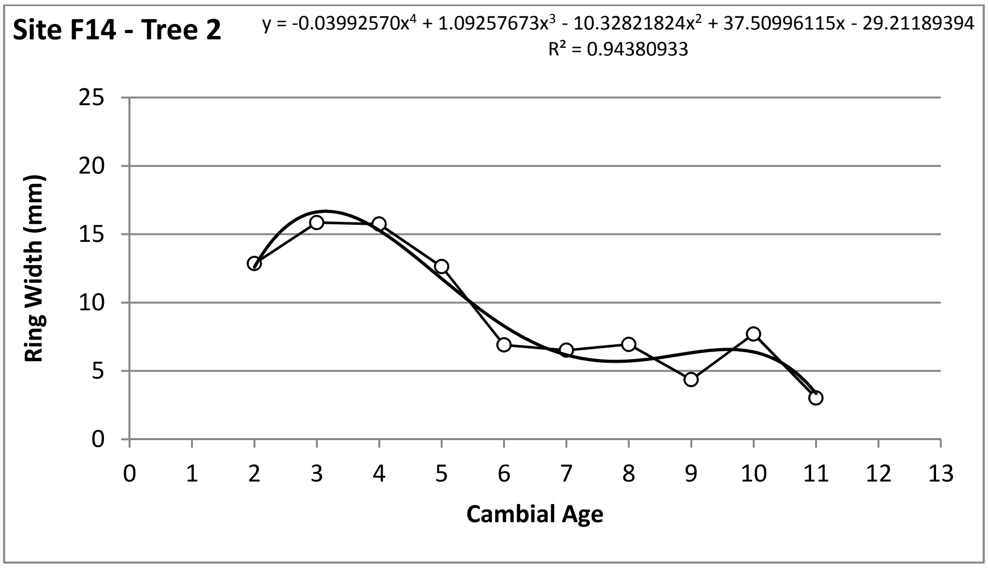

Site D3 - Tree 4
y = 0.00009761x4 - 0.04001198x3 + 0.69725670x2 - 3.51114187x + 14.86935509
R² = 0.74162319
Ring Width (mm)
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

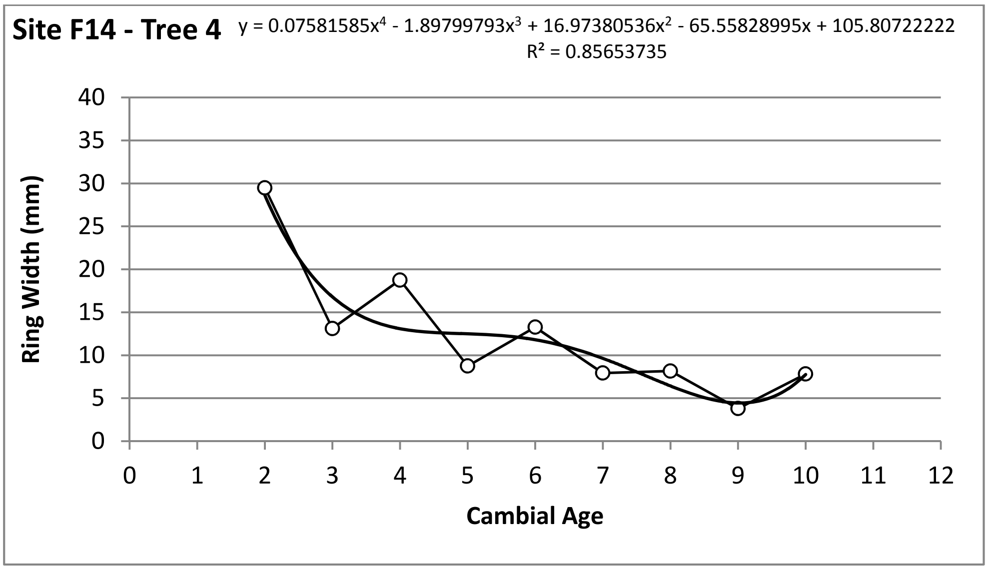

Site D10 - Tree 1
y = -0.06558858x⁴ + 1.64978244x³ - 15.06516900x² + 57.90097514x - 61.55000000
R² = 0.51999026
Ring Width (mm)
Cambial Age

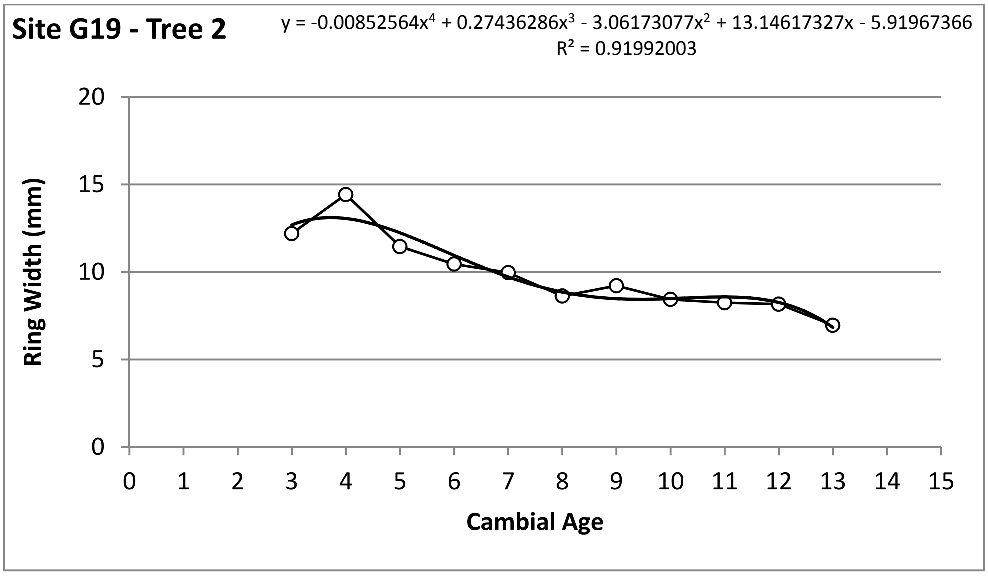

Site D10 - Tree 3
y = -0.08284091x⁴ + 2.25295455x³ - 21.68435606x² + 84.27424242x - 95.73833333
R² = 0.93257950
Ring Width (mm)
Cambial Age

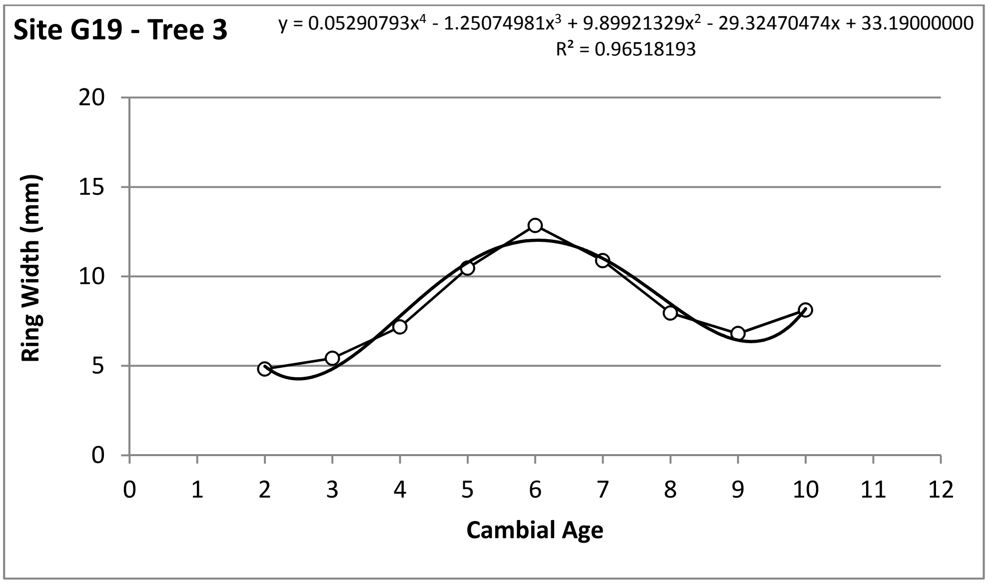

Site E18 - Tree 1
y = -0.00669325x⁴ + 0.24878521x³ - 3.20486269x² + 15.71381969x - 14.12339744
R² = 0.87221622
Ring Width (mm)
Cambial Age

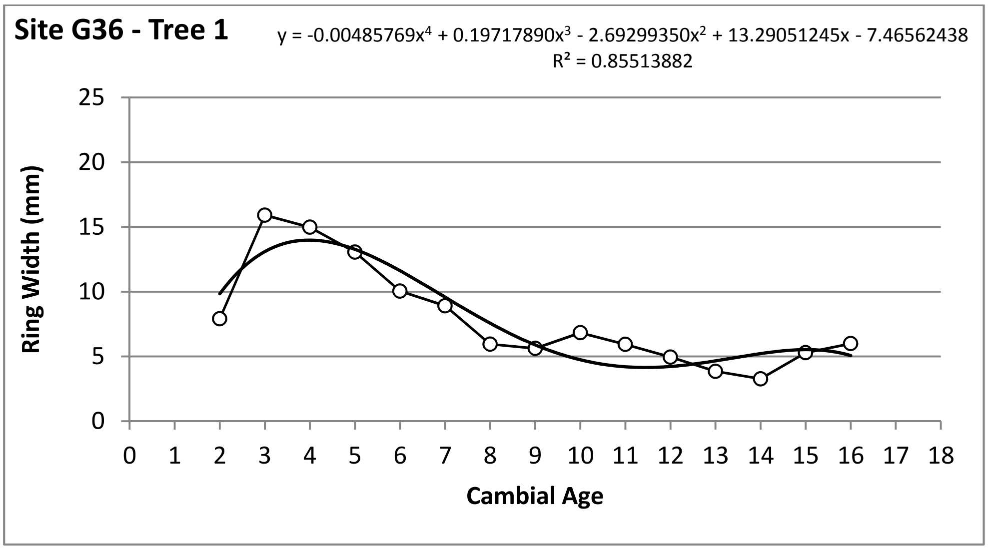

Site E18 - Tree 3
y = 0.00184149x⁴ - 0.03383450x³ + 0.05636364x² + 0.50618881x + 10.23671329
R² = 0.91416744
Ring Width (mm)
Cambial Age

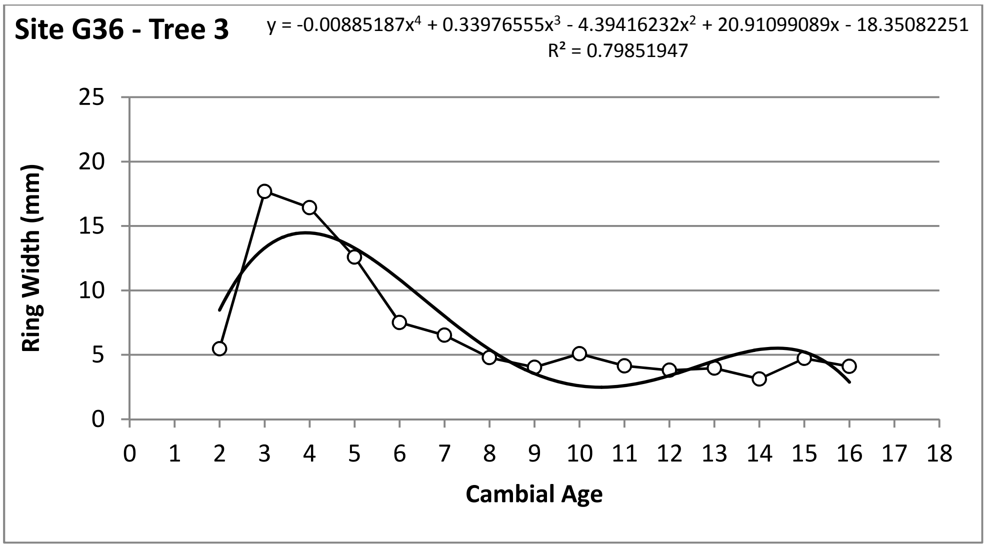

Site F14 - Tree 2
y = -0.03992570x⁴ + 1.09257673x³ - 10.32821824x² + 37.50996115x - 29.21189394
R² = 0.94380933
Ring Width (mm)
Cambial Age

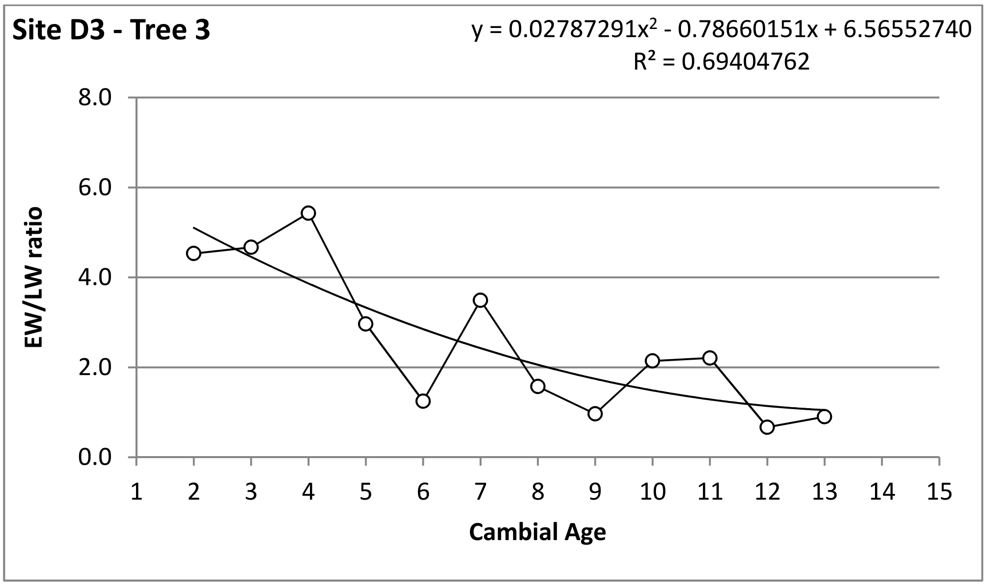

Site F14 - Tree 4
y = 0.07581585x⁴ - 1.89799793x³ + 16.97380536x² - 65.55828995x + 105.80722222
R² = 0.85653735
Ring Width (mm)
Cambial Age

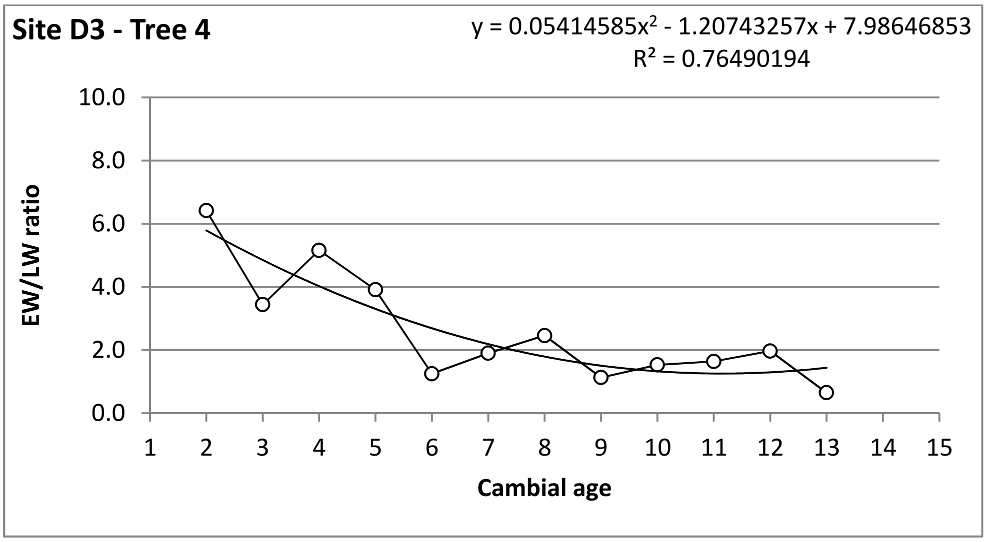

Site G19 - Tree 2
y = -0.00852564x⁴ + 0.27436286x³ - 3.06173077x² + 13.14617327x - 5.91967366
R² = 0.91992003
Ring Width (mm)
Cambial Age
0
5
10
15
20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

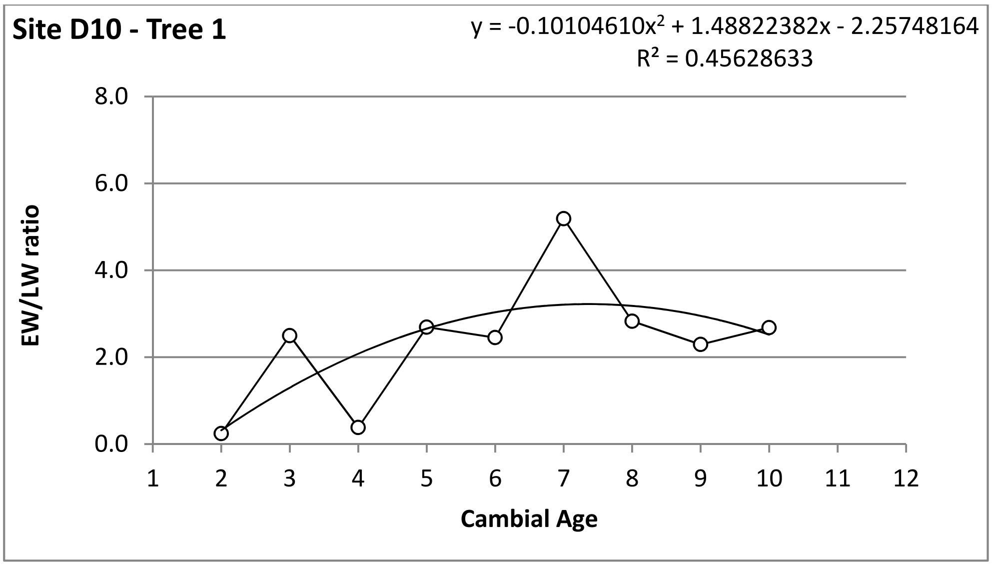

Site G19 - Tree 3
y = 0.05290793x⁴ - 1.25074981x³ + 9.89921329x² - 29.32470474x + 33.19000000
R² = 0.96518193
Ring Width (mm)
Cambial Age
0
5
10
15
20
0 1 2 3 4 5 6 7 8 9 10 11 12

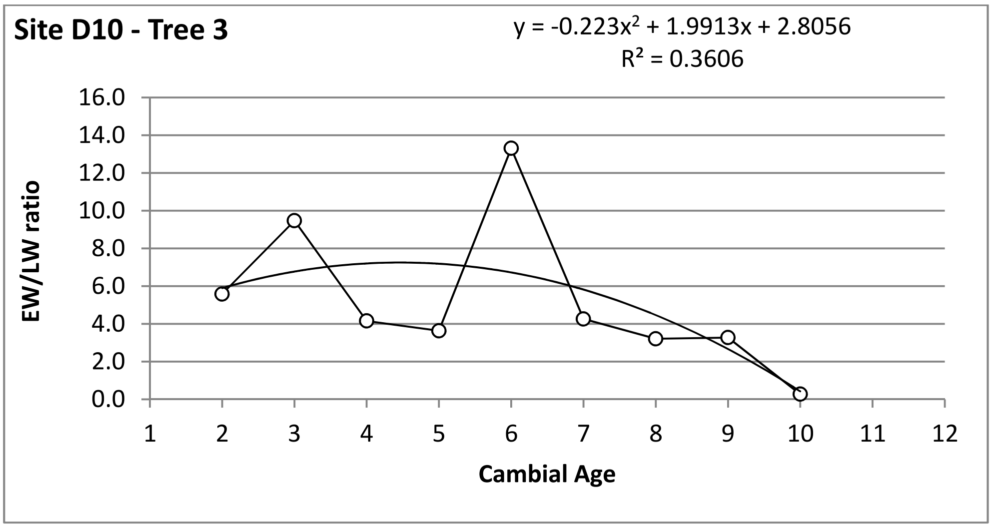

Site G36 - Tree 1
y = -0.00485769x⁴ + 0.19717890x³ - 2.69299350x² + 13.29051245x - 7.46562438
R² = 0.85513882
Ring Width (mm)
Cambial Age
0
5
10
15
20
25
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

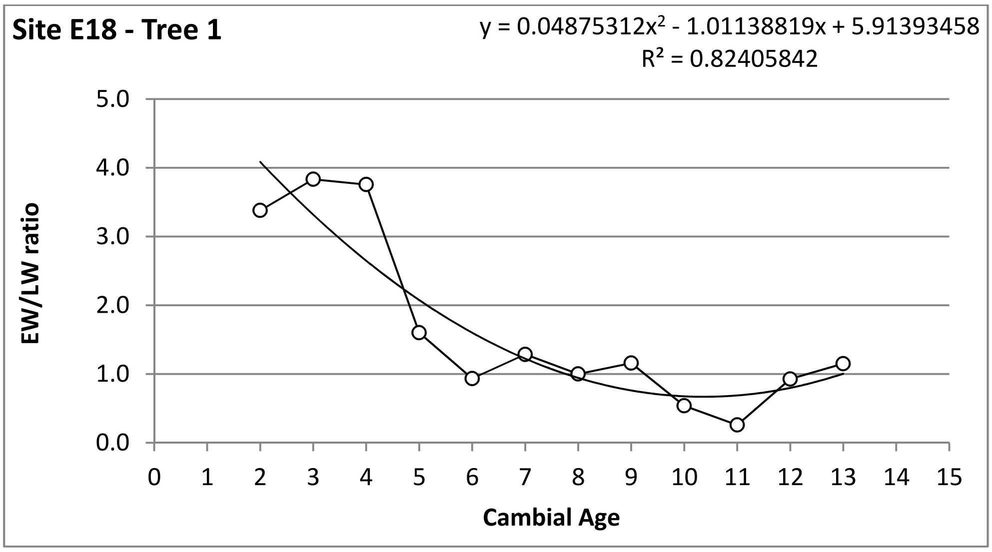

Site G36 - Tree 3
y = -0.00885187x⁴ + 0.33976555x³ - 4.39416232x² + 20.91099089x - 18.35082251
R² = 0.79851947
Ring Width (mm)
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

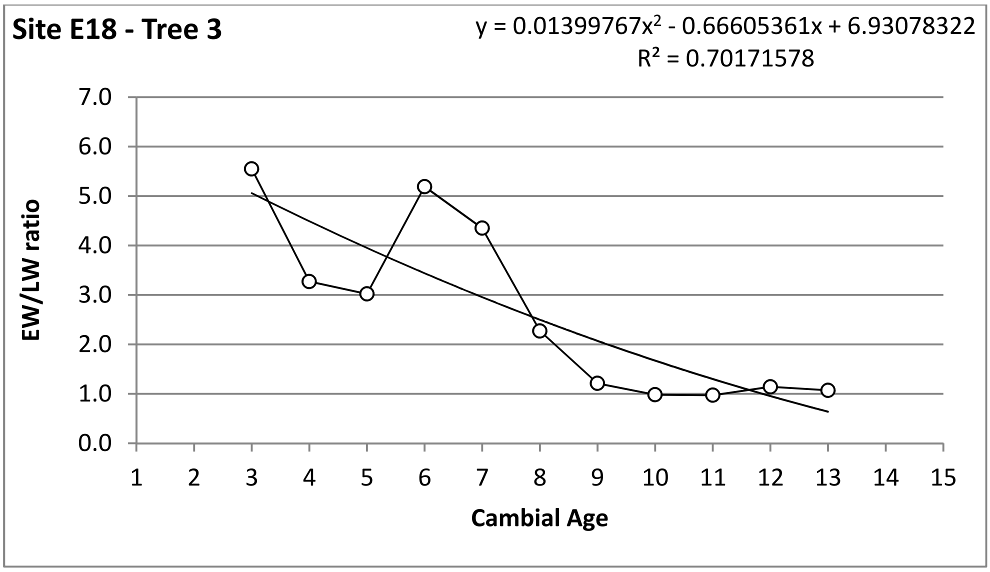

Site D3 - Tree 3
y = 0.02787291x² - 0.78660151x + 6.56552740
R² = 0.69404762
EW/LW ratio
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial Age

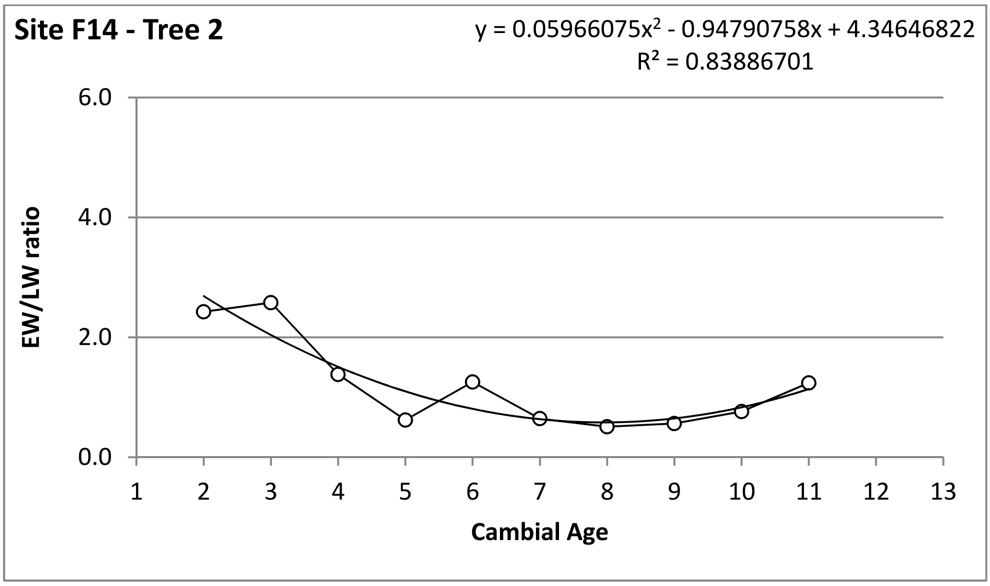

Site D3 - Tree 4
y = 0.05414585x² - 1.20743257x + 7.98646853
R² = 0.76490194
EW/LW ratio
10.0
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Cambial age

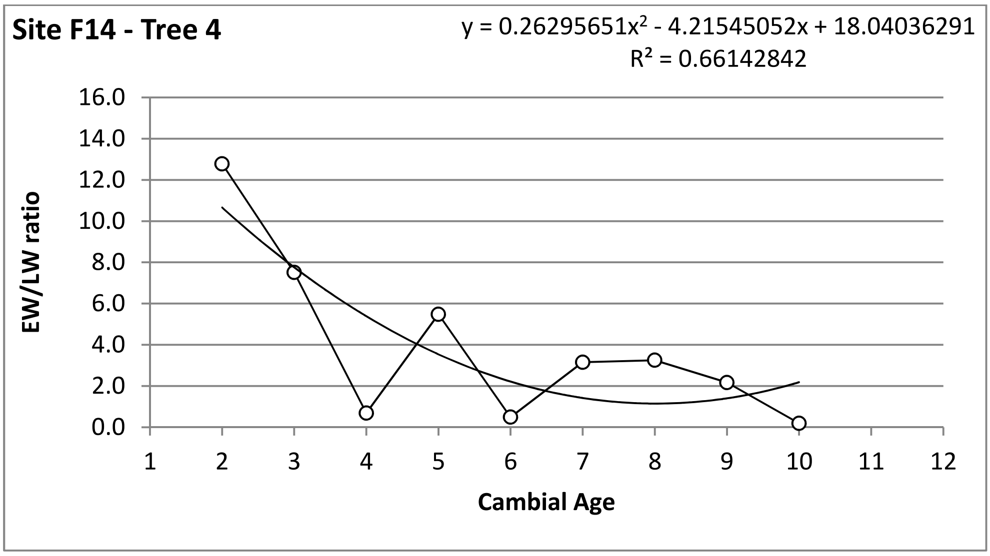

Site D10 - Tree 1
y = -0.10104610x² + 1.48822382x - 2.25748164
R² = 0.45628633
EW/LW ratio
Cambial Age

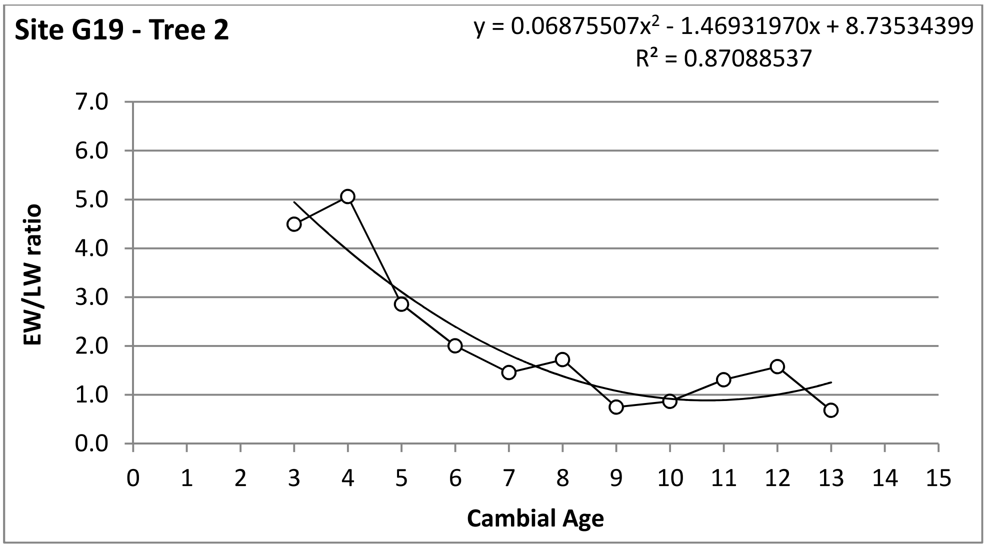

Site D10 - Tree 3
y = -0.223x² + 1.9913x + 2.8056
R² = 0.3606
EW/LW ratio
Cambial Age

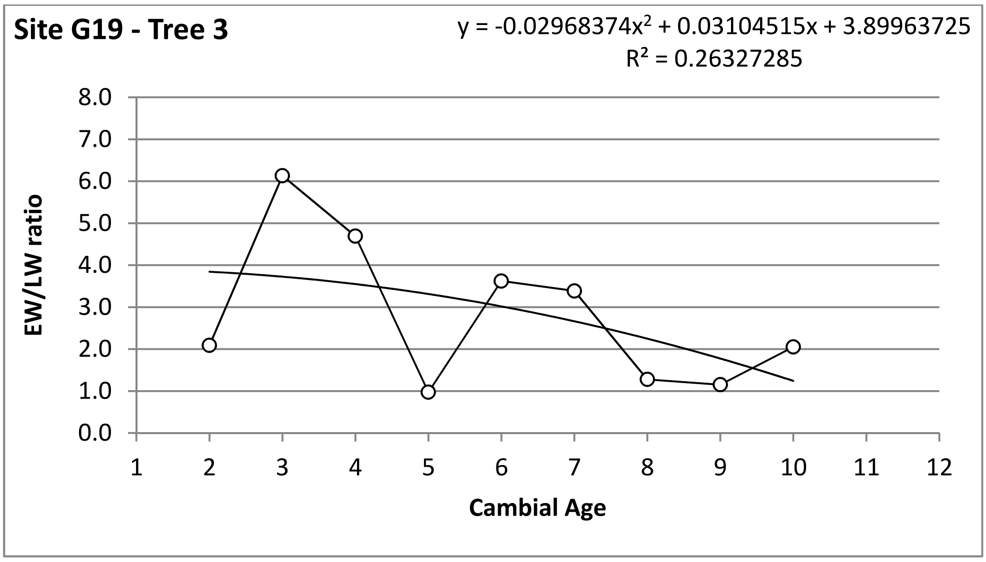

Site E18 - Tree 1
y = 0.04875312x² - 1.01138819x + 5.91393458
R² = 0.82405842
EW/LW ratio
Cambial Age

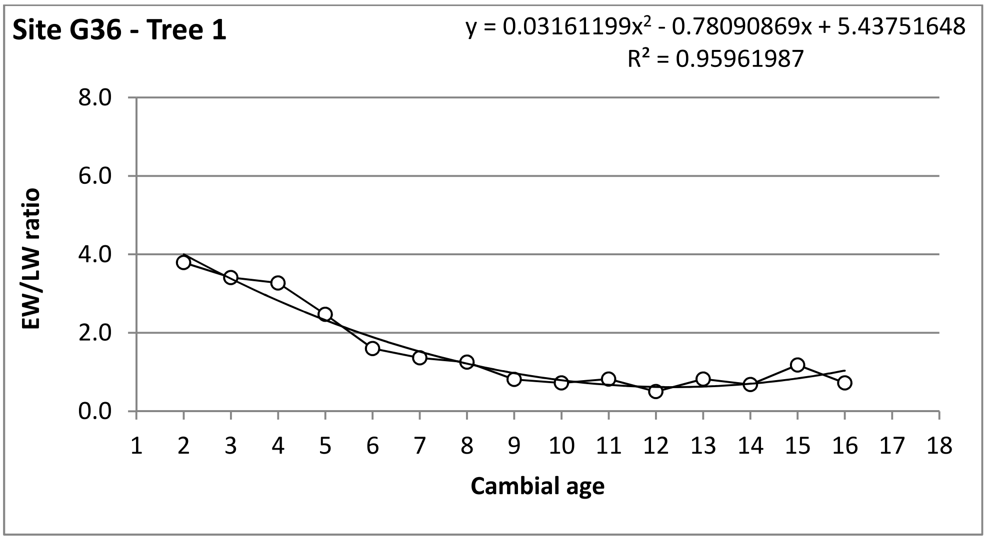

Site E18 - Tree 3
y = 0.01399767x² - 0.66605361x + 6.93078322
R² = 0.70171578
EW/LW ratio
Cambial Age

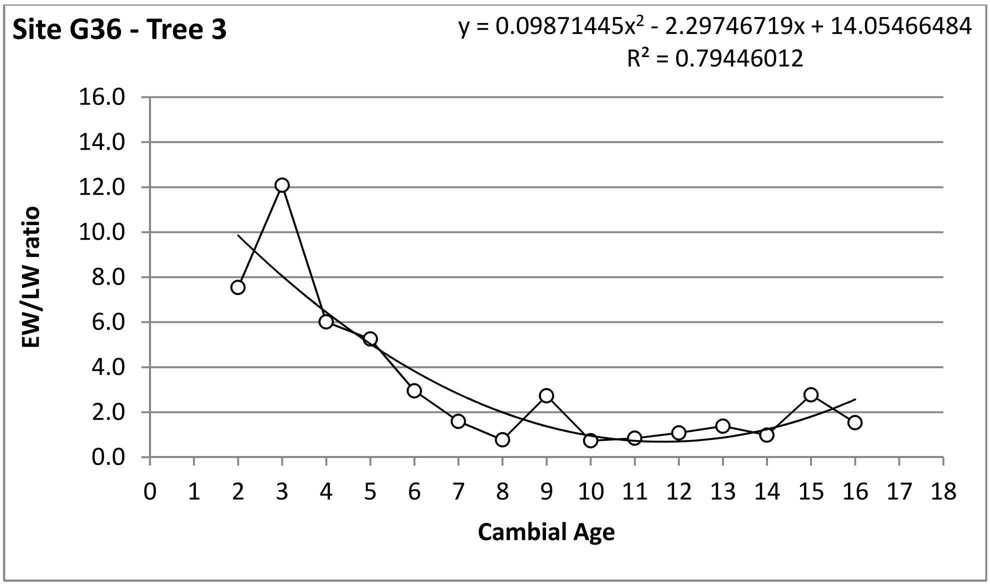

Site F14 - Tree 2
y = 0.05966075x² - 0.94790758x + 4.34646822
R² = 0.83886701
EW/LW ratio
Cambial Age


Site F14 - Tree 4
y = 0.26295651x² - 4.21545052x + 18.04036291
R² = 0.66142842
EW/LW ratio
Cambial Age


Site G19 - Tree 2
y = 0.06875507x² - 1.46931970x + 8.73534399
R² = 0.87088537
EW/LW ratio
Cambial Age

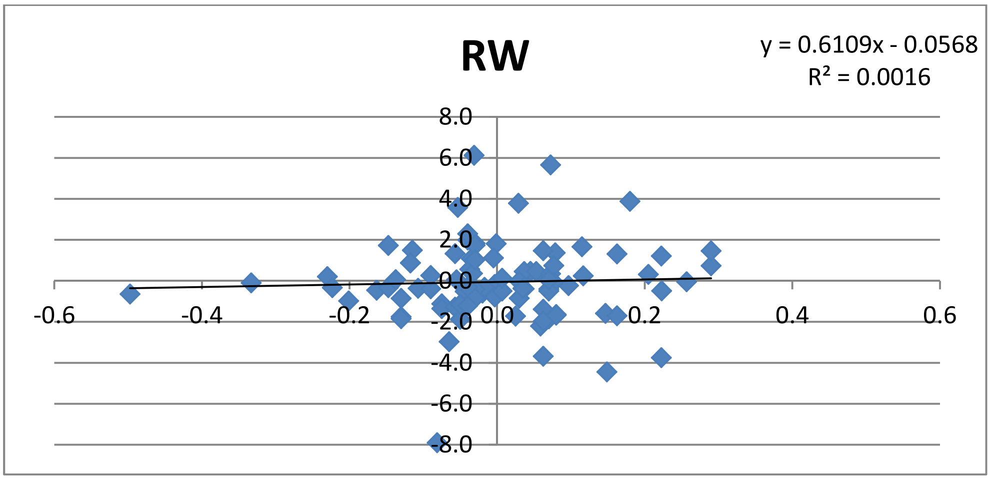

Site G19 - Tree 3
y = -0.02968374x² + 0.03104515x + 3.89963725
R² = 0.26327285
EW/LW ratio
Cambial Age

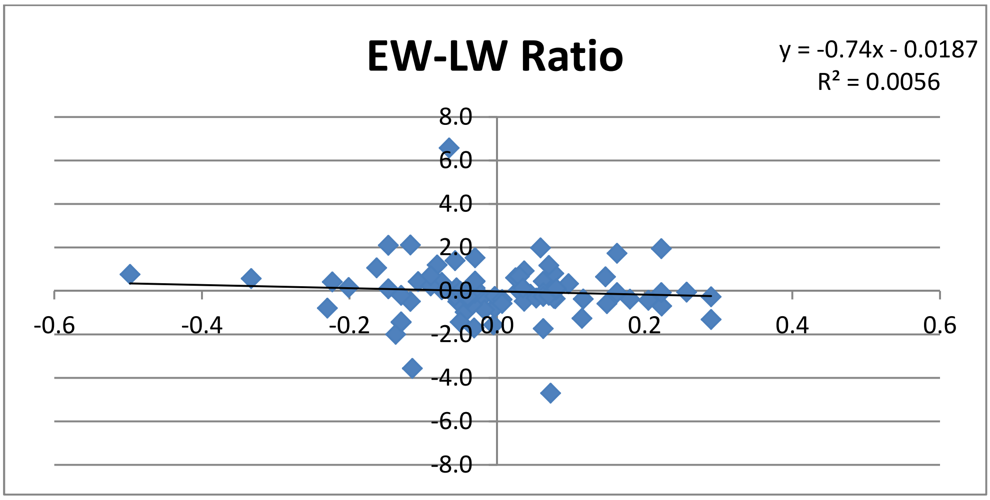

Site G36 - Tree 1
y = 0.03161199x² - 0.78090869x + 5.43751648
R² = 0.95961987
EW/LW ratio
Cambial age

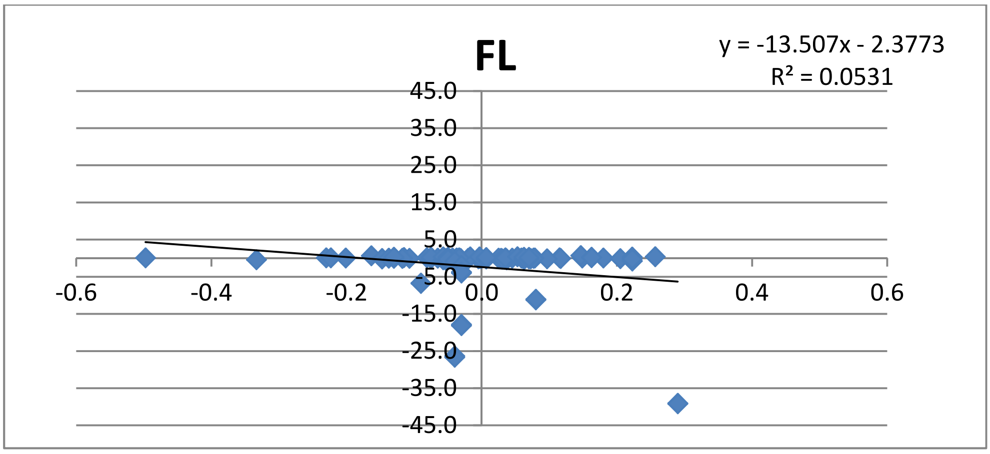

Site G36 - Tree 3
y = 0.09871445x² - 2.29746719x + 14.05466484
R² = 0.79446012
EW/LW ratio
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Cambial Age

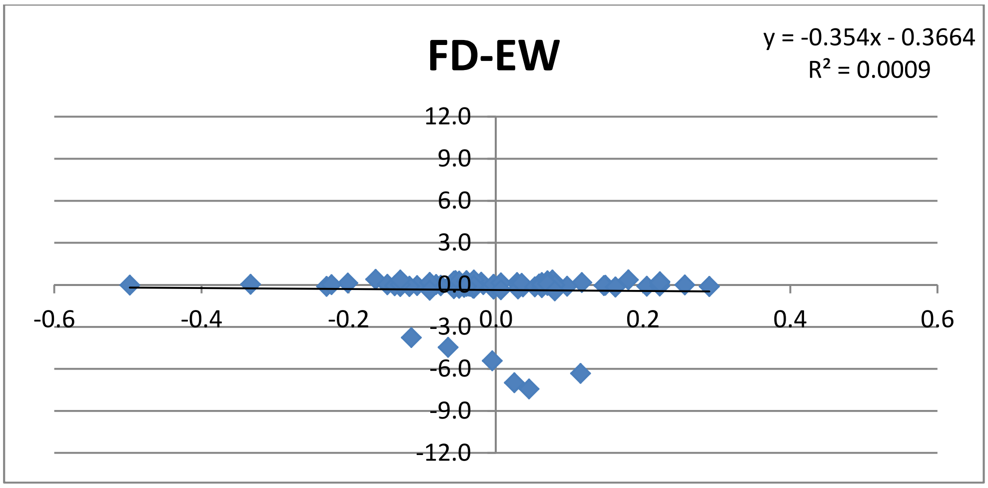
Appendix D

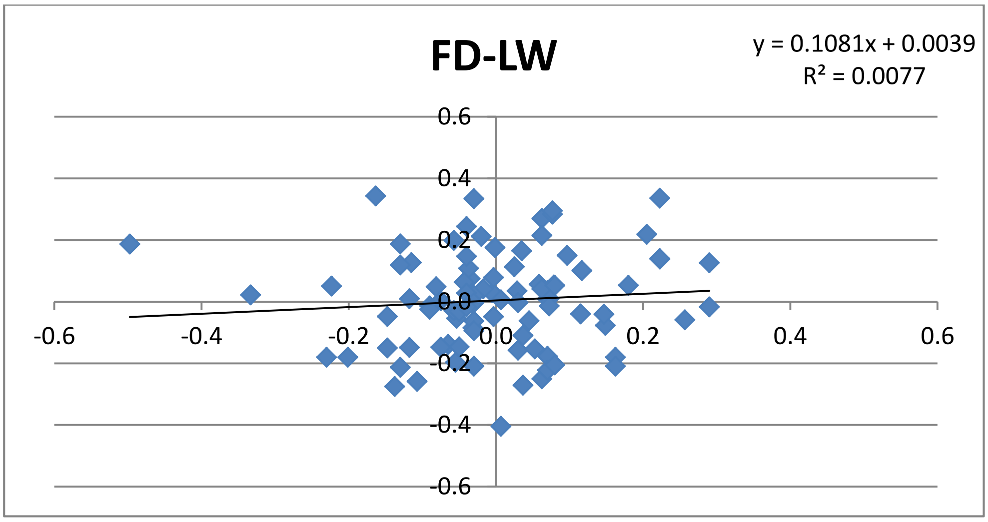
Correlation of ring and fibre properties with annual ETa/ETp. The regression function and R^2 are displayed in the graphs.

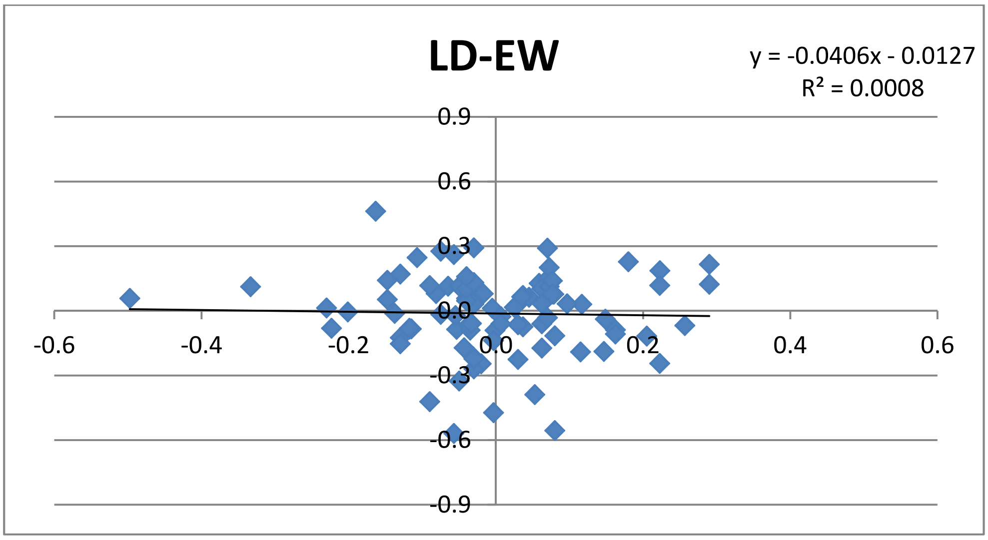


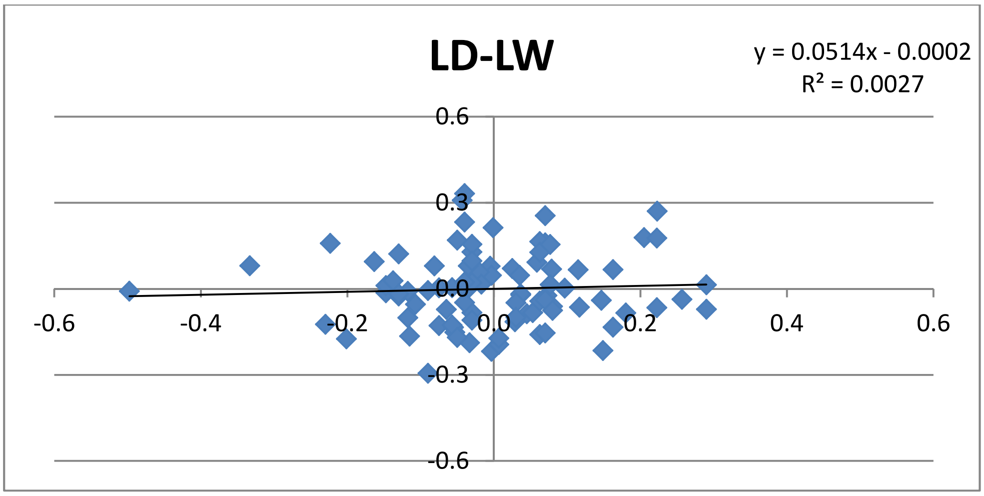


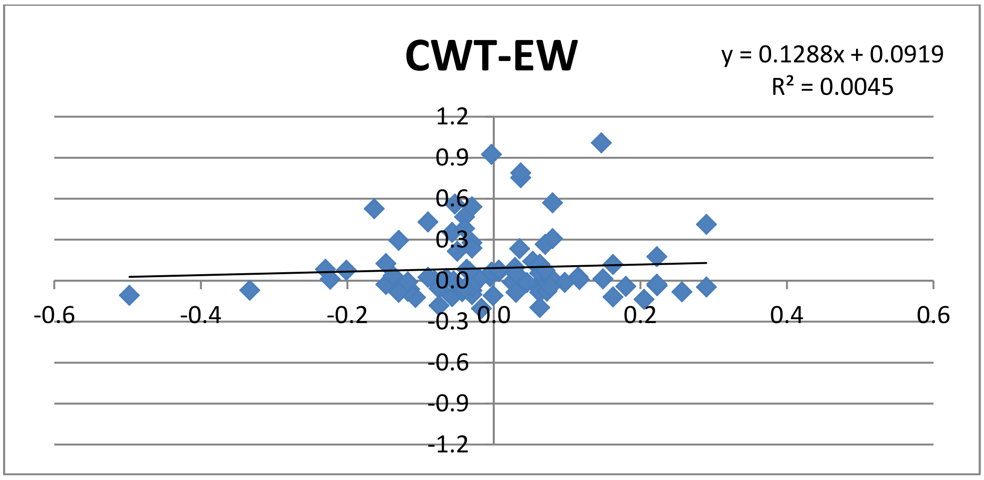


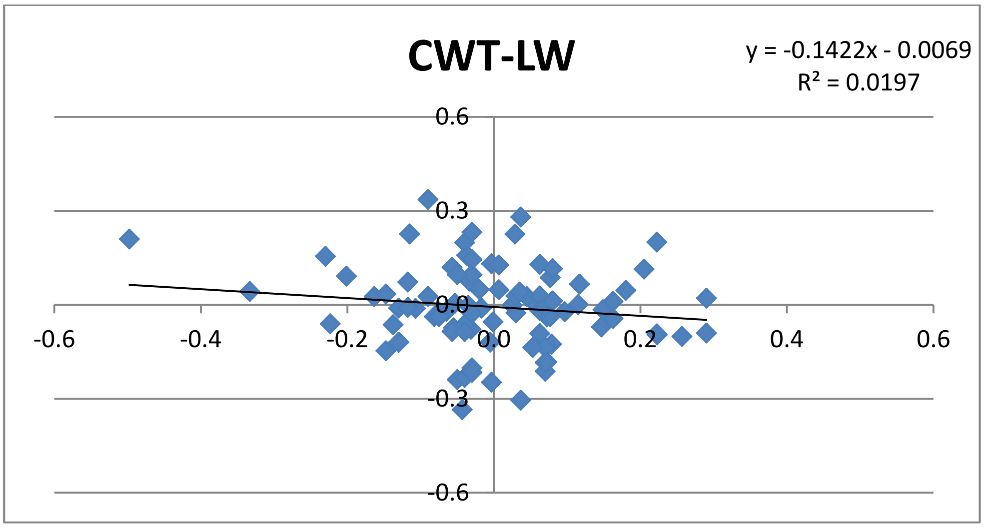

FD-EW
y = -0.354x - 0.3664
R² = 0.0009
12.0
9.0
6.0
3.0
0.0
-3.0
-6.0
-9.0
-12.0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6


FD-LW
y = 0.1081x + 0.0039
R² = 0.0077
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6


LD-EW
y = -0.0406x - 0.0127
R² = 0.0008
0.9
0.6
0.3
0.0
-0.3
-0.6
-0.9
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6


LD-LW
y = 0.0514x - 0.0002
R² = 0.0027
0.6
0.3
0.0
-0.3
-0.6
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6


CWT-EW
y = 0.1288x + 0.0919
R² = 0.0045
1.2
0.9
0.6
0.3
0.0
-0.3
-0.6
-0.9
-1.2
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6


CWT-LW
y = -0.1422x - 0.0069
R² = 0.0197
0.6
0.3
0.0
-0.3
-0.6
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6