Change in Leaf Area Index (LAI) and Tree Characteristics of Different Age Mountain Ash Stands to Determine Effects on Water Yield.

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Contents

Summary

Previous studies have shown that yield in water catchments after a bush fire has been largely affected by changes in leaf area of mountain ash (*Eucalyptus regnans F. Muell*) forests. This research aims to investigate the changes that occur in a mountain ash forest, within the Wallaby Creek Melbourne Water Catchment, as they age. These changes including; changes in leaf area, number of stems per hectare, diameter at breast height and tree height. This is done by showing the leaf area index of a 23 year old stand of 2.62 decreasing to 1.69 in a 350+ year old stand, the number of stems per hectare decreasing dramatically from 897.5 at the 1982 regrowth site to just 36.75 at the 350+ year old site, and the relationship between height and diameter as they increase with stand age, from trees at the 1982 regrowth having average diameters of 22 cm and heights of 21 m, to trees at the 350+ site with average diameters of 221 cm and heights of 80 m. These results were then all used to work out an allometric equation that relates the leaf area and diameter of individual trees by:

$$\text{Leaf area} = 60.551 \times e^{0.0153 \times \text{diameter}}.$$

From this and previous studies on mountain ash forests an allometric leaf area index was determined.

Introduction

Melbourne Water obtain water for the city of Melbourne from 1550 km^2 (155,000 ha) of forests in the central highlands of Victoria (Vertessy *et al.,* 1997; Vertessy *et al.,* 1995). Approximately half of these catchment areas are made up of mountain ash forests (*Eucalyptus regnans F. Muell*.). This area yields approximately 80% of the stream flow that makes up Melbourne's water supply because the forests grow on higher rainfall sites (Vertessy *et al.,* 1995; Haydon *et al.,* 1996). Fire is a very crucial, yet infrequent, component in the development and life cycle of mountain ash forests. For tree seedlings to survive and grow they need exposed soil with direct sunlight. In the environment these conditions are best created by bush fires (Vertessy *et al.,* 2001). Without the regeneration of mountain ash forests, caused by bush fires, they would die out in a few hundred years (as little as 500 years) (Haydon *et al.,* 1996). Bush fires that burnt through this area in both 1926 and 1983 converted 80% of the forest in the catchment from old growth (mature trees from 100-200 years of age) to regrowth (Vertessy *et al.,* 2001).

Studies showed that in the 30 years after a bush fire there was a considerable decline in stream flow compared to before fire (Haydon *et al.,* 1996; Dunn and Connor, 1993). The stream flow into catchments is measured using permanent measuring structures such as weirs, notches and flumes built and calibrated to measure the stream flow. Other measuring instruments such as current meters or ultrasonic flow/velocity meters are also used to measure stream flow at many sites. All weirs have been calibrated in the field using a portable measuring flume (Melbourne Water, 2005). Stream flow is then converted into a depth of millimetres by dividing the stream flow by the catchment area. Catchment areas are calculated using ground surveys of the surface topography (Moran and O'Shaughnessy, 1984). This decline in stream flow suggests that the amount of water yield from mountain ash forest catchments is related to stand age proposing that, among other things, there is a change in evapotranspiration over time (Vertessy *et al.,* 2001). Evapotranspiration is defined as the evaporation plus the transpiration (Bosch and Hewlett, 1982). Transpiration occurs *via* pores called stomata on the leaves of plants, which act as a channel between the leaf and the atmosphere. These pores capture and release carbon dioxide (CO_2) and oxygen (O_2) during photosynthesis exposing the inner tissue. This inner tissue is where evaporation occurs. The water vapour released into the atmosphere is a by-product of photosynthesis called evapotranspiration (Moran and O'Shaughnessy, 1984; Knox et al., 2001).

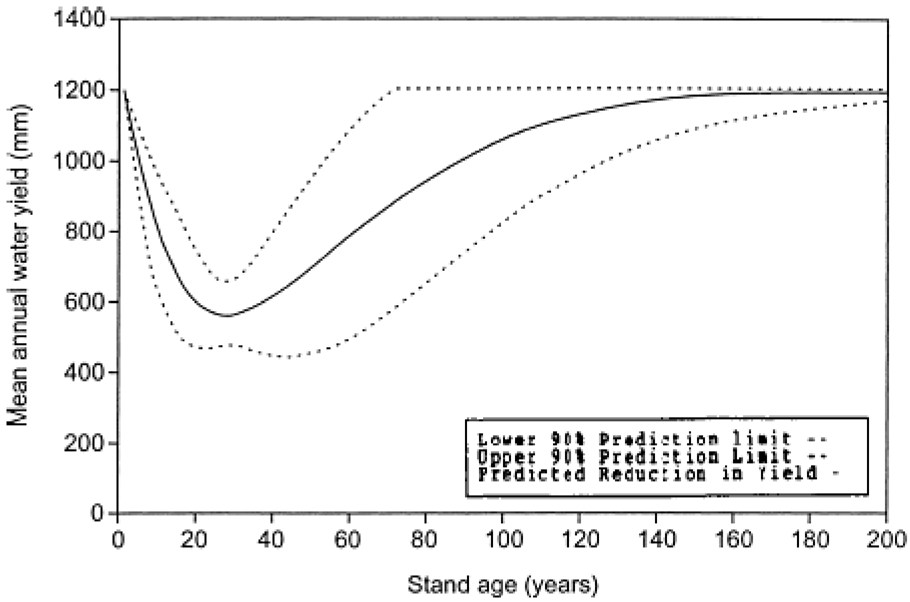

Figure 1. Kuczera's generalised relationship between mean annual stream flow and forest age for catchments with mountain ash forests (Haydon *et al.,* 1996).

Kuczera (1985) developed a relationship (Figure 1) between mean annual water yields and stand age for mountain ash forests by using rainfall runoff data from fire affected mountain ash forests. From this we can see that directly after a bush fire there was a rapid decline in yield by 580 mm in 27 years. After this time the yield slowly returned to the levels previous to the fires, taking up to 150 years to fully recover (Vertessy *et al.,* 2001). In cases that exhibit these characteristics, the water yield decline is attributed to changes in evapotranspiration (Haydon *et al.,* 1996). The yield is given by the amount of precipitation minus the evapotranspiration. As the forests age the evaporation stays reasonably constant, thus as a forest ages the transpiration changes more so then the evaporation (Haydon *et al.,* 1996). Therefore it is believed that as a forest ages and the leaf area decreases so does the overall transpiration affecting the water yield. For mountain ash forests growing under a particular set of soil and climatic conditions, evapotranspiration is strongly linked to forest leaf area index (the ratio of leaf area per unit of ground area) (Haydon *et al.,* 1996). A large mountain ash tree can transpire up to 300 litres of water on a summer day (Knox *et al.*, 2001).

The leaf area index (LAI) of a forest is a major determinant of its water balance. Allometric relationships, which are the change in proportion of various parts of an organism as a consequence of growth, exist to relate the leaf area of a tree to stem or canopy characteristics (Whitford *et.al*., 1995; West *et.al*., 1988). As a forest ages there is intense competition between the plants for sunlight, this results in rapid tree growth (both width and height of the tree) in a young stand resulting in the weaker trees being shaded out and dying. This thinning continues for the life of the stand but at a decreasing rate. After 100 to 200 years this results in large gaps forming in the canopy (Vertessy *et al.,* 2001). This results in decreasing leaf area of the dominant mountain ash trees over time as the stand ages, leading to less water being lost through transpiration by the over story, which is likely to affect runoff into water catchments. Younger age stands of approximately 25-30 years old, as shown in Figure 1, should have a higher leaf area and this would be reflected in a decreased runoff as seen in Kuczera's curve. The leaf area index of the undergrowth of forests acts in reverse to the leaf area index of the mountain ash trees as seen in Figure 2. Figure 2 shows that total leaf area (LAI_{tot}) of the forest increases rapidly to around 5.4 after 7 years, then declines steadily to 3.6 after 240 years. The leaf area index of the mountain ash trees (LAI_{ash}) rises to its maximum of 4.0 by 15 years and then decreases to around 1.3 after 235 years. This indicates roughly a threefold difference in the leaf area index of the mountain ash trees between old-growth and new-growth forests. The leaf area index of the undergrowth (LAI_{und}) in Figure 2 was not calculated for the first 5 years of forest regrowth due to the leaf area at this time being estimated to be negligible (close to zero) during this time. The leaf area index of the undergrowth decreases from 3.2 to its minimum of 1 between 6 and 13 years as the mountain ash over story establishes. Therefore as the mountain ash trees grow and the leaf area thins, the leaf area of the undergrowth gradually increases to a value of 2 after 100 years and increases slowly after this to a value of 2.4 after 240 years.

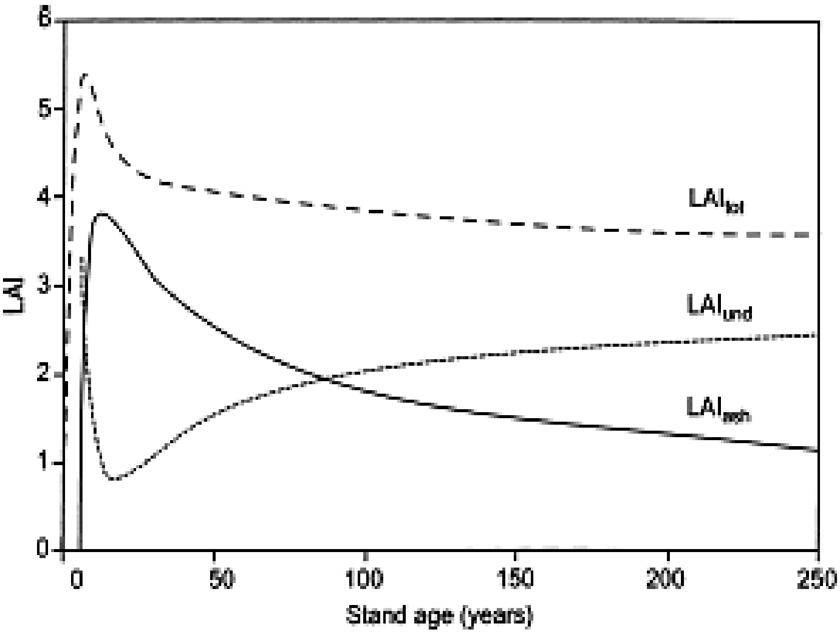

Figure 2. Effects of stand age on leaf area index (Vertessy *et al.,* 2001).

Aims of the Project

In mountain ash forests the water yield in catchments has been shown to relate to stand age (Vertessy *et al.,* 2001). The overall research question is to determine if the leaf area is directly related to the stand age and therefore could be used to determine water yield in catchments and changes in runoff as the stand ages. The primary aim is to measure the leaf area index of different age classes of mountain ash forests to test whether they follow the same pattern as the Kuczera curve and the curves shown in Figure 2 (i.e. newer growth forests have a higher leaf area index than older growth forests). A second aim is to determine a relationship between tree height, tree diameter at breast height, number of stems per hectare and the leaf area that may be related back to previous studies, including Kuczera's curve, which shows how water yield changes with stand age and studies carried out by Vertessy *et al.* (1995), which shows a relationship between diameter at breast height and the leaf area of individual trees. If a relationship can be found between these allometric relations and leaf area index of the mountain ash trees, then the aim is to determine what effect the under growth has on the total leaf area index, by determining the total leaf area index minus the leaf area index of the mountain ash trees. Using a relationship between the leaf area index and the diameter at breast height of trees, the leaf area index of the mountain ash trees might be calculated, to observe the effects that just the mountain ash trees and just the under story have on the total leaf area index of the forests.

Site Description

The site used in this study is located in the mountain ash forests of the Wallaby Creek Melbourne Water catchment, located near Kinglake, north east of Melbourne, Australia (Figure 3). The Wallaby Creek catchment is situated on the Hume Plateau at 600 to 750 m above sea level, with a maximum altitude of 863 m at Mount Disappointment, and also situated on the Kinglake Plateau at 490 to 595 m above sea level (Figure 4). The catchment area is made up of many creeks and rivers, such as: Plenty River, Silver Creek, Wallaby Creek, Jacks Creek and Big Ash Creek. A water channel was built from 1883 to 1885 to utilize the geography of the region. The channel captures the head waters of the Wallaby Creek and Silver's Creek at altitudes of 518 m and 533 m, which flow off the Hume Plateau into the channel and then flow down into Jacks Creek. The Big Ash Creek flows into the Plenty River which flows off the Hume Plateau. In 1884, the Plenty River was dammed below its junction with Jacks Creek, forming the Toorourrung Reservoir (Figure 3) (Ashton, 2000).

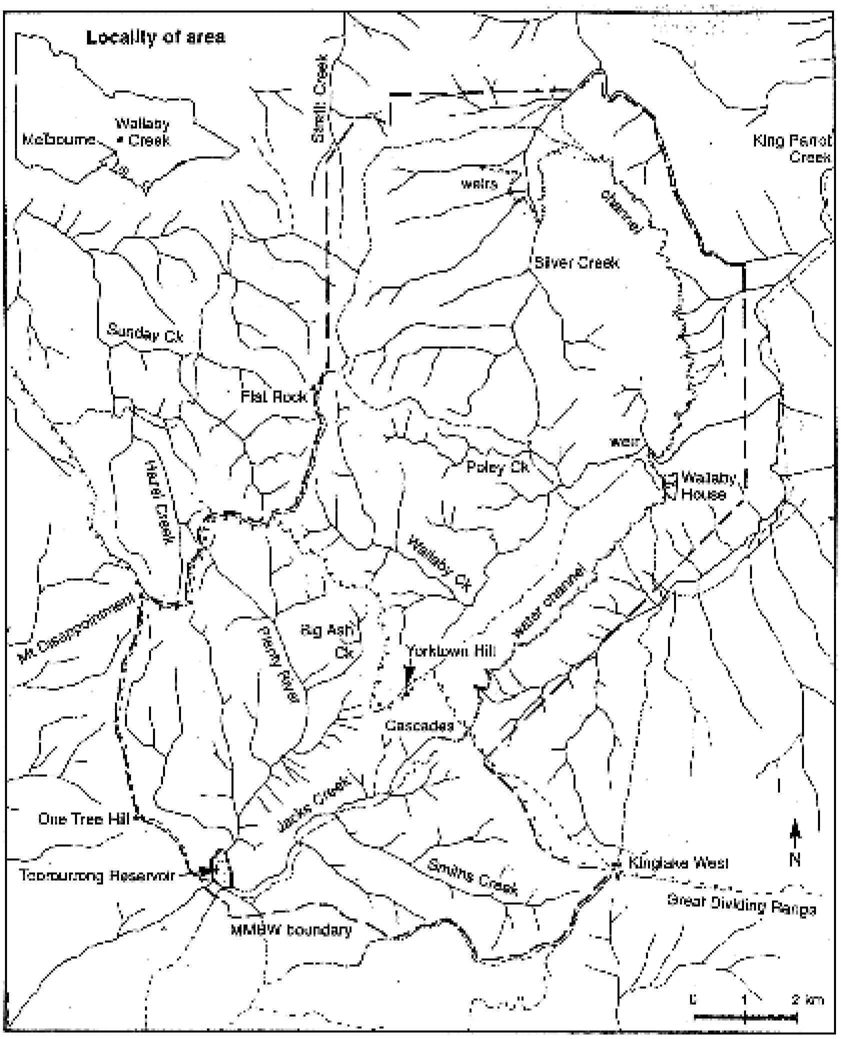

Figure 3. Location of the Wallaby Creek Melbourne Water Catchment, north east of Melbourne (Ashton, 2000).

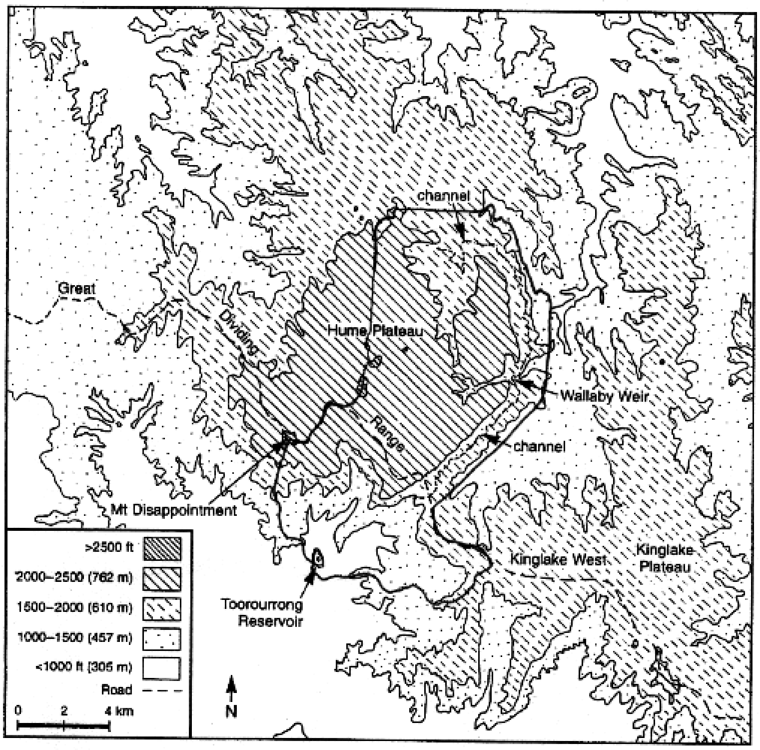

Figure 4. Map of the topography of the Hume Range, showing the position of the Wallaby Creek Melbourne Water Catchment (Ashton, 2000).

A major fire occurred throughout Victoria in February 1926 after a very dry season and another severe fire occurred in November 1982, both affecting the Wallaby Creek catchment. These fires have burnt some areas severely and repeatedly, but also left some areas untouched. Due to this, these fires have created areas of different aged mountain ash forests, as seen in Figure 5. The under story and its characteristics of these different aged forests have been affected by these fires, in relation to both the life of the under story and the longevity of the seed stored in the top soil. Since the 1926 fire, 79 years ago, there is strong evidence of a recovery of the wet sclerophyll under growth in the mountain ash forests. Damp and wet sclerophyll under growth has regenerated since the 1982 fires in mountain ash forests. The old growth mountain ash forests, which are dated at 350+ years of age, consist of a wet sclerophyll under story (Ashton, 2000).

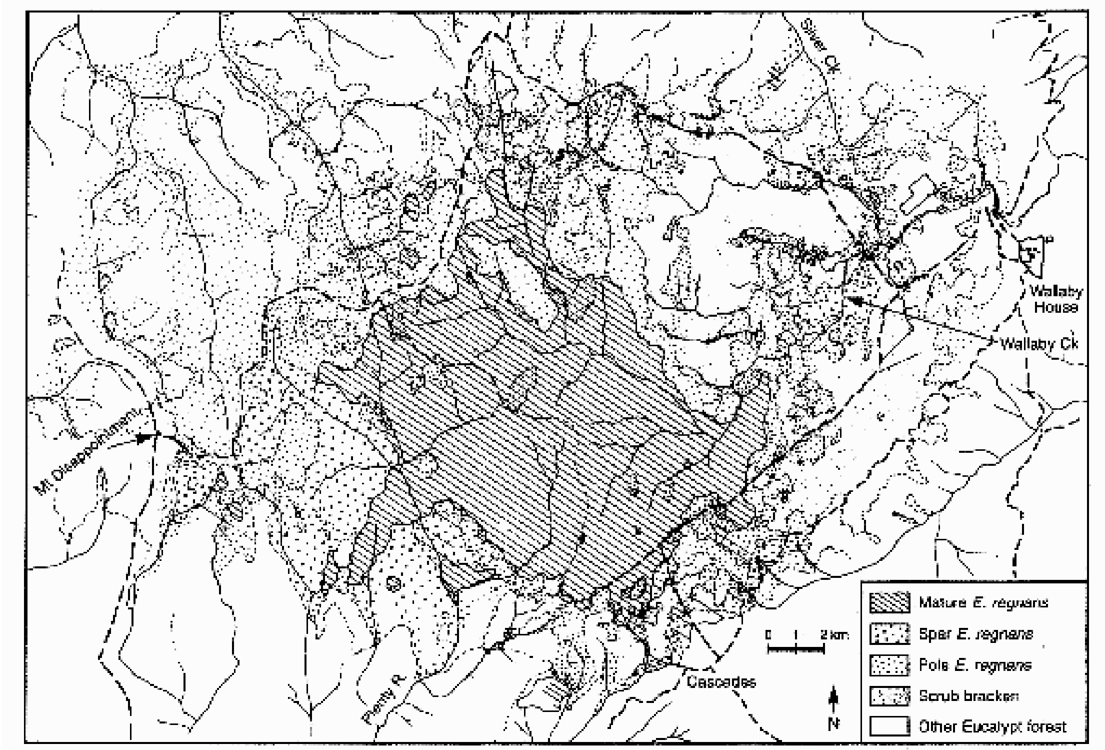

Figure 5. The distribution of mountain ash (*E. regnans*) trees at the Wallaby Creek Catchment (Ashton, 2000).

Methodology

There are a number of methods that can be used to measure the leaf area index; these include destructive and optical methods. Destructive methods involve cutting down trees in a sample area and stripping these trees of their leaves to measure leaf area. This is impractical at Wallaby Creek as it is a national park. Optical methods include hemispherical photography, which uses a fish-eye lens, and using the LAI-2000 Plant Canopy Analyser (Jonckheere *et al.,* 2004; Weiss *et al.,* 2004). This project is utilizing optical methods using the LI-COR LAI-2000 Plant Canopy Analyser to measure single sided leaf area. The LAI-2000 is a portable integrating radiometer that offers a non-destructive means of measuring the leaf area. The LAI-2000 measures diffuse radiation over a spectral domain of less than 490 nm through five different zenith angles (7°, 23°, 38°, 53° and 68°) (Cherry *et al.,* 1998). Two sensors used simultaneously measure the radiation above the canopy and the diffuse radiation below the canopy (Cherry *et al.,* 1998). The leaf area index is firstly calculated by:

$$\frac{\text{Diffuse intensity below the canopy at view angle } \theta}{\text{Diffuse intensity above the canopy at view angle } \theta} = T(\theta) \qquad \ldots (1)$$

Where T(θ) is the probability of diffuse non-interceptance for a given view angle (called the gap fraction). The leaf area index is then calculated as:

$$LAI = -2\int_0^{\frac{\pi}{2}} \ln(T(\theta))\cos(\theta)\sin(\theta)d\theta \qquad \ldots (2)$$

The LAI-2000 computes equation 2 by numerical integration using the five zenith angles. The LAI-2000 geometrically computes a constant weighting factor $w(\theta_i)$ for each zenith ring:

$$w(\theta_i) = \sin(\theta)d\theta \qquad \ldots (3)$$

The leaf area index in now calculated as:

$$LAI = -2\sum_{i=1}^{5} \ln(T(\theta_i))\cos(\theta_i)w(\theta_i) \qquad \ldots (4)$$

Where *i* refers to each of the five zenith angles (Li-Cor, 1991).

The sensor measuring the above canopy radiation is placed in a clearing, with an approximate radius of 130 m for a nearby 50 m tall forest, with an undisturbed view of the sky. The two meters are set in remote mode; the sensor in the clearing logs results of the changing conditions every 60 seconds, while the other sensor is used to log the change in conditions under the canopy. At the end of the data collection, the two sensors are hooked up to a computer where the FV2000 program provided with the equipment takes the measurements and computes the leaf area index. The LAI-2000 also measures the standard error of the LAI determinations, the fraction of the sky visible beneath the canopy, the foliage orientation as a mean tilt angle (MTA) and the standard error of the mean tilt angle (Li-Cor, 1991).

Mountain ash tree height in a forest aged 20 to 300 years old ranges from 15 to 100 metres tall. With the height of these trees they need to be measured using trigonometry. Measuring the angle from eye line to the top of the tree at a certain distance away from the tree (θ), and measuring the angle from eye level to the same height as eye level on the tree (φ), creates a small and a large triangle (Figure 6). Then by using the tan rule the height of each triangle can be measured:

$$H = d \times \tan(\theta) \ldots (5)$$

Where H is the tree height, d is the distance measured from the tree and θ is the angle from the ground to the top of the tree. Then, if looking up hill at the tree, the tree height equals the height of the small triangle plus the height of the large triangle, minus the part below the ground (shown in Figure 6, left-hand diagram). If looking down hill at the tree, the tree height equals the height of the large triangle plus the height of the small triangle, plus the height to eye level of the observer (Goodwin, A.N. 2004).

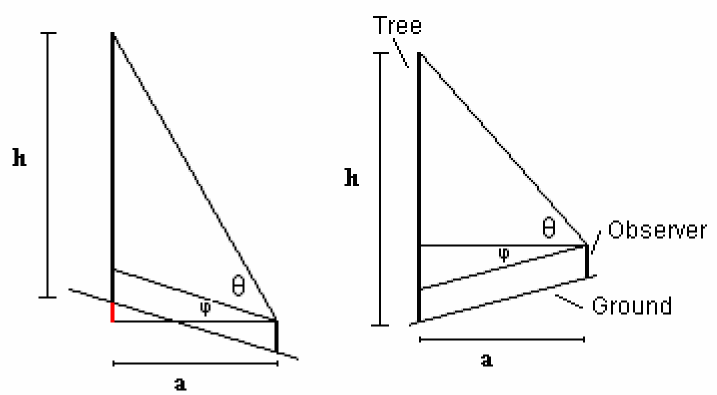

Figure 6. Example of measuring techniques for the height of trees, showing looking up hill at the tree (left) and looking down hill at the tree (right).

The over bark method is used to measure the diameter of the trees at breast height. This means taking a tape measure and wrapping it around a tree to measure the circumference, then working out the diameter by dividing this circumference by π (≈ 3.14).

Sampling Techniques

Monash University have established plots within the mountain ash forests of the Wallaby Creek water catchment. There are three plots, one positioned in the 1926 regrowth, one positioned in the 1982 regrowth and one in the unburnt 350+ year old forest (Figure 7). These plots are 200 m by 200 m (4 hectares) in size and have flags positioned every 20 m as shown in Figure 8. These flags were placed using a compass and a tape measure. A GPS (global positioning system) would be more accurate, however it doesn't work under the canopy. Leaf area index measurements in these sites are taken at each flag giving a good average of leaf area index in all the sites and allowing for a good comparison between sites. The total number of trees is counted in each plot and used to give an average of the number of trees per hectare. The diameters of the trees and the tree heights will be measured in a selected number of grid squares to give a good sample size showing an estimated average of these.

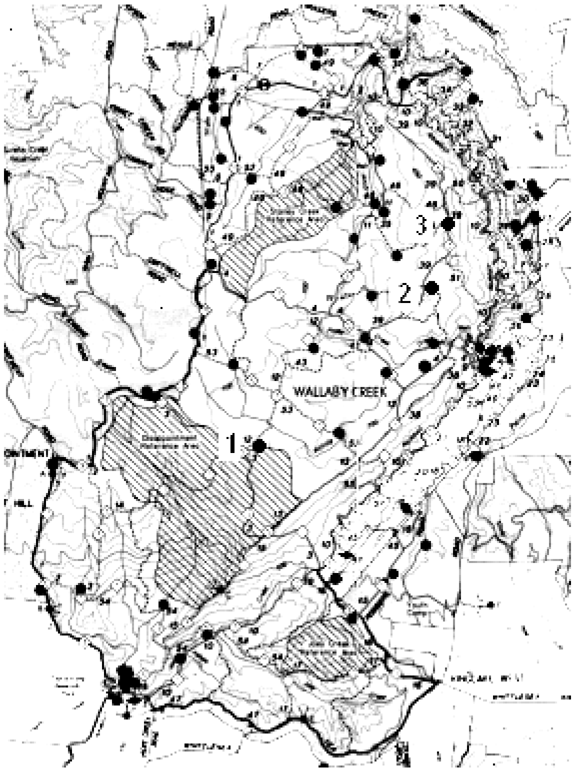

Figure 7. Sites within the Wallaby Creek catchment. Point 1 refers to the old growth 350+ year old site. Point 2 refers to the 1926 regrowth and point 3 refers to the 1982 regrowth (Ashton, 2000).

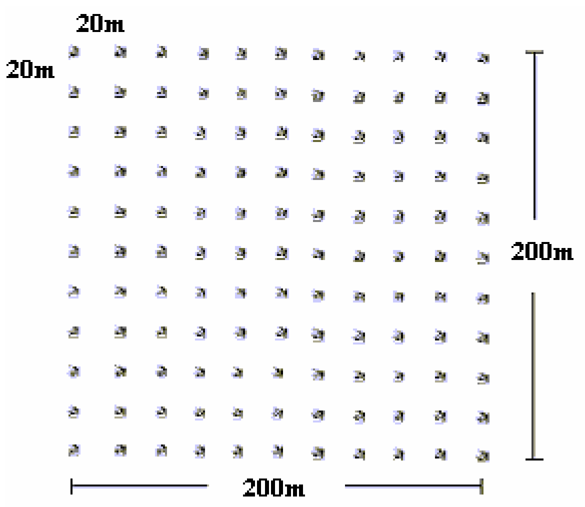

Figure 8. Diagram of Monash created sites. Dots represent flags where leaf area measurements are taken.

Results and Discussion

The leaf area index was measured at all 121 points of the grids using the LAI-2000 plant canopy analyser, as shown in Table 1. Due to the large undergrowth at the 350+ year old site the actual leaf area index recorded was a total leaf area index of both the mountain ash trees and the undergrowth; however due to recently fallen trees there was a large clear area where there was no undergrowth and just the mountain ash trees leaf area index was measurable. Due to the size of this gap in the undergrowth there was only enough room for a small number of measurements to be taken, for this only the first two zenith angles were used to cancel any interference from nearby trees. In Table 1, LAI refers to the leaf area index, SEL is the standard error of the leaf area index, DIFN is the fraction of the sky visible beneath the canopy, MTA is the foliage orientation as a mean tilt angle, SEM is the standard error of the mean tilt angle and SMP is the number of sample points.

Site	LAI	SEL	DIFN	MTA	SEM	SMP
1982	2.62	0.04	0.166	62	0.86	121
1926	2.09	0.04	0.19	49	1.3	121
Total 350+	3.36	0.07	0.068	46	2.3	121
350+	1.69	0.07	0.254	41	4.8	10

Table 1. The leaf area index, measured using the LAI-2000 plant canopy analyser.

The 350+ year old site is just the mountain ash trees, thus only has 10 sample points, where as Total 350+ is the mountain ash plus the undergrowth. Using these two values, the leaf area index of the undergrowth at the 350+ year old site was 1.67 compared to the leaf area of just the mountain ash trees of 1.69. This shows that there is an even distribution of leaf area between the mountain ash trees and the undergrowth at the 350+ year old site.

The data collected was compared to studies done by Vertessy *et al.* (2001), as shown in Figure 9.

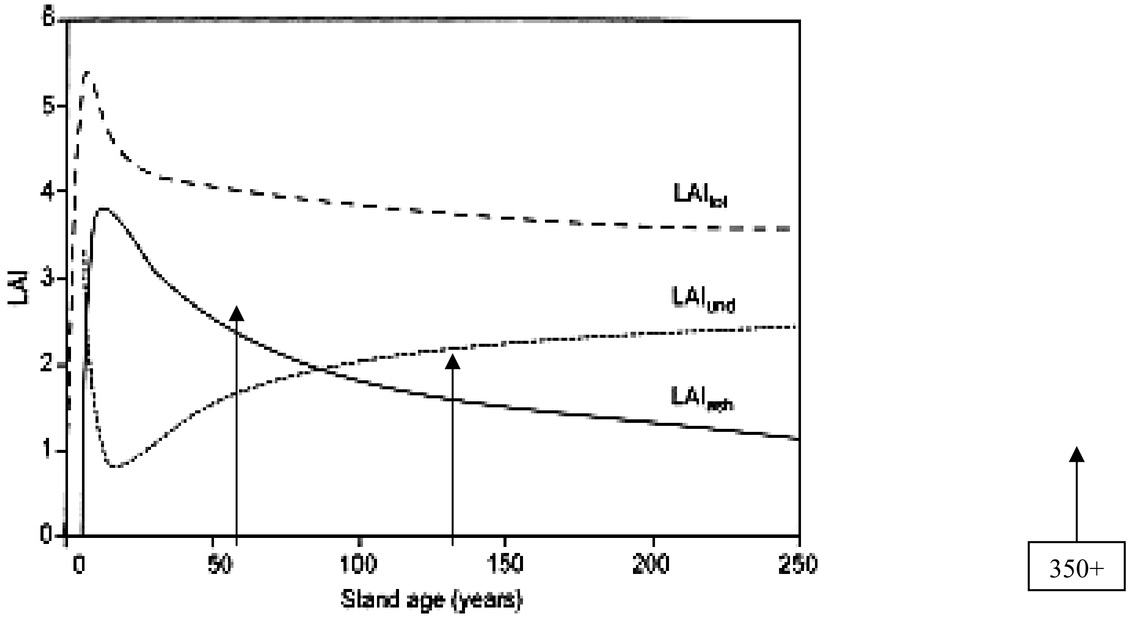

Figure 9. Effects of stand age on LAI compared to values from Table 1 (shown by arrows) (Vertessy *et.al.*, 2001).

From Table 1, the 23 year old stand had a leaf area index of 2.62 compared to LAI_{ash} in Figure 9, where a 23 year old stand shows a leaf area index of approximately 3.7. At the 1926 regrowth site the leaf area index was 2.09 compared to LAI_{ash} in Figure 9 for a 79 year old forest, where the leaf area index has the value of approximately 1.9. At 350+ years of age, there is no data from Figure 9, as there are no published results of mountain ash forests past 250 years of age. However, LAI_{ash} in Figure 9 has an approximate leaf area index of 1.2 at 250 years of age compared to 1.69 after 350+ years from Table 1.

From this comparison it can be seen that the leaf area index at 20 years of age from Table 1 is significantly less than the studies done by Vertessy *et al.* in 2001. At 80 years of age, however, the leaf area index of both results are considerably close. After

250 years of age there has been a reversal and the measured leaf area in Table 1 is higher than that of the past study. There are a number of reasons for the nature of this. The 1982 regrowth site that was measured seemed to have a lot of recently fallen trees on the ground, most likely due to a storm that past through the area on the 2nd of February 2005. The number of fallen trees could be the reason for a lower the leaf area index. Also the studies done by Vertessy *et al.* (2001) looked at 33 different plots of different sizes and used this to work out a relationship between leaf area indexes and stand age. The data from Table 1 are the results from only a single plot at each stand age. The results may correspond more closely if measurements were carried out to assess variability over the different aged stands.

Another interesting difference between the two sets of data is the change of the leaf area index of the undergrowth. In Figure 9, after 250 years, the leaf area index of the undergrowth appears higher, thus, more dominant than that of the mountain ash trees, and seems to continue to diverge as the stand ages. The data collected in Table 1 shows that after 350+ years the leaf area indexes for undergrowth and mountain ash trees are very similar (1.67 to 1.69). This is likely to be caused by the variability between sites and more measurements of 350+ year age stands would be needed to observe more effects of this.

However, the data from Table 1 shows there is a change and decrease in leaf area as the forest ages. The data shows that the leaf area decreases more rapidly in the younger forest as it changes from 2.62 to 2.09 in approximately 60 years, compared to changing from 2.09 to 1.69 over approximately the next 270 years. This can be seen further when looking at the number of mountain ash trees per hectare as shown in Table 2.

1982 regrowth		1926 regrowth		350+ years	
number of trees in plot	3590	number of trees in plot	954	number of trees in plot	147
trees per hectare	897.5	trees per hectare	238.5	trees per hectare	36.75
Average Trees in 20m × 20m square	35.9	Average Trees in 20m × 20m square	9.54	Average Trees in 20m × 20m square	1.47

Table 2. The number of trees per hectare across the three different sites.

Table 2 shows the total number of trees in each 4 hectare plot, which were used to give an average number of trees per hectare. Initial estimates for the 1982 regrowth were that there would be around 1700 trees per hectare compared to the 897.5 as measured. This difference is most likely due to the large number of trees that appeared to have recently fallen. Despite this, the data shows a rapid initial growth of mountain ash trees after a bush fire. The 1926 regrowth had 238.5 trees per hectare, showing a rapid decline in mountain ash trees from 20 years of age to 80 years of age. The 350+ year age stand had only 36.75 trees per hectare. The rate of decline in the number of mountain ash trees was less from 80 years of age to 350+ years of age, yet is still considerable. The decreasing trend shown here reflects the same observed trend in the leaf area index.

The number of trees per hectare shows how after a fire there was rapid tree growth and once the trees reach a certain age they start competing with each other for sunlight and soil nutrients. After this the number of trees starts decreasing, rapidly at first but slowing with stand age.

There are errors associated with counting the number of trees per plot. For this 350+ year old site there will be very small to no error in the tree count. There aren't many trees within the plot and they are quite large in diameter, therefore it's very unlikely that the trees were missed or counted twice. The flags marking the grid points were extremely hard to see within the plot, due to the large undergrowth, but with the substantial size in diameter of the trees it became negligible. In the 1926 regrowth the error in the tree count is larger, there are a lot more trees and thus there is more chance that trees were counted twice or missed altogether. The marking flags were somewhat easier to see yet the main error lies in missing or recounting trees. The 1982 regrowth has the largest error in counting trees due to the large number of trees present. The marking flags like the 350+ year old site were incredibly hard to see, so trees could have been counted more than once or missed altogether. As there were only two people counting trees at any site at any time it became unclear as to where the grid squares started and finished. To overcome this and decrease error it would have been best to have at least four people counting trees at once, with one person standing on each marker flag for given grid squares.

The diameter of mountain ash trees increases as the forests age, as shown in Table 3. The diameters of the mountain ash trees within the forests vary greatly from the largest diameter at 47.75 cm to the smallest diameter at 6.05 cm within the 1982 regrowth. The same can be seen in the 1926 regrowth where the largest diameter is 162.0 cm compared to the smallest at 46.8 cm. It is very likely that these smaller trees within these two sites are the ones that die off and lead to the thinning out of the plots as seen in Table 2. This shows that, as the forest ages, the intense competition between the plants for sunlight and nutrients results in rapid tree growth (diameter of the tree) in a young stand, resulting in the weaker trees being shaded out and dying. This leads to the large gaps forming in the canopy (Vertessy *et al.,* 2001). At the 350+ year old site the largest diameter measured was 316.1 cm and the smallest was 140.1 cm. However at the 350+ year old site there was greater error in measuring the trees diameter at breast height, as the trees near the base are no longer round. The errors shown in Table 3 are associated with the errors in using the tape measure. It is possible that as the tape measure was wrapped around the tree it wasn't perfectly horizontal, which adds to errors in the measured circumference.

1982 regrowth		**1926 regrowth**		**350+**	
Average diameter (cm)	22.07±5.0	Average diameter (cm)	97±5.0	Average diameter (cm)	221.32±5.0
Standard Deviation (cm)	11.29±5.0	Standard Deviation (cm)	25.20±5.0	Standard Deviation (cm)	55.18±5.0

Table 3. The average diameter at breast height of a sample of mountain ash trees across the 3 different aged stands.

The tree height of mountain ash trees is closely related to the diameter, as they both increase with forest age. The height of the mountain ash trees varies greatly within the three stands. The tallest tree in the 1982 regrowth from those measured was 35.20 m tall and the smallest was 6.3 m tall. Within the 1926 regrowth the tallest tree from those measured was 74 m tall and the smallest was 47.9 m tall. Again this variability in size of trees can be related back intense competition between the plants for sunlight and nutrients resulting in rapid tree growth (height of the tree) in a young stand, resulting in the weaker trees being shaded out and dying. The tallest tree from those measured at the 350+ year old site was 89.97 m all and the smallest is 67.23 m tall. The tallest mountain ash tree currently on record stands at 92 m tall (Hickey *et al.*, 2000)

1982 regrowth		**1926 regrowth**		**350+**	
Average height (m)	21.23±1.31	Average height (m)	60.11±2.18	Average height (m)	80.44±2.18
Standard Deviation (m)	8.29±1.31	Standard Deviation (m)	5.43±2.18	Standard Deviation (m)	7.93±2.18

Table 4. The Average height of a sample of mountain ash trees across the 3 different aged stands.

These results from Table 4 can be related to a study done in Tasmania by Hickey *et al.* (2000), where tree heights were measured over different aged stands as shown in Figure 10 and modelled by the equation:

Height = -0.37 + 2.78(ln age)^2 … (6)

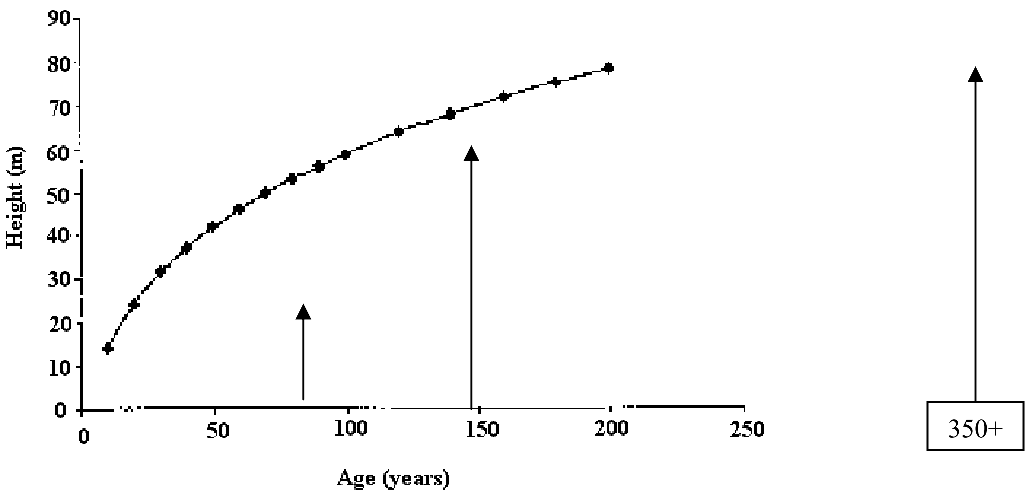

Figure 10. Height growth for Mountain ash trees, modelled by Equation 6. Data from Table 4 is shown by arrows (Hickey *et al.*, 2000).

From looking at Figure 10 there is a strong correlation between the two sets of data. At the 1982 regrowth, shown at 23 years, Hickey *et al.* (2000) gives a height of 26.96 m, whilst from the 1982 regrowth the height was 21.23 m. The 1926 regrowth from

Table 4 shows a height of 60.11 m compared to Hickey *et al.*, with a height of 52.7 m. The graph in Figure 10 only goes up to 200 years of age but from the equation it's modelled on the tree height after 350 years of age is 95 m, Table 1 after 350+ years of age shows a height of 80.44 m.

The difference in mountain ash tree height between the two sets of data is expected for a number of reasons. The most likely explanation is that the study done by Hickey *et al.* looks at a larger sample size. The sample size chosen within the three different stands is only a relatively small one; for best results it would be necessary to sample a range of sites in each age class to test variability. Another explanation for the differences is climate. The studies done by Hickey *et al*. were done in Tasmania, whilst the data collected above was taken from Wallaby Creek, north of Melbourne in Victoria. These two sites are likely to have a very different climate along with very different soil conditions. Tree growth on these two different sites could vary greatly due to these conditions.

No studies of mountain ash forests have been published beyond a stand age of 250 years, so it is very unclear what happened with the tree height beyond this point. Figure 10 shows that beyond this point tree growth will continue. Observed data sees the average tree height after 350+ years of age to be at 80.44 m, which is less than expected. A reason for this may be that as the mountain ash trees continue to grow and reach great heights the tree tops are falling off as they can no longer support this weight. Weather and climate conditions, such as strong wind makes tall trees more susceptible to this. There was large evidence for this within the 350+ year old plot as there are large branches and tree tops on the stand floor.

The individual tree heights and diameters of the three different aged stands were plotted in Figure 11 to show the relationship between the increase in tree height and increase in tree diameter as mountain ash forests grow.

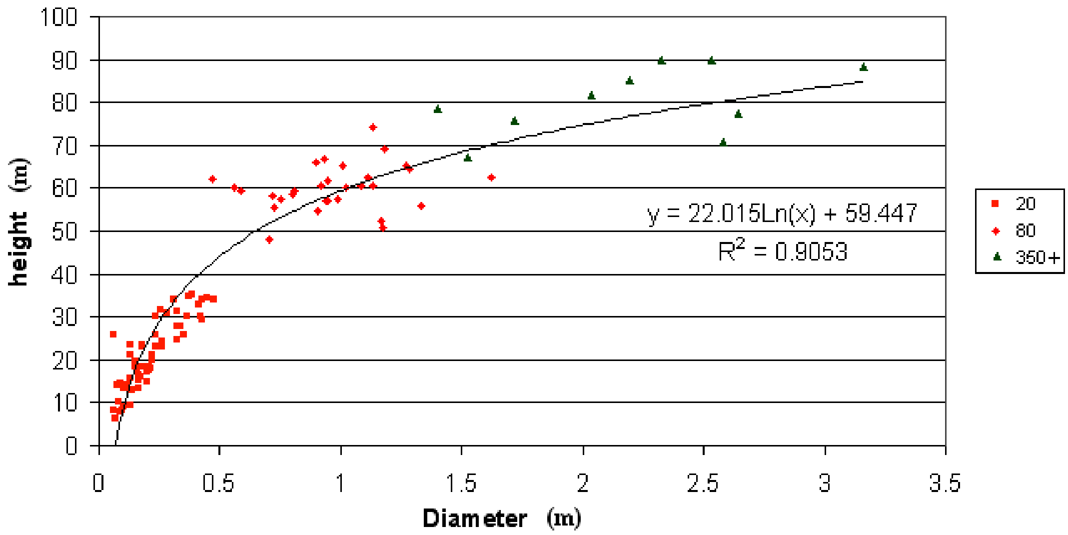

Figure 11. Relationship of height versus diameter at breast height for mountain ash trees, across all three stands.

Trees in the 1982 regrowth show a good relationship between tree diameter and tree height; as the tree diameter at breast height increases so does the tree height. The trees in the 1926 regrowth show a slight relationship between tree height and diameter at breast height, the height continues to increase with the diameter but at a slower rate compared to the 1982 regrowth. Trees in the 350+ year old site show an increase between diameter at breast height and height but again at a much slower rate. However the overall relationship between height and diameter at breast height shows that height of the trees is increasing faster than the diameter at first, and then appears that the height increases at a slower rate, while the diameter continues to grow. Previous studies have shown that there is a decrease or cease in height late in tree development whilst the diameter continues to increase (Thomas, 1996). In the 350+ year old stand it is likely that the tops of the trees are falling off as the trees get too tall to support their own weight leading to the much slower rate of increasing height with diameter. It appears that in the 1982 and 1926 regrowth that the taller trees have greater diameters, whilst in the 350+ year old stand a relationship can't be easily determined due to the tree tops falling off.

There are a number of errors associated with measuring the heights of tall trees. The first main problem is to measure the height of a tree with maximum accuracy (minimum error); the angle with the ground to the top of the tree needs to be at 45^{o}. For a tree that is 80 metres high this means being 80 metres away from it, however being 80 metres away from a tree limits the vision of that tree when using the inclinometer. For the 1982 regrowth this was no trouble; it means being an average of 21.23 m from the desired tree. For the 1926 regrowth and the 350+ year old plots this was impractical, so measurements were taken at a distance of 50 m away from these trees adding error to tree heights. Another source of error is the error associated with using the inclinometer. Holding it up to eye level and viewing the top of the tree with one eye and reading the scale on the inclinometer with the other eye adds an element of human error to the tree height. This error was added to when taking into account the slope of the ground. The slope of the ground means that there are two angles measured to calculate the height of the trees, as shown in Figure 6. Because there are two angles measured any error associated with using the inclinometer is increased.

Using the diameter at breast height of the trees shown in Table 3 and relationships determined in previous studies such as Vertessy *et al.*(1995) (Figure 12), which relate diameter at breast height to leaf area, and from this an allometric leaf area index is be determined.

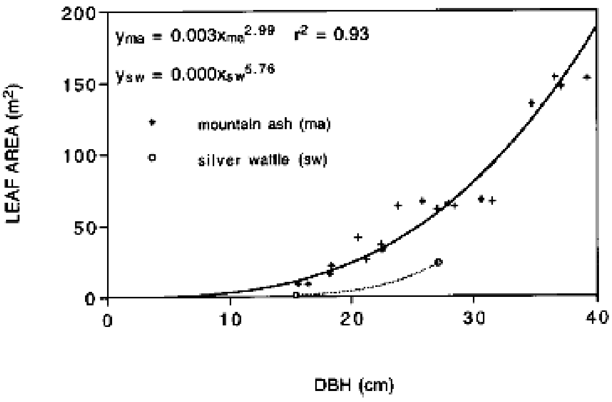

Figure 12. Relationship of diameter at breast height versus leaf area for a sample size of 19 mountain ash trees in a 15 year old stand. Mountain ash trees are denoted by plus signs (Vertessy *et al*., 1995).

The equation for the relationship between diameter at breast height and leaf area in the study is given as:

$$\text{Leaf area} = 0.003 \times \text{diameter}^{2.987} \qquad \ldots (7)$$

By taking the diameters of the mountain ash trees sampled from all three sites and applying this formula the individual leaf areas of each tree was determined. By adding these leaf areas together for each individual stand age the total leaf area for that sample size was calculated. To turn this into an allometric leaf area index the total leaf area was divided by the area of ground that the measured trees occupy; that is, how many 20 m by 20 m grids the trees occupy. The allometric leaf area index is shown in Table 5.

1982 regrowth		1926 regrowth		350+	
Total LA m^2 for 4 grids	3248.5	**Total LA m^2 for 6 grids**	92667	**Total LA m^2 for 8 grids**	353598.6
total area 4 grids	1600	**Total area 6 grids**	2400	**total area 8 grids**	3200
ALAI	2.03	**ALAI**	28.96	**ALAI**	110.5

Table 5. The allometric leaf area index (ALAI) as determined using the allometric relationship shown in Equation 7.

This allometric leaf area index correlates well with the measured leaf area index for the 1982 regrowth. The allometric leaf area index is 2.03 and the actual leaf area index of the 1982 regrowth was measured to be 2.62. This close correlation is due to the study of a 15 year old mountain ash stand, by Vertessy *et al.* (1995), with tree diameters ranging from 15.6 cm to 39.2 cm. Whereas, the actual leaf area of a 23 year old forest has diameters ranging from 6.0 cm to 47.7 cm. Equation 7 from Vertessy *et al.* doesn't work at all for any diameters over 40 cm. This also explains why the allometric leaf area indexes for the 1926 regrowth and the 350+ year old site are unrealistic, with values of 28.96 and 110.5 compared to the measured value of 2.09 and 1.69 respectively. It is also important to remember that the allometric leaf area index that was calculated in Table 5 is the leaf area index of only a selected number of mountain ash trees in the plot, not the whole plot.

To get a better allometric leaf area index for the 1982 regrowth plot it would be best to measure more tree diameters from more grid points, for a better idea of variability across the site. Another reason for any difference is due to the fact that the formula was created using only 19 trees from a 50 m by 50 m plot, so it is only created from one specific sample.

Using the number of stems in each plot and knowing the area of the plots is 4 hectares, the area each stem covers per plot was calculated. This was then multiplied by the total leaf area index of the whole site, to work out the average leaf area of each individual stem, as shown in Table 6.

Site	LAI ($m^2.m^{-2}$)	stems($stems.ha^{-1}$)	Stems (m^{-2})	Leaf area per stem
1982 regrowth	1.69	36.75	1088.44	1839.46
1926 regrowth	2.09	238.5	167.72	350.52
350+	2.62	897.5	44.57	116.77

Table 6. The leaf area of each individual stem for the three different aged plots.

By taking this value of leaf area per stem and graphing it against the average diameter at breast height of the sites, an allometric relationship similar to that of Figure 12 was established, showing the relationship between diameter at breast height and the leaf area of individual trees for the three different aged stands. The relationship obtained by the trend line is:

$$\text{Leaf area} = 20.786 \times e^{0.0143 \times \text{diameter}} \quad \ldots(8)$$

with an R^2 value of 0.999.

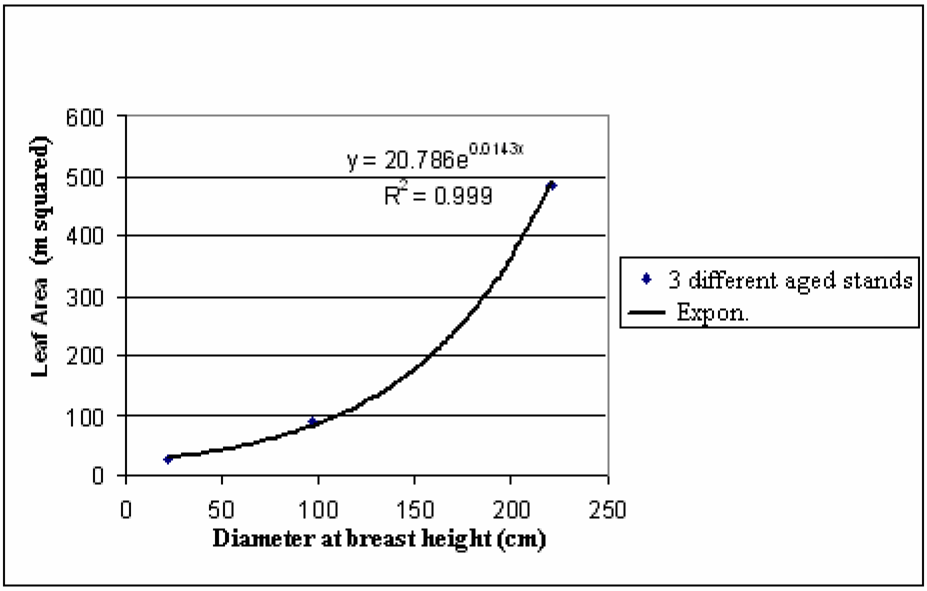

Figure 13. The relationship between the diameter at breast height and the leaf area of individual trees across the three different aged stands.

Using this graph it is possible to be able to work out an estimate of a mountain ash trees leaf area by knowing only its diameter. This relationship correlates well with previous relationship such as that shown in Figure 12. This can be shown by taking the data from Vertessy *et al.* (1995), which was used to make the relationship shown in Figure 12, and working out the average tree diameter and average leaf area, then adding this as a data point to Figure 13, shown as Figure 14. The extra data point only changes the relationship slightly and fits well with the rest of the data, hence showing strong correlation. The new relationship obtained by the trend line is:

$$\text{Leaf area} = 60.551 \times e^{0.0153 \times \text{diameter}} \quad \ldots(9)$$

with an R^2 value of 0.9037.

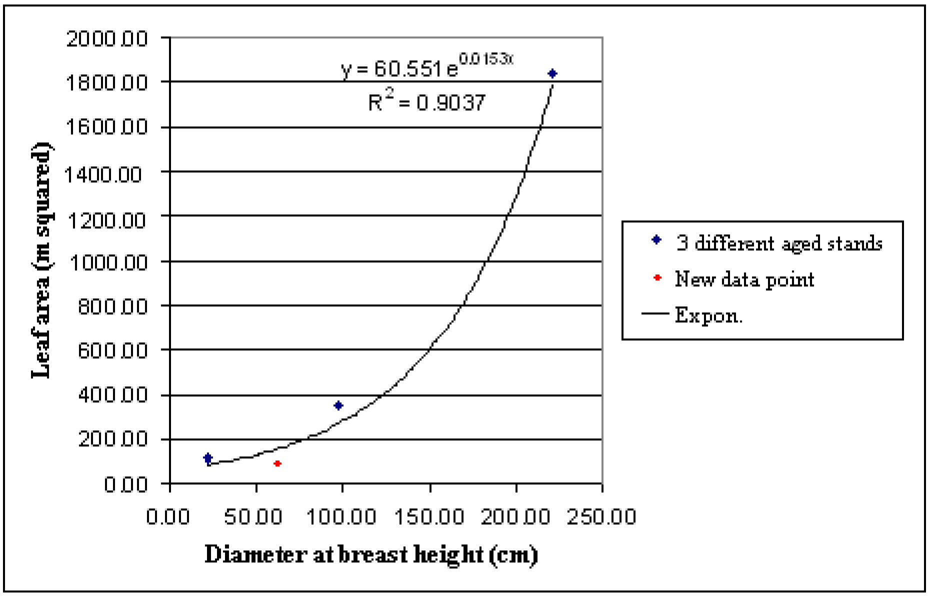

Figure 14. The relationship between the diameter at breast height and the leaf area of individual trees across the three different aged stands with the extra data point added from Vertessy *et al.* 1995, to show correlation.

This new relationship was then taken and used to work out an allometric leaf area index, similar to that of Table 5. This new allometric leaf area index (Table 6) shows a much more realistic value for all three of the measured sites. The total leaf area of the grids within each site is also now more realistic than the previous results in Table 5. The 1982 regrowth allometric leaf area index is now 3.02 compared with the measured leaf area index of 2.26. The 1926 regrowth allometric leaf area index is now 3.59, compared to 2.09, and the 350+ year old site allometric leaf area index is now 7.62, compared to 1.69. The difference in allometric leaf area index to the measured leaf area index is due to the allometric leaf area index being the leaf area index for only a selected number of grid points, not the whole site. This is why the allometric leaf area index increases with stand age.

1982 regrowth		1926 regrowth		350+	
Total LA m^2 for 4 grids	4,826	**Total LA m^2 for 6 grids**	8,627	**Total LA m^2 for 8 grids**	24,382
Total area 4 grids	1,600	**Total area 6 grids**	2,400	**Total area 8 grids**	3,200
ALAI	3.02	**ALAI**	3.59	**ALAI**	7.62

Table 6. New allometric leaf area index (ALAI) determined by using the new allometric relationship.

Conclusion

Mountain ash forests in catchment areas display evident characteristics as they age after bush fires, which have effects on the water yield and runoff into water catchments. The most important characteristic displayed is the decrease in the overall leaf area of the mountain ash trees. This was measured using an LAI-2000 plant canopy analyser and showed there was an overall decrease in leaf area index, thus a decrease in leaf area as the forests age. The 1982 regrowth leaf area index was measured to be 2.62, compared to the 1926 regrowth leaf area index of 2.09, and the 350+ year old forest of 1.69. The decrease in leaf area of the mountain ash trees is further enhanced by looking at the number of stems (mountain ash trees) per hectare at the three different age classes, because the decrease in leaf area is due to a decrease in the number of mountain ash trees present. The 1982 regrowth had 897.5 stems per hectare, the 1926 regrowth had 238.5 stems per hectare and the 350+ year old site had only 36.75 stems per hectare. The decrease in leaf area of mountain ash trees as the forests ages is counteracted by an increase in leaf area of undergrowth. However, after a bush fire the yield of water in catchments is decreased do to a large leaf area index, thus a more water lost through evapotranspiration. Over time, this yield increases as the leaf area index decreases. Therefore as a young mountain ash forest has a larger leaf area, the water lost through evapotranspiration by the mountain ash trees in the young forest is going to be more than that lost by the mountain ash trees in an old growth forest with a smaller leaf area. Thus we see the shape shown by Kuczera's curve, Figure 1. The measurements of leaf area index from the three age classes within the Wallaby Creek Catchment reflect this effect on water yield as the forest ages due to a decreasing leaf area with stand age. It is believed that, although as the mountain ash forests leaf area decreases and the undergrowth leaf area increases, the total leaf area of the forests decrease with stand age. Further studies of the leaf area index and transpiration for the undergrowth and studies of transpiration of mountain ash trees would give a clearer picture of these affects.

As the mountain ash forests age, the diameter at breast height and height of the trees increase. Tree diameters range from an average of just 22.07 cm at the 1982 regrowth to an average of 221.3 cm at the 350+ year old site. The tree heights range from an average of just 21.23 m at the 1982 regrowth to and average of 80.44 m at the 350+ year old site. The relationship between diameter at breast height and tree height shows that as diameter increases so does the tree height, logarithmically. This is due to the fact the trees grow rapidly at a young age and then less as they age. At the 350+ year age site it is seen that the tree heights were less than first expected due to the tops of the trees falling off as they age.

By working out an allometric relationship between diameter at breast height and leaf area of each individual tree, it is possible to estimate a trees leaf area when knowing its diameter. This relationship was calculated to be:

$$\text{Leaf area} = 60.551 \times e^{0.0153 \times \text{diameter}}$$

with an R^2 value of 0.9037.

From this and previous studies by Vertessy *et al.*, (1995) an allometric leaf area index was calculated by working out the leaf areas of a sample group of trees and dividing it by the ground area these trees inhabit. When compared to the measured leaf area index from each site, there is strong correlation between the two values for the 1982 regrowth, with the allometric leaf area index of 3.02, compared with the measured leaf area index of 2.62. There is no correlation between the allometric leaf area index and the measured leaf area index at the other two sites, as the allometric leaf area index increases with stand age.

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